Effects of One Night of Sleep Deprivation on Hormone Profiles and Performance Efficiency

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This study examined the effects of one night of sleep deprivation on melatonin and cortisol profiles, as well as performance efficiency of military service members. Sleep intervention consisted of total lack of sleep ($N = 7$) or 8 hours of sleep (control group; $N = 7$) during the night. All parameters were measured at selected time intervals before (day 1), during (only in sleep-deprived individuals), and after (day 2) sleep intervention. Rotary pursuit scores and handgrip strength data were used as indices of psychomotor and physical performance, respectively. In sleep-deprived individuals, more salivary melatonin, but not cortisol, was secreted than in subjects who slept adequately. Significant increases in melatonin and cortisol were noted, especially at 1:30 p.m. on the day after nighttime sleep deprivation. In contrast, the tracking scores for rotary pursuit and grip strength among sleep-deprived and rested individuals were comparable. Across a normal working day (day 1), all parameters studied revealed time-specific fluctuations in both control and sleep-deprived groups. Irrespective of nighttime sleep schedule, the patterns of performance on day 2 differed from those on day 1. The tracking performance improved on day 2, whereas grip strength worsened, which may reflect inherent learning and muscle fatigue, respectively. During the night of sleep deprivation, performance declined. In conclusion, the present study showed that one night of sleep deprivation (8 hours) resulted in significant hormonal changes on the next afternoon but did not modify tracking and muscular strength performance.

Introduction

In many modern work places, including those in the military, sleep deprivation is a common condition resulting from extended work periods, shift work, and night work. In some situations, such as during combat in the military and night shift for doctors and nurses, the demand for high levels of mental and physical performance could be seriously threatened by sleep deprivation and the accumulation of sleep debt. Well-known psychological disturbances associated with insufficient sleep include increased sleepiness and fatigue, decreased vigilance, deterioration in mood states, and difficulty in concentration,[1-3] all of which contribute to performance retardation, increased errors, greater risk of accidents, and ultimately failure of mission accomplishment. There is a need for the development of reliable investigative techniques to study how sleep deprivation affects performance, which, in turn, could provide ideas for the formulation of measures to reduce sleep-related accidents.

The detrimental effects of sleep deprivation on performance are apparently related linearly to the amount of sleep loss, such that the longer the duration of sleep deprivation, the more pronounced the disturbance.[4] For that reason, one night of sleep deprivation is usually associated with a minimal or no change in performance. Nevertheless, our interest lies in short-term sleep loss because it represents the most common form of sleep deprivation seen in the real world.

In this study, we investigated the effects of one night of sleep deprivation on the performance efficiency of military personnel and evaluated the sensitivity and suitability of the rotary pursuit and grip strength tests as indicators of psychomotor and physical performance. The rotary pursuit test is a target-aiming task that requires individuals to make rapid detection and correction responses and, hence, can be used to assess reaction time as well as concentration span. Concurrently, the establishment of salivary melatonin and cortisol profiles was used to observe the possible sleep deprivation-induced changes in circadian rhythmicity. This is the first in a series of studies to evaluate the efficacy of different types of tests in detecting the detrimental effects of sleep deprivation on performance.

Methods

Subjects and Design

Fourteen healthy male military service members between 20 and 30 years of age with no history of health or sleep problems and free of medication and drugs were randomly and equally assigned to two groups, control group 1 and sleep-deprived group 2. They were housed in the military camp, and during waking hours they were in rooms at the camp with normal office ambient light of 500 lux. They did light reading and watched television to occupy their time. At these settings, sleep and the types of activities were controlled.

On day 1 of the study, saliva samples were collected and the rotary and grip strength tests were performed at 8:00 a.m., 1:30 p.m., 6:00 p.m., 9:00 p.m., and 12:00 midnight in both groups. After the collection of saliva and the test at midnight, subjects in group 1 went to sleep. They awoke at 8:00 a.m. the next day (day 2), and saliva collection and tests were carried out at the following time intervals: 8:00 a.m., 1:30 p.m., and 6:00 p.m. For group 2 subjects who remained awake, saliva collection and tests were carried out at the additional times at 3:00 a.m. and 6:00 a.m. as well as at 8:00 a.m., 1:30 p.m., and 6:00 p.m.

Saliva Collection

At the specified time intervals, saliva samples were collected into 10-mL plastic cuvettes. Before each collection, subjects

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refrained from eating and avoided beverages containing artificial colorants and coffee. About 4 mL of saliva was collected over 5 to 10 minutes using the tongue to stimulate the salivary gland below it.

Rotary Pursuit Test

Psychomotor performance was assessed by means of the rotary pursuit task. This test involved tracking a rotating target with a stylus and simultaneous measurement of the performance scores (time on target). The pursuit rotor apparatus (Lafayette Instrument Co.) consisted of a platform with a round target of 2 cm in diameter. The platform was set to rotate at a constant speed of 45 rpm in a clockwise direction. Standard procedure involves starting with the stylus tip in contact with the target. As the target rotates for 20 seconds, the stylus tip must be kept in contact with the rotating target using the preferred hand. At each time of measurement, 10 trials per person were conducted.

Grip Strength Test

Grip strength was measured using the preferred hand on a grip dynamometer (Takei KiKi Kogyo Co. Ltd., Japan). Three trials were performed at each time point.

Sample Preparation and Hormone Assays

Saliva samples were kept frozen at −70°C for 48 hours. Subsequently, samples were thawed and transferred to plastic tubes for centrifugation for 5 minutes at 3,000 rpm using a Beckmann CS-6R centrifuge. The supernatant was collected and kept frozen in 3-mL tubes until required for assay of hormones. Salivary melatonin was measured using the salivary melatonin kit from Buhlmann Laboratories (Switzerland). Salivary cortisol was determined using the scintillation proximity assay (SPA) method developed at our institution. This method involved the overnight incubation of 100 μL of saliva with 100 μL of cortisol antibody (working dilution of 1:4,000; World Health Organization, London), 100 μL of tritium-labeled cortisol (10,000 cpm; TRK 407 B91, Amersham Life Science), and 100 μL of SPA reagent (anti-sheep; Amersham Life Science) in assay tubes. After the incubation period, the contents of each tube were counted directly in a liquid scintillation counter (Wallac, Finland). Tubes containing known concentrations of cortisol (Sigma, H-4001) in place of saliva were used to generate a dose-response curve so that unknowns could be interpolated from the curve. Samples for each individual were analyzed in the same assay. Intraassay coefficients of variation for all hormone assays were always less than 15%. Interassay coefficients of variation of two quality controls for melatonin (more than six assays) were 12% and 8%. For cortisol, the interassay coefficient of variation was always less than 15%.

All data were expressed as means ± SEM. Differences among control and sleep-deprived groups were tested by two-way analysis of variance (sleep status × time) for repeated measures using the General Linear Models procedure on the Statistical Product and Service Solutions (SPSS Inc., Chicago). Pairwise comparisons were performed with a post-hoc Tukey's test. Because there were no corresponding control data for the 3:00 a.m. and 6:00 a.m. time points, they were not considered in these analyses. The sleep-deprived group was also analyzed separately with the intervention times at 3:00 a.m. and 6:00 a.m. included. In addition, correlations between data of all parameters studied were calculated using Spearman's correlation test. A maximal p value of 0.05 was used to denote statistical significance.

Results

Hormone Variables

Melatonin

Variation in melatonin levels as a function of time of day was evident in both groups ($F_{7,84} = 22.708$, $p < 0.001$). Within both the control and sleep-deprived groups, post-hoc analyses showed that salivary melatonin levels were significantly higher at midnight compared with the other times ($p < 0.05$). On both pre-sleep and post-sleep intervention days, lower daytime melatonin levels at 1:30 p.m. and 6:00 p.m. compared with levels at 8:00 a.m. were noted based on significant ($p < 0.05$) and near significant analyses. An interaction between sleep status and time of day was also found ($F_{7,84} = 5.355$, $p < 0.001$). At midnight, the increase in melatonin from the low daytime levels was significantly greater in the sleep-deprived group ($p < 0.01$) than in the control group. In addition, the melatonin levels at 1:30 p.m. after sleep deprivation were significantly higher than the corresponding levels in the control group ($p < 0.01$). In the sleep-deprived group, melatonin levels increased further at 3:00 a.m., although the increase over levels at midnight was not significant. A decrease in melatonin levels at 6:00 a.m. was noted.

The two-way analysis of variance indicated that sleep-deprived subjects had significantly greater total melatonin output during the entire study period than individuals in the control group who had an adequate amount of sleep ($F_{1,12} = 9.114$, $p < 0.05$) (Fig. 1).

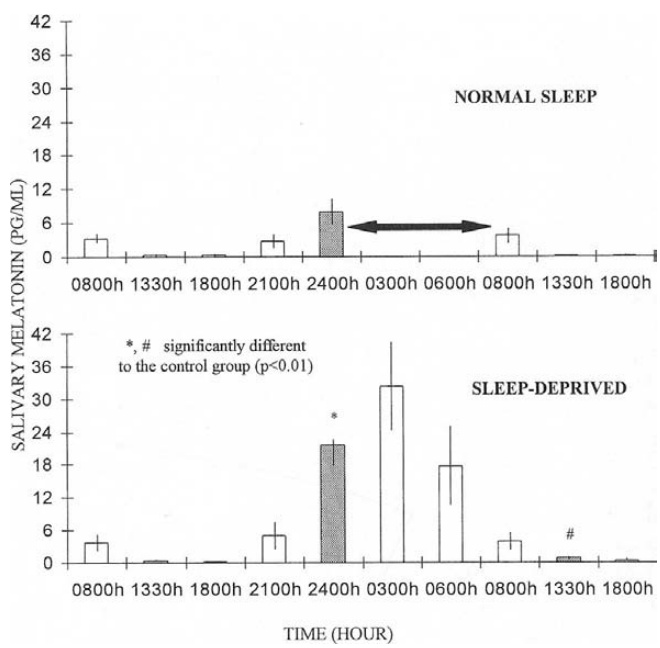

Fig. 1. Salivary melatonin profiles for the control and sleep-deprived groups (mean ± SEM, $n = 7$ per group). Black arrow represents time of sleep.

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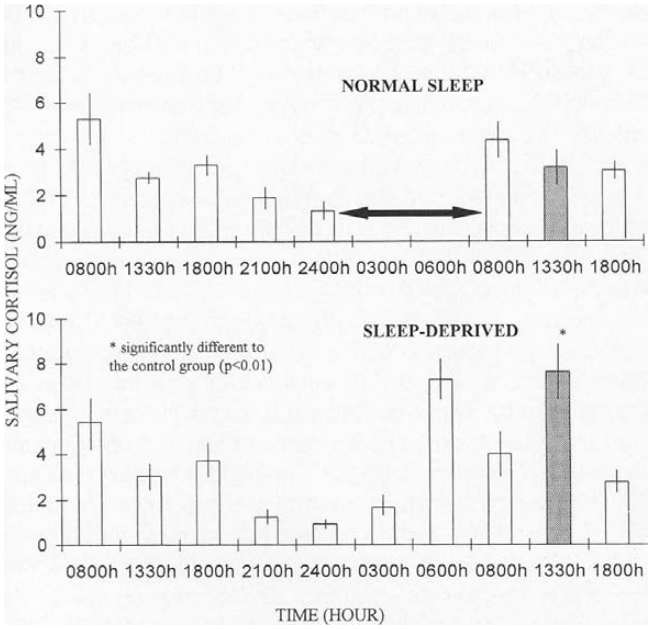

Fig. 2. Salivary cortisol profiles for the control and sleep-deprived groups (mean ± SEM, n = 7 per group). Black arrow represents time of sleep.

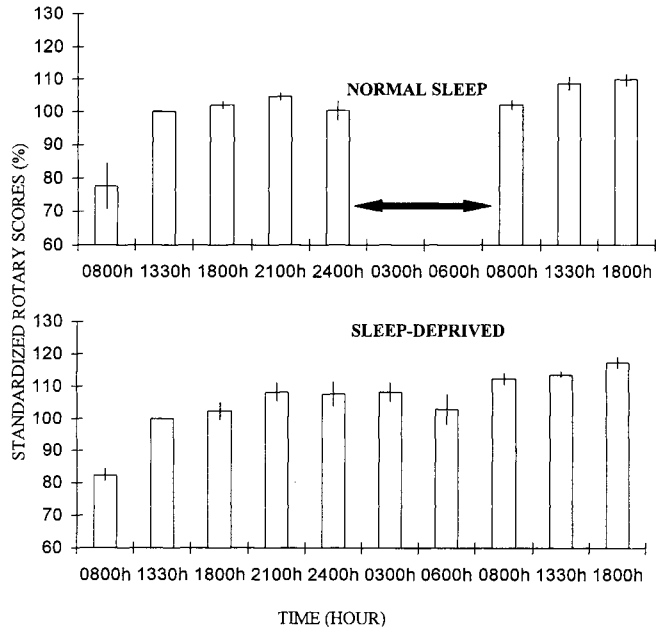

Fig. 3. Rotary tracking scores for the control and sleep-deprived groups (mean ± SEM, n = 7 per group). Black arrow represents time of sleep.

Cortisol

Mean salivary cortisol varied with time of day ($F_{7,84}$ = 13.515, $p < 0.001$) (Fig. 2). Levels were lowest at night between 9:00 p.m. and midnight ($p < 0.05$). Although there was no main effect of group (sleep status), there was an interaction effect ($F_{7,84}$ = 3.721, $p < 0.005$) whereby cortisol levels at 1:30 p.m. were increased after sleep deprivation ($p < 0.01$). In the sleep-deprived group, salivary cortisol at 6:00 a.m. was increased significantly compared with levels at 9:00 p.m., midnight, and 3:00 a.m. ($p < 0.05$).

Performance Variables

Wide individual variations in the rotary pursuit and grip strength tests were noted. These variations were standardized by using the score at 1:30 p.m. on day 1 as the common denominator and expressing all other values for each individual as percentages of this score. The score at 8:00 a.m. was not chosen because of the apparent learning effect from 8:00 a.m. to 1:30 p.m. As with the grip strength data, the maximum of three trials taken at every time point was expressed as the percentage of each individual's maximum grip strength measured for the entire test period.

Rotary Pursuit

Tracking performance varied during the day in both the control and sleep-deprived groups ($F_{7,84}$ = 32.331, $p < 0.001$) (Fig. 3). Rotary performance at the first time point (8:00 a.m.) was significantly lower than at the other time points ($p < 0.05$). As the day progressed, a steady improvement in performance was evident until 9:00 p.m., followed by a nonsignificant decline at midnight. In the sleep-deprived group, results obtained at 6:00 a.m., but not at 3:00 a.m., showed a decline, but this did not reach a significant level. After sleep intervention, further improvement occurred the next day, such that day 2 (post) rotary performance was better than that of day 1 (pre), regardless of sleep intervention ($p < 0.05$). Overall performance in the sleep-deprived group was better than that in the control group ($F_{1,12}$ = 16.746, $p < 0.005$). However, no significant interaction was found. Spearman's test revealed a significant negative correlation between rotary performance and cortisol ($r = -0.157$, $p < 0.05$).

Grip Strength

Changes in grip strength occurred as a function of time of day ($F_{7,84}$ = 4.584, $p < 0.001$) (Fig. 4). Grip performance increased progressively during the day but declined during the night.

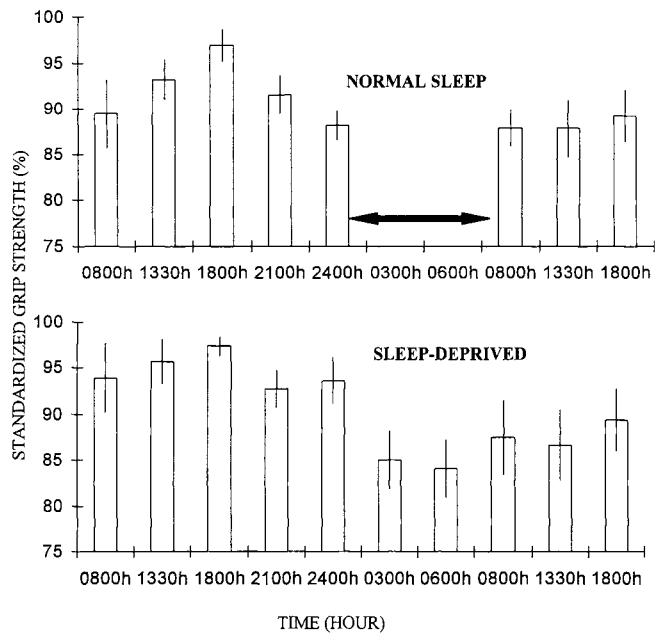

Fig. 4. Grip strength measurements for the control and sleep-deprived groups (mean ± SEM, n = 7 per group). Black arrow represents time of sleep.

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Additional sampling in the sleep-deprived group revealed a decline, albeit not a significant one, at 3:00 a.m. The reduction at 6:00 a.m. was significant, but only compared with the performance at midnight ($p < 0.05$). The next day, however, significant deterioration was observed regardless of sleep condition (adequate sleep or lack of sleep; $p < 0.05$). Neither an effect of group nor an interaction between time of day and group was found. Grip strength and rotary performance were significantly and negatively correlated ($r = -0.157$, $p < 0.05$).

Discussion

Depriving military personnel of 8 hours of sleep during one night resulted in significant hormonal changes the next day. More melatonin was secreted in sleep-deprived individuals. On the other hand, overall salivary cortisol secretion was not significantly different between the control and sleep-deprived groups. In agreement with these findings, previous studies have also reported increased melatonin secretion[5,6] and have found that cortisol secretion was less prone to change[6,7] after partial sleep deprivation.

More importantly, interactions between sleep condition and time of day existed with respect to the hormonal changes. For instance, the increase in melatonin after sleep deprivation was noted to be significant only in the afternoon (at 1:30 p.m.) after sleep deprivation, and this was accompanied by a prominent increase in cortisol at the same time. Increased levels of melatonin during the afternoon after sleep deprivation would lead to increases in daytime sleepiness as a result of its sleep-promoting properties.[8] Having to cope with staying awake despite increased sleepiness would lead to psychological stress, which may account for the increase in the stress hormone cortisol at 1:30 p.m. These findings are supported by those of Parkes,[9] who documented that the effect of one night of total sleep loss is generally greater after the morning of the next day. Interestingly, a significant increase in melatonin was also noted at midnight, before the sleep intervention. This observation, which has not been documented elsewhere, perhaps represents an anticipatory response to the ensuing sleep disturbance, because the subjects knew that they were to be deprived of sleep before the study began.

Despite staying awake during the night, the basic circadian rhythms of melatonin and cortisol remained intact in the sleep-deprived individuals, with nighttime values significantly higher than daytime values. As with cortisol, the lowest levels were found in the initial hours of the night (9:00 p.m. and midnight) and the highest levels were found in the early hours of the morning (6:00 a.m.).

Another finding of this study was that rotary pursuit tracking performance varied significantly during the day. The absence of any interaction between sleep condition and time of day indicates that the patterns of performance during the day were similar for both adequately slept and sleep-deprived groups. In both control and sleep-loss conditions, tracking performance improved during the day. Even before the night's sleep intervention, performance improved steadily as the day progressed. In particular, the increase in performance was most dramatic after the first time point of measurement at 8:00 a.m. Thereafter, a progressive improvement in performance ability was observed until 9:00 p.m. The observed enhanced pursuit performance can be explained in terms of improved motor skills as a result of learning. According to Eysenck and Frith,[10] pursuit tracking comprises an initial response involving visual feedback for the detection and correction of any misalignment between the stylus and the target, followed by the acquisition of motor programs. With practice, learning occurs, and subsequently, there is a greater reliance on the more efficient programmed motor skills and less on the visual feedback responses to accomplish the tracking task.[11] Hence, if any decrements in performance are present during the day, they are probably masked by inherent learning. During the night, however, nonsignificant decreases in performance were seen at midnight for the control group and at 6:00 a.m. but not at 3:00 a.m. for the sleep-deprived group. These declines in tracking performance may represent true circadian changes in psychomotor performance, because they occurred within the periods of the circadian trough of body temperature and the nocturnal increase of melatonin, which have been documented to correlate with reduced vigilance performance and increased sleepiness.[12] Therefore, the lack of statistically significant decline may be due to the positive effect arising from repeated performance of the tracking test. Interestingly, the times at which retardation in tracking performance occurred in both groups were noted to correspond with the last time points of measurement before sleep. Therefore, another alternative explanation is that these nonsignificant decrements in pursuit performance may represent a reduction in focused attention caused by distraction, because the subjects were aware that they could stop tracking and go to bed afterward. The ability of many momentary effects, such as motivation or interest level, to influence performance has been described elsewhere.[13]

Regardless of whether nighttime sleep was curtailed or not, the next day's tracking performance improved further and was found to be significantly greater than that during pre-sleep intervention. Apparently, the subjects' performance may still improve after dozens or even hundreds of test sessions.[14]

In the literature, impaired performance after sleep loss is a well-documented phenomenon. Furthermore, some studies[15] have shown more pronounced effects of sleep deprivation on performance during the night without sleep, when the individual is normally asleep, than the next day. Because contrasting rotary results were obtained in this study, it appears that the rotary pursuit test may not be sensitive to the detrimental effects of short-term sleep deprivation on psychomotor performance. In support of this conclusion, it has been noted that tasks that involve visual stimulation[16] or constant or nearly constant movement (rotary pursuit tracking) are less susceptible, whereas tasks that require high levels of vigilance[4] or cognition[17] are particularly sensitive to the effects of sleep loss. Inherent learning clearly is a confounding factor. Moreover, because of the simplicity of the tracking task, there is the possibility that increased concentration can overcome the impairment in performance induced by one night of sleep deprivation. Perhaps the pursuit task is sensitive to the effects of longer periods of sleep deprivation. Hence, further investigations are warranted.

With respect to the handgrip test, muscular strength was not affected by sleep deprivation (no group or interaction effect), which agrees with existing reports.[18,19] Insufficient stress on the

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upper muscles during sleep deprivation may account for the lack of effect. Another plausible explanation is that handgrip strength may not be a sensitive measure of the decrease in muscular strength induced by sleep deprivation. Nonetheless, the grip test was sensitive to time-of-day fluctuations in muscular strength. Before the nighttime sleep intervention, grip strength increased progressively during the day, attained maximal at 6:00 p.m., and decreased steadily during the night. Grip strength measured in subjects who stayed awake during their usual bedtime decreased further during the early hours of the morning (3:00 a.m. and 6:00 a.m.). These time-specific changes in grip performance may represent a true circadian profile of muscular strength. On the other hand, there is the possibility that the task is itself fatiguing and, hence, adds to the ongoing decline in strength performance during the night. The "fatigue" factor is clearly evident the next day, because muscular strength in both sleep-deprived and rested states did not return to the levels observed before the sleep intervention. Hence, the appearance of the fatigue effect at the time of possible manifestations of impaired muscular strength caused by sleep deprivation would result in integration of these responses.

In conclusion, this study has shown that one night of sleep deprivation can elicit significant physiological changes the next afternoon with respect to melatonin and cortisol levels in the saliva. However, impairment in tracking and muscular strength performance attributed to the deprivation was not observed. Mild decrements induced by the short-term sleep loss may be present, but most likely they are masked by test-specific confounding factors. Hence, emphasis should be placed on the choice of tests used to measure performance efficiency.

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