THE HUMAN CIRCADIAN CLOCK regulates the temporal organization of physiological functions in accordance not only with the day-night alternation, but also with the seasonal change in photoperiod (2, 3). Seasonality in circadian rhythms, especially in phase, has been observed in humans (16). In Sapporo city (latitude 43° north, longitude 141° east), the circadian rhythms in plasma melatonin and rectal temperature in male students were reported to undergo a seasonal change. On the other hand, the peak phase of melatonin rhythm was phase delayed by 4.1 h in winter compared with summer. When the analysis is limited to the Dome data, the seasonal difference was reduced to 1.3 h. Similarly, the trough phase of rectal temperature rhythm in two of three subjects was phase delayed by ~2 h in winter. From these findings, the sleep or activity rhythm is concluded to be reset predominantly by the work schedule, whereas the circadian rhythm in plasma melatonin and rectal temperature is substantially influenced by the photoperiod.

Yoneyama, S., S. Hashimoto, and K. Honma. Seasonal changes of human circadian rhythms in Antarctica. Am. J. Physiol. 277 (Regulatory Integrative Comp. Physiol. 46): R1091–R1097, 1999.—The human circadian rhythms in sleep, activity, plasma melatonin, and rectal temperature were explored under two conflicting time cues in Antarctica: an extreme photoperiod and a strict work schedule. The nine healthy male subjects stayed at the Antarctic zone (latitude 66.5–90° south) for 15 mo including a 13-mo wintering at the Dome station (latitude 77° south). Neither the phases nor the amounts of sleep and daily activity underwent a seasonal change. On the other hand, the peak phase of melatonin rhythm was phase delayed by 4.1 h in winter compared with summer. When the analysis is limited to the Dome data, the seasonal difference was reduced to 1.3 h. Similarly, the trough phase of rectal temperature rhythm in two of three subjects was phase delayed by ~2 h in winter. From these findings, the sleep or activity rhythm is concluded to be reset predominantly by the work schedule, whereas the circadian rhythm in plasma melatonin and rectal temperature is substantially influenced by the photoperiod.

sleep; melatonin; rectal temperature; social cue; photoperiod

MATERIALS AND METHODS

Subjects. The subjects were nine healthy males aged from 26 to 50 years at the beginning of the experiment (mean ± SD: 38.0 ± 8.5 yr). They were members of the 37th Japanese Antarctic Research Expedition and stayed at Dome Fuji Station (Dome) as the wintering members. All subjects gave informed consent, and the study protocol was approved by the Headquarters of Japanese Antarctic Research Expedition and National Institute of Polar Research.

Location and climate. Dome is located on the ice sheet in Queen Maud Land, East Antarctica (latitude 77° south, longitude 39° east, altitude 3,810 m above sea level), and 1,000 km removed from the main station of Japan, Syowa. The atmospheric pressure was 600 hPa. The mean outside temperature was –54.4°C, and the lowest recorded temperature was –79.7°C. Almost half of the year it was below –60°C. Because of its high latitude, the sun did not rise for 114 days in winter (from April 26 to August 16) and did not set for 116 days in summer (from October 26 to February 18). Only in the remaining 4 mo was there a day-night alternation.

Experimental procedures. The subjects left Japan on November 14, 1995, and entered into the Antarctic area on December 13, 1995. They reached the transportation point called S16 (latitude 69° south, longitude 40° east, altitude 553 m above sea level) at the coast of Antarctica on December 17, 1995, and stayed there for a week. Three weeks later, they arrived at Dome on January 12, 1996, and stayed there for 13 mo until January 25, 1997. Two weeks later, they reached S16
and boarded the return ship on February 10, 1997. Finally, they left the Antarctic area on March 12, 1997.

In the base, each subject had an individual room without a window. Only in the living room were there a few small windows without curtains. The light intensity in the inside of the building was ~300 lx, except in the living room, where the maximum intensity was 500 lx measured at head level (fluorescent light). The base was separated into resident and drill sites. The drill site was located 5 m below the snow surface. In the resident site, the ambient temperature was ~20°C and the relative humidity was about 20%. On the other hand, in the drill site, the temperature was below ~30°C. The subjects were permitted to have contact with persons outside Dome by telephone or fax. During the experiment, they had no visitors from other bases.

As the routine work, subjects bored and analyzed the Antarctic glacier for 8 h. They dug the ice sheet with the use of a computer-controlled drill to get the ice core and analyzed the core sample. The duty was in rotation. Two subjects worked together from 0630 to 1430 and were replaced by another pair from 1430 to 2230. Another three analyzed the sample from 1000 to 1800. The eighth subject performed daily living tasks and was expected to get up before breakfast at 0730. The rotation of duties proceeded as followed: each subject performed early digging for 1 to 2 days, followed by late digging for 1 to 2 days. Next, each subject turned to sample analysis for 1 to 2 days, followed by daily living tasks. Finally, each subject had 1 day off duty. This schedule rotated every 6–9 days. The subjects, except for those involved in the early digging and in daily living tasks, sometimes skipped breakfast because of late waking. After lunch, all members, except the first pair, went to a nearby ice bunker to collect ice blocks for water. It took about 30 min for digging. All subjects were permitted to bathe, engage in light physical exercise, and nap. They retired at around midnight.

Measurements. A sleep diary was kept by the subjects every day from December 1995 to March 1997. In three subjects, wrist activity was recorded every 30 s with an ambulatory logger (Actigram, AMI) worn all day on the nondominant wrist for 13 mo. Rectal temperature was also recorded in these subjects every 20 s with an ambulatory device (LT-8, Gram) through a probe inserted into the rectum. Light intensity actually received by one subject was measured every 1 min with sensors worn on the wrist and head cap (Actillum, AMI). These data were fed into a computer once a week.

Blood sampling. Blood sampling was performed in eight subjects for eight times during the experimental period. Sampling was done two times on the ship (December 1995: latitude 68° south, longitude 39° east; March 1997: latitude 67° south, longitude 48° east) and six times at Dome (March 1996-December 1996). Every second month, a 24-h blood sampling was undertaken through an indwelling catheter placed in the forearm vein. Blood was sampled at 2-h intervals from 1400 to 1200 on the following day. Ten milliliters of blood were taken at each sampling. Plasma was separated immediately by centrifugation and stored at ~60°C. Melatonin was determined in Japan by radioimmunoassay with a two-antibody method (12). The intra- and interassay variance were 6.6 and 7.0%, respectively.

Data analyses. The 24-h profiles of activity, plasma melatonin, and rectal temperature were analyzed by a cosine curve-fitting method (10). The peak phase, the area under the curve, the duration and the amplitude of plasma melatonin rhythm, and the trough phase of rectal temperature were obtained. The sleep phases and duration were also calculated.

We analyzed both the sleep onset and offset, in addition to the midpoint between the sleep onset and offset, and calculated the mean values of these phases for each month. With the use of these values, the period was obtained by a linear regression method. Repeated measures ANOVA and post hoc multiple t-test (Fisher, Scheffé’s, Bonferroni/Dunn) were used for statistical analyses with Stat View version 5.0, SAS Institute.

RESULTS

Climate. Figure 1 illustrates the annual change of the climate at Dome. In winter, the mean ambient temperature was lower than ~60°C. The energy of the global reflected solar radiation was almost 0 MJ/m², and the light intensity actually received by the subjects was from 0 to 300 lx. In summer, the mean ambient
temperature was −30°C. The global reflected solar radiation was 40 MJ/m², and the light intensity was up to 100,000 lx. The subject was occasionally exposed to bright light of 70,000–90,000 lx. The intensity of artificial lighting at Dome was constant throughout the year. For example, the dining room was 300 lx, the drill site was 100 lx, the analyzing site was 200 lx, the individual room was 100–200 lx, and the snow cave and the passageway were <50 lx, which were measured at the head level of a standing subject.

Sleep rhythm. The annual profiles of the sleep-wake cycle are illustrated individually in Fig. 2. From December 1995 to February 1997, sleep phases are monthly averaged and shown as solid bars. In February 1996, a sleep diary was not kept because all subjects were busy preparing for winter. In March 1997, the subjects were on the return ship to Australia, and therefore in a different time zone from Dome. These data were not included. In subjects YK and KY, neither the phase nor the duration of sleep changed throughout the year. The sleep phases in the other subjects, except subject BE, were slightly delayed in winter and advanced in summer, but the duration of sleep was not changed. The sleep rhythm in subject BE started to produce continuous shift delays (ANOVA, P < 0.01) from the end of winter. The period of sleep rhythm calculated by linear regression was 24.7 h in reference to the sleep onset and 24.9 h to the sleep end, respectively. The mean phase and duration of sleep in eight subjects are summarized in Table 1. The data of subject BE were not included because of continuous phase delaying. The midpoint between the sleep onset and offset is defined as the phase of sleep rhythm and the duration between the onset and offset as the length of sleep. Neither the phase (P = 0.25) nor the duration (P = 0.27) was changed significantly throughout the year.

Activity rhythm. Figure 3 illustrates the circadian rhythm in the wrist activity throughout the year in subject YK. The mean activity was calculated every 10 min and the monthly mean of each 10-min bin is expressed as the histogram. In March 1996, many data were missed due to mechanical trouble, so results were not included. By visual inspection, there was no definite change in the amount or the phase of activity rhythm from April to December. In early January, the subject had an emergent mission of 1 wk almost without sleep for fuel transport, so that the activity in the nighttime was high compared with other months. The seasonal changes in the peak phase and the amounts of activity in three subjects are shown in Fig. 4. Two of three subjects had no significant change in the peak phases. In subject BE, the peak phase had delayed similarly to his sleep-wake cycle. In the amount of activity, there was no significant change throughout the year. In April, the subjects had mechanical troubles with the device, so part of the data were missed.

Melatonin rhythm. Figure 5 illustrates a seasonal change in the mean melatonin rhythm of six subjects. Results of statistical analyses are shown in Table 2. Subject KY did not show a nocturnal elevation of plasma melatonin, and the melatonin rhythm in subject BE continuously phase delayed similarly to the sleep-wake cycle. These results were excluded from the statistical analysis. There was a significant change in

Fig. 2. Annual profile in individual sleep-wake cycle. Monthly means of sleep timing are shown as solid bars. Shaded area indicates period without sunlight. For details, see MATERIALS AND METHODS.
the peak phase throughout the year ($P < 0.0001$). Post hoc multiple t-test revealed the maximum phase difference of 4.1 h at Antarctica (December 1995 vs. August 1996) and 1.3 h at Dome (March 1996 vs. August 1996). When the seasonal change was considered on an individual basis, the difference became much larger. At Dome, the maximum phase delay was observed in April (1 subject), June (2 subjects), August (2 subjects), and October (1 subject), whereas the maximum phase advance was in March 1996 (4 subjects) and December 1996 (2 subjects). In all subjects, the melatonin rhythm was phase advanced in summer and phase delayed in winter. The seasonal difference in individuals varied from 1.5 to 5.2 h. The mean was 2.3 h (SD = 1.4). On the other hand, the area under the curve and the duration and the amplitude of melatonin rhythm did not change significantly.

Rectal temperature rhythm. Figure 6 demonstrates the seasonal change in the trough phases of rectal temperature rhythms in three subjects. The trough phases were calculated for a 24-h window of data at 10-min intervals. By visual inspection, the trough phases in subjects YO and YK were delayed by 2 h in winter compared with summer. But in subject BE, the phase was advanced by 4 h in winter compared with summer.

Seasonal changes in the phases of circadian rhythms. Figure 7 demonstrates the seasonal changes in the phases of melatonin and sleep rhythms. The melatonin rhythm was phase delayed 4 h in winter. On the other hand, the phase of sleep rhythm did not change throughout the year. As a result, the phase-angle difference

Table 1. Seasonal change in sleep rhythm

<table>
<thead>
<tr>
<th></th>
<th>Phase, h</th>
<th>Length, h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 95</td>
<td>3.4 ± 0.1</td>
<td>6.7 ± 0.2</td>
</tr>
<tr>
<td>Jan 96</td>
<td>3.3 ± 0.1</td>
<td>6.7 ± 0.2</td>
</tr>
<tr>
<td>Mar</td>
<td>3.5 ± 0.2</td>
<td>6.7 ± 0.6</td>
</tr>
<tr>
<td>Apr</td>
<td>3.6 ± 0.2</td>
<td>6.8 ± 0.5</td>
</tr>
<tr>
<td>May</td>
<td>3.6 ± 0.1</td>
<td>7.0 ± 0.4</td>
</tr>
<tr>
<td>Jun</td>
<td>3.5 ± 0.2</td>
<td>6.8 ± 0.5</td>
</tr>
<tr>
<td>Jul</td>
<td>3.5 ± 0.1</td>
<td>6.7 ± 0.4</td>
</tr>
<tr>
<td>Aug</td>
<td>3.7 ± 0.1</td>
<td>7.3 ± 0.3</td>
</tr>
<tr>
<td>Sep</td>
<td>3.8 ± 0.1</td>
<td>7.4 ± 0.2</td>
</tr>
<tr>
<td>Oct</td>
<td>3.7 ± 0.1</td>
<td>7.4 ± 0.1</td>
</tr>
<tr>
<td>Nov</td>
<td>3.9 ± 0.1</td>
<td>7.6 ± 0.2</td>
</tr>
<tr>
<td>Dec</td>
<td>3.8 ± 0.1</td>
<td>7.5 ± 0.2</td>
</tr>
<tr>
<td>Jan 97</td>
<td>3.5 ± 0.1</td>
<td>6.9 ± 0.2</td>
</tr>
<tr>
<td>Feb</td>
<td>3.6 ± 0.1</td>
<td>7.2 ± 0.2</td>
</tr>
<tr>
<td>ANOVA</td>
<td>P = 0.25</td>
<td>P = 0.27</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 8. Phase means midpoint between sleep onset and offset. Both phase and length did not change significantly.
The present study clearly shows the seasonal change in the phase of circadian melatonin rhythm but not of the sleep or activity rhythms in Antarctica. The melatonin rhythm was phase delayed by 4.1 h (1.3 h at Dome) in winter compared with in summer (Fig. 5). When the seasonal change was considered individually, the difference became 2.3 h on the average at Dome. The rectal temperature rhythm was also phase delayed by 2.8 h in two of three subjects (Fig. 6). Similar seasonal shifts have been previously observed in polar regions (1–3). Because human circadian rhythms respond to bright light (7, 8, 14), the seasonal change in the phase of circadian rhythm is most probably due to the seasonal change in the photoperiod.

At Dome, the sun does not set for 4 mo, and the light intensity outside exceeds 100,000 lx in summer. By contrast, the sun does not rise for 4 mo and the light intensity is almost at an undetectable level in winter. The human circadian rhythms phase advance in response to bright light in the subjective morning and phase delay in response to bright light in the subjective evening. Because the sun in summer rises earlier and its energy is much stronger than in winter, the circadian rhythm was changed seasonally.

### DISCUSSION

Table 2. Seasonal change in melatonin rhythm

<table>
<thead>
<tr>
<th>Month</th>
<th>Achrophase, h</th>
<th>AUC × 10^3, pg/24 h</th>
<th>Duration, h</th>
<th>Amplitude, pg/ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 95</td>
<td>1.8 ± 0.2</td>
<td>6.5 ± 1.2</td>
<td>7.8 ± 0.6</td>
<td>19 ± 3.2</td>
</tr>
<tr>
<td>Mar 96</td>
<td>4.6 ± 0.2</td>
<td>4.8 ± 0.7</td>
<td>6.9 ± 0.3</td>
<td>15 ± 1.7</td>
</tr>
<tr>
<td>Apr</td>
<td>5.9 ± 0.4</td>
<td>4.5 ± 1.0</td>
<td>6.9 ± 0.4</td>
<td>16 ± 2.9</td>
</tr>
<tr>
<td>Jun</td>
<td>5.6 ± 0.3</td>
<td>5.5 ± 1.4</td>
<td>7.5 ± 0.4</td>
<td>17 ± 4.4</td>
</tr>
<tr>
<td>Aug</td>
<td>5.9 ± 0.3</td>
<td>5.6 ± 1.7</td>
<td>6.9 ± 0.3</td>
<td>17 ± 4.4</td>
</tr>
<tr>
<td>Oct</td>
<td>5.7 ± 0.4</td>
<td>4.8 ± 1.0</td>
<td>6.5 ± 0.3</td>
<td>15 ± 3.2</td>
</tr>
<tr>
<td>Dec</td>
<td>4.5 ± 0.6</td>
<td>5.2 ± 1.4</td>
<td>5.8 ± 0.5</td>
<td>16 ± 4.0</td>
</tr>
<tr>
<td>Mar 97</td>
<td>3.4 ± 0.9</td>
<td>3.4 ± 0.5</td>
<td>6.5 ± 0.5</td>
<td>12 ± 1.7</td>
</tr>
</tbody>
</table>

Values are means ± SE; n = 6. Achrophase had significant seasonal change but area under curve (AUC), duration, and amplitude did not change significantly.

Fig. 5. Seasonal changes in monthly mean plasma melatonin rhythm in 6 subjects. Values are expressed with mean and SE. Shaded area indicates period without sunlight.

Fig. 6. Seasonal changes in trough phase of rectal temperature rhythm in 3 subjects. ○, subject BE; △, subject YO; □, subject YK. Trough phase was calculated by a cosine curve-fitting method and monthly means are shown.
Circadian rhythms phase advance in summer and phase delay or even start to free run in winter. The phase difference of the circadian rhythm in the two seasons may depend on the difference in the photoperiod and the light intensity (11). However, the observed phase difference of 4.1 h (1.3 h at Dome) was not so large as expected from the extreme seasonal change of photoperiod in Antarctica. The value was only slightly larger than that observed in the temperate zones (10, 15). The effect of photoperiod in Antarctica might be attenuated by forced indoor life because of the harsh environment. In winter, the subjects could stay outdoors only ~15 min because of the extremely low temperature. Even in summer, they could not work outside >1 h due to low temperature and oxygen concentration. As a result, an actual range of seasonality in the light intensity was ~300–9,000 lx during the waking period (Fig. 1).

On the other hand, seasonality was not detected in the sleep-wake rhythm or in the wrist activity rhythm (Figs. 2 and 3). In some individuals, however, there was a tendency to phase delay in winter. Furthermore, the sleep rhythm in subject BE was continuously phase delaying from the end of winter (Fig. 2), suggesting free running of the circadian pacemaker. Subject BE was involved in meteorological observations and spent a relatively short time on duty compared with other members, which permitted him to use time more freely. This might be related to a failure of stable entrainment in this particular subject due to less-strict zeitgebers.

The present results can be compared with previous studies (13, 20), which had two kinds of social zeitgebers. The circadian rhythms of melatonin, cortisol, and sleep were free running in Antarctic winter when subjects had no daily structure, although they knew the time of day (13). In contrast, technical staff of the Air Force at Tromsø, whose daily life seemed to be strictly scheduled, showed no difference in sleep parameters or in the circadian rhythms of cortisol and growth hormone in four seasons (20).

It has been a matter of debate whether the human circadian pacemaker responds to social factors (non-photic time cue) and entrains to social time cues (4, 6). The effect of bright light on the circadian pacemaker has been considered as primary, and the social time cue has been interpreted as a gate for light information (5). However, the forced sleep schedule, a kind of social time cue, was recently demonstrated to have differential effects on the sleep rhythm and circadian rhythms in plasma melatonin or in rectal temperature (9). The sleep rhythm entrained to the time cue independently of the circadian pacemaker, whereas the circadian melatonin rhythm was less influenced by it. As a result, when there is a discrepancy in the phases of two time cues, light and social cues, internal desynchronization is induced between sleep and the circadian rhythms (10). Because the seasonal change in photoperiod is large in Antarctica, a discrepancy between the phases of light and social cues is easily expected to become largest in a particular season if the social cue is kept constant throughout the year, as demonstrated in Fig. 7. Under these conditions, three possibilities are conceivable for the entrainment of sleep and circadian rhythms. Seasonal variations of sleep and circadian rhythms would be large when social time cues are weak. In this case, the entrainment of sleep and circadian rhythms are regulated exclusively by the photoperiod, as exemplified by the study at Cape Evans. Seasonality would not be detected when social cues are extremely strong. In this case, the entrainment of sleep and circadian rhythms are regulated by the social time cues (which also regulate light exposure), as exemplified by the study at Tromsø. On the other hand, when the strength of social cues is intermediate, the sleep rhythm would be kept constant throughout the year, whereas the circadian rhythm in melatonin or rectal temperature would change seasonally. In this case, the entrainment of sleep rhythm is regulated by social time cues and that of circadian rhythms by photoperiod, as exemplified by the present study. The social time cues possibly counteract the effect of photoperiod on the circadian rhythm. Therefore, the extent of seasonality in the circadian rhythms may depend on the relative strength of photoperiod and social cues. This seems to be another reason why the phase difference of melatonin rhythm between summer and winter was not much different from that observed in the temperate zones (10, 15).

Internal desynchronization between sleep and circadian rhythms is regarded as the major cause of jet lag or sleep disturbance associated with shift workers. Similar sleep disturbances have been reported in win-
ter at polar regions (17). Actually, some subjects in the present study complained of insomnia or inefficiency of their work in winter. It is not known, however, whether these malfunctions are due to internal desynchronization between sleep and circadian rhythms or a lack of bright light.

In conclusion, the sleep or activity rhythms of the present subjects in Antarctica were controlled predominantly by the work schedule, whereas the circadian rhythm in plasma melatonin and rectal temperature were substantially influenced by the photoperiod. The strict work schedule might counteract the effect of photoperiod on the circadian rhythms. These results can be explained by differential effects of social time cues on the sleep and circadian rhythms.

Perspectives

In the present study, human circadian rhythms in rest-activity, plasma melatonin, and rectal temperature were shown to be affected differentially by photoperiodism (seasonal changes in daytime duration as well as in light intensity) and social schedules. The rest-activity or sleep-wake rhythm was strongly influenced by social schedule, whereas the circadian rhythms in rectal temperature and plasma melatonin were much more affected by environmental light conditions.

First, the findings of this work provide a new insight into the functional structure and regulatory mechanism of the human circadian system. The human circadian system has been proposed to consist of two different oscillation mechanisms: one driving circadian rhythms in rectal temperature and plasma melatonin and the other regulating the sleep-wake rhythm. Light is a zeitgeber for the former mechanism, but it is a matter of debate whether the latter mechanism is regulated independently or secondarily from the former. The present study strongly suggests that the sleep-wake rhythm can be regulated by social schedules independently from the circadian rhythms.

Second, the present results may provide a clue to clarify the pathophysiology of season-related sleep or waking disorders. Because the sleep-wake rhythm can be regulated independently by social schedules as mention above, a discrepancy between the two zeitgebers, light and social schedule, will result in the so-called internal desynchronization, which is believed to be a major cause of sleep-wake rhythm disorders.

Finally, the present results will contribute to the planning of time structures of society in new frontiers, such as deep sea, space, and other planets. Appropriate combination of artificial light and social schedule would be most important to keep our bodily functions well.

The authors deeply appreciated the generous supply of melatonin antibody by Prof. K. Kawashima, Kyoritu Pharmaceutical College. The present study was financially supported by a grant from the 37th JAPANESEx Antarctic Research Expedition.

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Received 2 November 1998; accepted in final form 4 J une 1999.

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