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Hormonal responses to exercise after partial sleep deprivation and after a hypnotic drug-induced sleep

F. MOUGIN,[1,2]* H. BOURDIN,[2] M.L. SIMON-RIGAUD,[2] U. NGUYEN NHU,[3]
J.P. KANTELIP[2] and D. DAVENNE[4]

[1]UFR STAPS, Laboratoire des Sciences du Sport, 25000 Besançon Cedex, [2]Laboratoire de Physiopathologie Respiratoire et Cérébrale, Médecine et Biologie du Sport, [3]Laboratoire d'Explorations Fonctionnelles Rénales et Métaboliques, CHU 25030 Besançon Cedex and [4]Centre de Recherche en APS, Université de Caen, 14032 Caen, France

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The aim of this study was to determine the hormonal responses, which are dependent on the sleep–wake cycle, to strenuous physical exercise. Exercise was performed after different nocturnal regimens: (i) a baseline night preceded by a habituation night; (ii) two nights of partial sleep deprivation caused by a delayed bedtime or by an early awakening; and (iii) two nights of sleep after administration of either a hypnotic compound (10 mg zolpidem) or a placebo. Eight well-trained male endurance athletes with a maximal oxygen uptake of 63.5 ± 3.8 ml · kg^{-1} · min^{-1} (mean value $\pm s_{\bar{x}}$) were selected on the basis of their sleeping habits and their physical training. Polygraphic recordings of EEG showed that both nights with partial sleep loss led to a decrease ($P < 0.01$) in stage 2 and rapid eye movement sleep. A delayed bedtime also led to a decrease ($P < 0.05$) in stage 1 sleep. Zolpidem had no effect on the different stages of sleep. During the afternoon after an experimental night, exercise was performed on a cycle ergometer. After a 10-min warm-up, the participants performed 30 min steady-state cycling at 75% $\dot{V}O_{2max}$ followed by a progressively increased workload until exhaustion. The recovery period lasted 30 min. Plasma growth hormone, prolactin, cortisol, catecholamine and lactate concentrations were measured at rest, during exercise and after recovery. The concentration of plasma growth hormone and catecholamine were not affected by partial sleep deprivation, whereas that of plasma prolactin was higher ($P < 0.05$) during the trial after an early awakening. Plasma cortisol was lower ($P < 0.05$) during recovery after both sleep deprivation conditions. Blood lactate was higher ($P < 0.05$) during submaximal exercise performed after both a delayed bedtime and an early awakening. Zolpidem-induced sleep did not affect the hormonal and metabolic responses to subsequent exercise. Our results demonstrate only minor alterations in the hormonal responses to exercise after partial sleep deprivation.

Keywords: catecholamines, cortisol, exercise, growth hormone, hypnotic compounds, prolactin, sleep deprivation.

Introduction

Sleep is a part of daily life and is assumed to be a restorative process for the function of the central nervous system. Disturbances to sleep may be experienced by athletes who have to get up early in the morning to travel to a competition or who cannot fall asleep because of the stress of a major event. Such disturbed sleep might have an effect on the sleep–wake cycle and on the nocturnal secretion of, for example, growth hormone, prolactin and cortisol. Thus, the chronobiological patterns of hormones may be affected by sleep deprivation. Few studies have assessed the function of the endocrine system the day after disturbed sleep. Growth hormone, prolactin and cortisol secretions are closely related to the sleep–wake cycle (Takahashi *et al.*, 1968; Sassin *et al.*, 1969; Weitzman *et al.*, 1971; Bispink *et al.*, 1990; Spiegel *et al.*, 1994, 1995; Van Cauter *et al.*, 1998). The release of growth hormone occurs during the first 'non-rapid eye movement' (non-REM) period of sleep. This hormone has often been associated with slow wave sleep (Honda *et al.*, 1969; Printz *et al.*, 1983; Jarrett *et al.*, 1990; Van Cauter *et al.*, 1998). Prolactin secretion is enhanced during sleep and peaks

* Author to whom all correspondence should be addressed.

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early in the morning (Sassin *et al.*, 1973; Spiegel *et al.*, 1994). Cortisol secretion is low during the first hours of sleep, but increases dramatically during early morning when the individual is still asleep (Krieger *et al.*, 1971; Kupfer *et al.*, 1983). Such secretions are inhibited by exposure to light (Kostoglou-Athanassiou *et al.*, 1998). However, sleep is not the only factor responsible for the secretion of growth hormone, prolactin and cortisol. These hormones are often secreted in response to psychological and physical stress (Kindermann *et al.*, 1982; Galbo, 1983; Smallridge *et al.*, 1985; Melin *et al.*, 1998). Other hormones, such as adrenaline and noradrenaline, also increase markedly during stress (Christensen *et al.*, 1979; Escourrou *et al.*, 1984; De Meirleir *et al.*, 1985; Mazzeo and Marshall, 1989), but they do not show any episodic burst during the night (Lakatua *et al.*, 1986; Nishihara and Mori, 1988). Thus, growth hormone, prolactin, cortisol and catecholamine concentrations are usually considered good indices of physiological stress. To our knowledge, no study has shown that loss of sleep increases the stress imposed by exercise. In an attempt to answer this question, we assessed the effects of partial sleep deprivation on plasma concentrations of growth hormone, prolactin, cortisol, adrenaline and noradrenaline during a daytime standardized exercise test and recovery in young highly trained individuals. To prevent sleep loss, increasing numbers of athletes are taking a hypnotic compound to get a 'good night's sleep' before competition. Thus, in the present study, we also evaluated the effects of an imidazopyridine drug, zolpidem, on the subsequent hormonal responses to exercise.

Methods

Participants

Eight highly trained male athletes (mean ± $s_{\bar{x}}$: age 24.0 ± 0.8 years, height 1.77 ± 0.08 m, body mass 71.5 ± 1.8 kg) participated in the study after signing a consent document approved by our institutional review board. They were selected according to their maximal oxygen uptake ($\dot{V}O_{2max}$), which had been measured directly during previous maximal exercise that consisted of a progressively increased workload of 50 W every 3 min and then by 10 W every minute until exhaustion. Their maximal oxygen uptake averaged 63.5 ± 3.8 $ml \cdot kg^{-1} \cdot min^{-1}$. The participants were also selected based on their chronotype using a sleep questionnaire (Horne and Östberg, 1976). They had an intermediate chronotype, estimated their sleep duration to be 8.0 ± 0.4 h, they reported no sleep disturbances, no use of alcohol or tobacco and none of them was taking any medication.

Experimental design

There were five sleep conditions:

- A reference night preceded by a habituation night during which the lights were turned off from approximately 22:30 h to about 07:00 h.
- Two nights at the beginning of which the participants took a capsule, containing either 10 mg zolpidem (Stilnox®) or a placebo, 10 min before going to bed. Lights out was at approximately 22:30 h and the lights were turned on again at approximately 07:00 h. Zolpidem and placebo were randomized in a double-blind design.
- A sleep-deprived night during which the participants went to bed at 22:30 h and were woken at 03:00 h. They were not allowed to sleep thereafter.
- A sleep deprived night during which the participants were not allowed to sleep before 03:00 h; they were then allowed to sleep until 07:00 h.

Sleep was recorded using electroencephalogram (EEG), electromyogram (EMG) and electrooculogram (EOG) electrodes. All sleep records were scored according to the procedures of Rechtschaffen and Kales (1968) with a paper speed of 15 $mm \cdot s^{-1}$. During sleep deprivation, the participants were kept awake by passive means such as reading books or watching television. They were not allowed to ingest food, caffeine or stimulants and were observed continuously by a technician. Polygraphic EEG for the two nights of sleep deprivation was recorded during sleep only.

Zolpidem pharmacology

Zolpidem, an imidazopyridine derivative, is a rapid-acting hypnotic drug, with weak muscle relaxing properties and no effects on memory or cognitive performance. In clinical studies, it has been reported to increase slow-wave sleep, but not to suppress rapid eye movement (REM) sleep or to decrease performance after waking up. Zolpidem is more rapidly and completely absorbed after oral administration than a benzodiazepine compound. It has an average maximum time of 1.8 ± 0.3 h. The bioavailability of a 10-mg tablet is about 70%. The ingestion of food, alcohol and caffeine does not interfere with its rate of absorption. Zolpidem is rapidly eliminated from the body with a half-life of 0.7–3.5 h. The metabolites are pharmacologically inactive and also rapidly eliminated. No residual effect has been observed (Lorizio *et al.*, 1990).

Exercise protocol

At 14:00 h on the day after each experimental night, the participants exercised on a cycle ergometer (Siemens)

as previously described by Mougin *et al.* (1991). The protocol consisted of a 10-min warm-up, 30 min at the same predetermined steady-state work rate equivalent to 75% $\dot{V}O_{2max}$ followed by a progressively increasing work rate (10 W every minute) until exhaustion. The recovery period lasted 30 min. Before each trial, a catheter was inserted into a superficial forearm vein. Blood specimens were obtained at rest, at the end of the steady-state exercise, at exhaustion and after 30 min into recovery.

Blood specimens were immediately placed on ice and centrifuged for 10 min at 2500 *g* at 4°C. The plasma was stored at −75°C until assayed. Plasma growth hormone and prolactin determinations were performed by radioimmunoassay (RIA) techniques using an RIA kit (Biomerieux, Craponne, France). Cortisol was evaluated using a different RIA kit (Amersham, Les Ulis, France). Adrenaline and noradrenaline concentrations were determined from 1 ml plasma using high-performance liquid chromatography with electrochemical detection (Guilland and Klepping, 1986). Lactic acid was assayed using an enzymatic ultraviolet method (Boehringer).

Statistical analysis

The results for the different conditions (after reference night, hypnotic and placebo nights and sleep-deprived nights) were compared using analysis of variance. *Post-hoc* analysis was performed using the Fisher test. Statistical significance was accepted at $P < 0.05$.

Results

Sleep

The polygraphic variables were modified by partial sleep loss. Both a delayed bedtime and an early awakening resulted in a decrease in total sleep and in the percentages of stage 2 and REM sleep ($P < 0.01$; Table 1), but no change in the percentages of stage 3 and 4 sleep. Only a delayed bedtime led to a decrease in stage 1 sleep ($P < 0.05$), when compared with the reference and placebo nights. Zolpidem 10 mg did not result in a change in total sleep or in any of the stages of sleep compared with the reference conditions.

Maximal workload

The maximal work rate developed by the participants appeared to be significantly lower after the delayed bedtime and after an early awakening (294 ± 11 and 292 ± 13 W, respectively; $P < 0.01$) compared with the baseline night (309 ± 10 W). However, maximum work rate was not significantly different between the zolpidem and placebo treatments (312 ± 13 and 301.2 ± 9.6 W, respectively).

Lactate concentration

There was a rise in lactate concentrations between rest and maximal exercise followed by a fall after recovery. After partial sleep loss, lactate concentrations increased dramatically for the same workload compared with after the baseline night. Maximal and recovery lactate concentrations were unchanged, possibly because of the lower maximal sustained workload. Zolpidem administration had no effect on plasma lactate concentrations (Table 2).

Hormone concentrations

In all conditions, plasma growth hormone, prolactin, cortisol and catecholamines showed a significant progressive increase related to the intensity of exercise. Plasma growth hormone fell after 30 min recovery, but prolactin and cortisol remained elevated (Tables 3 and 4, Figs 1 and 2).

After the two partial sleep deprivation conditions, the exercise-induced changes in plasma growth hormone and catecholamines were similar to those observed when exercise was performed after the reference night

Table 1. Time (min) spent in the different stages of sleep for the five experimental conditions ($n = 8$; mean ± $s_{\bar{x}}$)

	Stage 1 sleep	Stage 2 sleep	Stage SWS sleep	Stage REM sleep
Reference night	8.2 ± 5.4	310.8 ± 16.4	63.2 ± 8.9	69.2 ± 8.7
Placebo night	15.9 ± 7.6	289.5 ± 13.1	68.2 ± 9.2	87.8 ± 13.7
Zolpidem night	18.2 ± 8.0	294.5 ± 17.3	73.4 ± 8.8	81.8 ± 7.9
Delayed bedtime	4.8 ± 3.0*	160.0 ± 16.2**	55.8 ± 8.6	34.7 ± 7.9**
Early awakening	17.8 ± 10.1	166.0 ± 11.1**	45.0 ± 8.1	27.6 ± 7.7**
	$F = 2.60$; $P < 0.05$	$F = 6.85$; $P < 0.001$	$F = 2.50$; N.S.	$F = 14.5$; $P < 0.001$

* $P < 0.05$, ** $P < 0.01$ compared with the reference night. SWS = slow wave sleep, REM = rapid eye movement sleep.

Table 2. Blood lactate concentration (mmol•l^{-1}) measured at rest, during exercise and after recovery for the five experimental conditions (n = 8; mean ± $s_{\bar{x}}$)

	Rest	Steady state, 30 min	Maximal exercise	Recovery, 30 min
After reference night	1.28 ± 0.41	4.42 ± 1.23	8.51 ± 1.49	2.68 ± 0.68
After placebo night	1.64 ± 0.37	5.15 ± 1.69	9.22 ± 1.83	3.03 ± 1.31
After zolpidem night	1.32 ± 0.26	4.20 ± 1.87	9.23 ± 1.98	2.65 ± 0.76
After delayed bedtime	1.50 ± 0.48	5.83 ± 1.26**	9.16 ± 1.68	2.57 ± 0.60
After early awakening	1.36 ± 0.29	5.31 ± 1.45*	9.10 ± 2.53	2.90 ± 1.35
	F = 1.20; N.S.	F = 3.35, P < 0.05	F = 0.42; N.S.	F = 1.57; N.S.

* P < 0.05, ** P < 0.01 compared with the reference night.

Table 3. Plasma growth hormone concentration (ng · ml^{-1}) measured at rest, during exercise and after recovery for the five experimental conditions (n = 8; mean ± $s_{\bar{x}}$)

	Rest	Steady state, 30 min	Maximal exercise	Recovery, 30 min
After reference night	3.5 ± 1.3	42.1 ± 3.3	55.8 ± 3.1	26.8 ± 1.9
After placebo night	3.7 ± 1.5	46.0 ± 4.0	60.3 ± 4.4	26.4 ± 2.0
After zolpidem night	5.2 ± 2.2	47.4 ± 7.5	53.1 ± 6.5	24.0 ± 3.2
After delayed bedtime	5.4 ± 2.6	36.3 ± 6.7	41.2 ± 6.0	20.9 ± 4.6
After early awakening	3.1 ± 1.1	40.4 ± 5.0	44.5 ± 5.5	17.7 ± 3.1

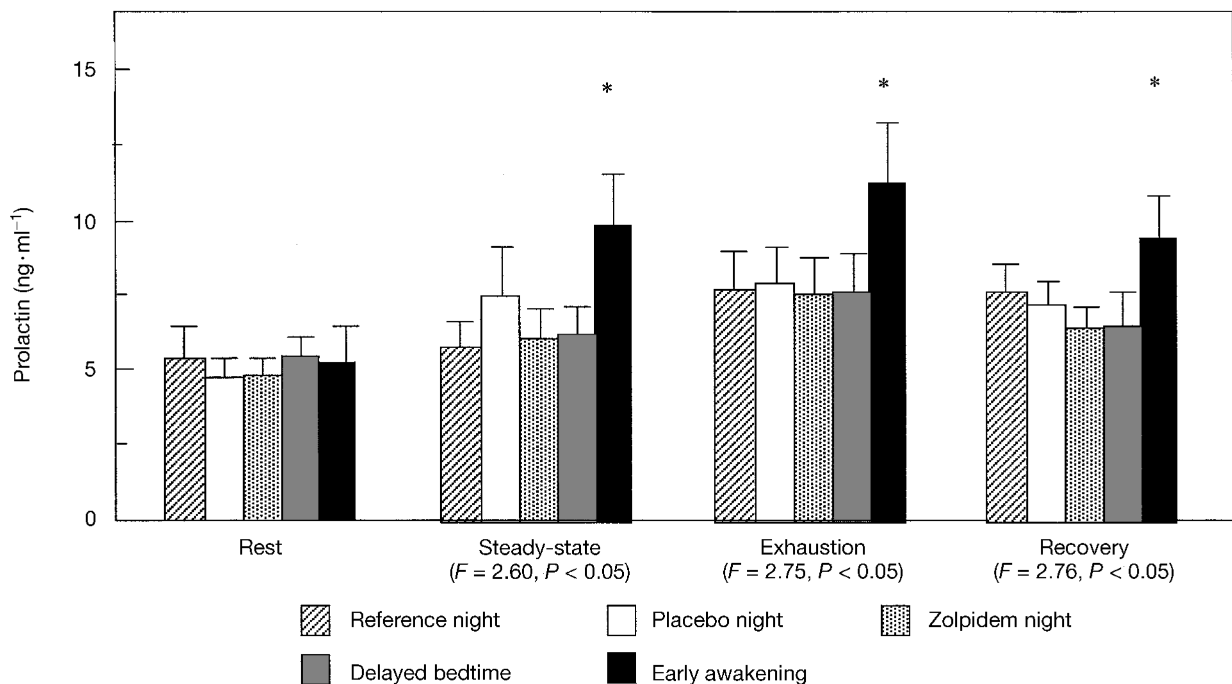

Fig. 1. Plasma prolactin concentration (ng · ml^{-1}) measured at rest, at the end of steady-state exercise, at exhaustion and 30 min post-exercise in the five experimental conditions (n = 8; mean ± $s_{\bar{x}}$). * P < 0.05 compared with after the reference night.

(Tables 3 and 4). The exercise-induced increase in prolactin concentration observed after a delayed bedtime was also identical to that seen after the reference night, while it was markedly higher at the end of submaximal and maximal exercise and at 30 min post-exercise after an early awakening (P < 0.05; Fig. 1). After both partial

Table 4. Plasma adrenaline (A) and noradrenaline (NA) concentrations ($pg \cdot ml^{-1}$) measured at rest, during exercise and after recovery for the five experimental conditions ($n = 8$; mean ± $s_{\bar{x}}$)

	Rest		Steady state, 30 min		Maximal exercise		Recovery, 30 min	
	A	NA	A	NA	A	NA	A	NA
After reference night	51 ± 7.1	355 ± 56.0	560 ± 105	4271 ± 463	807 ± 172	6278 ± 764	57 ± 8.8	582 ± 63.1
After placebo night	39 ± 5.3	270 ± 42.5	336 ± 62.5	3924 ± 407	500 ± 165	6927 ± 912	84 ± 13.1	727 ± 93.6
After zolpidem night	39 ± 3.9	302 ± 37.2	380 ± 76.2	3111 ± 258	850 ± 220	6542 ± 937	69 ± 10.6	502 ± 51.4
After delayed bedtime	39 ± 8.5	331 ± 49.2	433 ± 79.8	3915 ± 295	507 ± 131	6106 ± 1411	69 ± 12.0	557 ± 67.0
After early awakening	42 ± 8.9	291 ± 40.0	300 ± 66.3	3696 ± 454	539 ± 203	6995 ± 1014	60 ± 10.3	552 ± 94.7

sleep deprivation conditions, the exercise-induced rise in plasma cortisol was similar during the exercise test, but a significant decrease in this hormone was seen 30 min post-exercise ($P < 0.05$; Fig. 2).

After the zolpidem and placebo treatments, all modifications to hormone concentrations observed during exercise and recovery were identical to those observed after the reference night (Tables 3 and 4, Figs 1 and 2).

Discussion

In the present study, we found that partial sleep deprivation did not change markedly the subsequent hormonal responses to a strenuous exercise bout performed in the early afternoon. However, after an early awakening, the plasma prolactin response was increased during submaximal exercise and at exhaustion. Moreover, zolpidem-induced sleep did not modify the responses of any hormone measured.

In a previous study, we showed that partial sleep deprivation altered some physiological responses to subsequent exercise (Mougin *et al.*, 1991). Increases in ventilation, heart rate and plasma lactate concentration have been observed after both submaximal and maximal exercise (Mougin *et al.*, 1991). These changes could be linked to alterations in some endocrine responses to exercise after sleep deprivation. Indeed, hormonal secretions vary under different conditions, such as exercise, sleep, circadian rhythmicity and stress (Leproult *et al.*, 1997). To the best of our knowledge, the present study is the first to assess the endocrine responses caused by exercise after a short night's sleep and the administration of a hypnotic compound. In these conditions, the question arises as to whether partial sleep deprivation increases 'stress-sensitive hormones' or affects the circadian rhythmicity of these hormones?

Exercise induces a general stress response involving the activation of the neuroendocrine system, reflected here by the high concentrations of growth hormone, prolactin and cortisol. If we consider the concentrations of these hormones as indices of physical stress, there is no evidence that loss of sleep increases the stress of subsequent exercise. However, there are some discrepancies in the hormonal data of sleep-loss studies. O'Connor *et al.* (1991) reported a decrease in salivary cortisol after a swim of 183 m at an intensity equal to 90% of maximal speed, performed after sleep disturbance caused by jet lag. However, they did not take into account the 4-h phase delay of the circadian rhythm caused by travelling across time zones. Therefore, the changes in cortisol

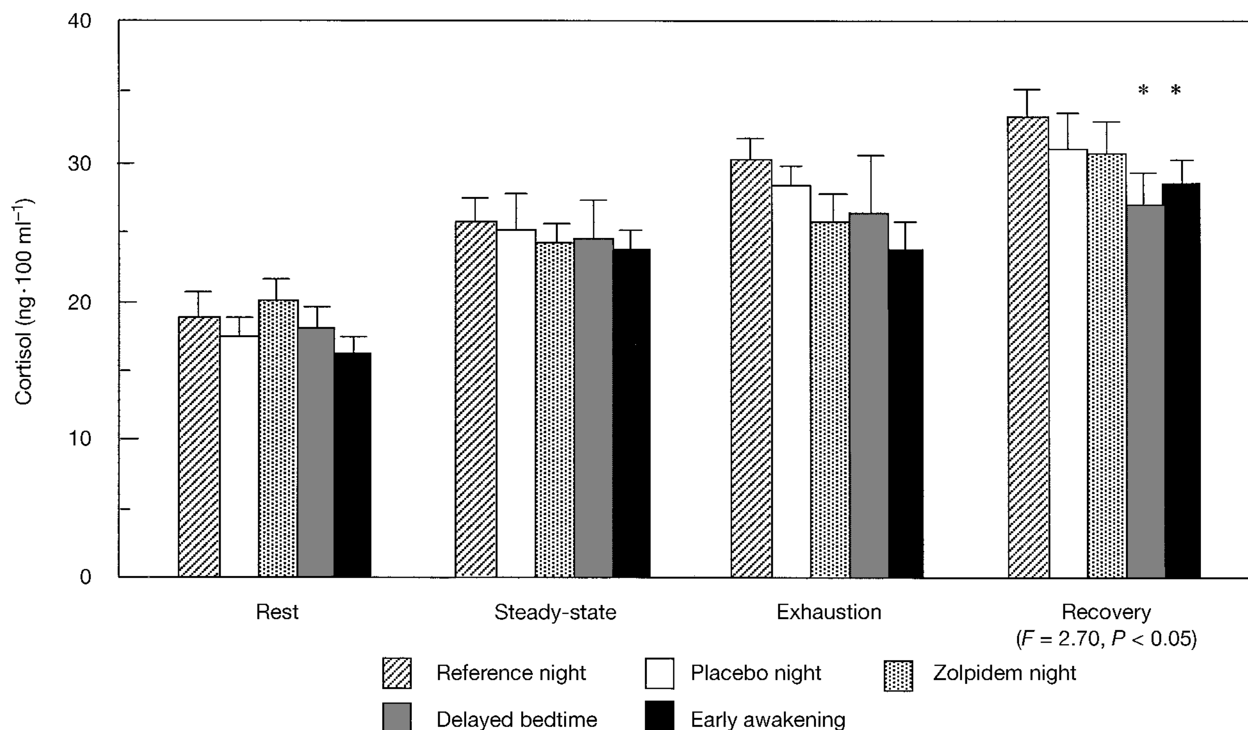

Fig. 2. Plasma cortisol concentration ($ng \cdot 100\ ml^{-1}$) measured at rest, at the end of steady-state exercise, at exhaustion and 30 min post-exercise in the five experimental conditions ($n = 8$; mean $\pm s_{\bar{x}}$). * $P < 0.05$ compared with after the reference night.

concentrations are probably due to the 4-h phase delay of the circadian rhythm rather than sleep loss. However, Martin *et al.* (1986) found no change in cortisol concentrations during 3 h of mild exercise after prolonged sleep loss, or during 30 min of exercise at 65% $\dot{V}O_{2max}$ after two nights of fragmented sleep. In individuals exposed to 107 h with less than 2 h sleep, Opstadt *et al.* (1980) reported an increase in plasma cortisol on day 3 and then a decrease on day 5. In our study, the concentrations of cortisol were lower only at 30 min post-exercise after the two partial sleep deprivation conditions. This drop in plasma cortisol may be the result of an exaggerated fatigue that represses adrenocortical activity (Francesconi *et al.*, 1978). This fatigue is reflected in our athletes by a marked lactate acidosis response to exercise (Chin and Evonuk, 1971). This high concentration of lactate could result in changes in the rate of secretion of cortisol or changes in its catabolism. Some authors have also reported a possible decrease in activity after sleep deprivation (Murawski and Crabbe, 1960; Francesconi *et al.*, 1978). Our results, however, cannot be compared with those of previous studies because individuals were often exposed to total sleep deprivation for many days or the duration of exercise was different.

In the present study, partial sleep deprivation and the administration of zolpidem before bedtime did not affect the plasma growth hormone response to daytime exercise and recovery. It has been demonstrated that, when sleep onset is delayed, the pulse of growth hormone release, which is associated with stage 3 and 4 sleep, is also delayed (Takahashi *et al.*, 1968; Sassin *et al.*, 1969). Nocturnal secretion of growth hormone is decreased or eliminated only in the absence of slow wave sleep (Sassin *et al.*, 1969; Karacan *et al.*, 1971); rapid eye movement sleep has no effect on the pattern of growth hormone secretion (Honda *et al.*, 1969). However, Steiger *et al.* (1987) suggested that resting in bed during the late evening hours or waiting for permission to sleep may be sufficient to trigger the release of growth hormones. So, in the present study, we suggest that changes in sleep schedules or in sleep structure had no influence on the nocturnal and exercise-induced secretion of growth hormone.

Plasma prolactin was higher during exercise and recovery after the night during which the participants were awoken at 03:00 h. The prolactin concentrations observed during the conditions in which the participants went to bed late (03:00 h) or when they took 10 mg zolpidem before sleep were identical to those observed after the control trial. The increased prolactin response to exercise after an early awakening could be the result of a disruption to the fluctuation of this hormone. Peak secretion, which usually occurs at about 05:30 h, could be removed by deprived sleep (Bispink *et al.*, 1990) with a reappearance during exercise.

Both adrenaline and noradrenaline did not differ in any of the experimental conditions. The peripheral adrenergic and noradrenergic system is markedly activated by physical stress (Escourrou *et al.*, 1984). However, this stress does not appear to be exaggerated when exercise is performed after sleep deprivation. Finally, our results are in line with those of previous studies in which minor catecholamine changes were shown to be due to loss of sleep (for a review, see Horne, 1978).

In conclusion, it appears that sleep deprivation affects the exercise recovery processes, as reflected in lowered cortisol concentrations related to an exaggerated fatigue. Early awakening appeared to be more important than a late bedtime for disturbances to cortisol concentrations, although both conditions were less stressful than we had anticipated. Indeed, growth hormone and catecholamines were secreted in the same way during exercise and recovery after sleep deprivation as after the control night's sleep. However, stress owing to long-term sleep deprivation remains an open question and relationships between sleep EEG parameters and hormones secreted during exercise the next day need to be investigated further.

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References

Bispink, G., Zimmermann, R., Weise, H.C. and Leidenberger, F. (1990). Influence of melatonin on the sleep-independent component of prolactin secretion. *Journal of Pineal Research*, **8**, 97–106.

Chin, A.K. and Evonuk, E. (1971). Changes in plasma catecholamine and corticosterone levels after muscular exercise. *Journal of Applied Physiology*, **30**, 205–207.

Christensen, N.J., Galbo, H., Hansen, J.F., Hesse, B., Richter, E.A. and Trap-Jensen, J. (1979). Catecholamines and exercise. *Diabetes*, **28**, 58–62.

De Meirleir, K.L., Baeyens, L., L'Hermite-Baleriaux, M., L'Hermite, M. and Hollmann, W. (1985). Exercise-induced prolactin release is related to anaerobiosis. *Journal of Clinical Endocrinology and Metabolism*, **60**, 1250–1252.

Escourrou, P., Johnson, D.G. and Rowell, L.B. (1984). Hypoxemia increases plasma catecholamine concentrations

in exercising humans. *Journal of Applied Physiology*, **57**, 1507–1511.

Francesconi, R.P., Stokes, J.W., Banderet, L.E. and Kowel, D.M. (1978). Sustained operations and sleep deprivation: Effects on indices of stress. *Aviation, Space and Environmental Medicine*, **49**, 1271–1274.

Galbo, H. (1983). *Hormonal and Metabolic Adaptation to Exercise*. Stuttgart: Georg Thieme Verlag.

Guilland, J.C. and Klepping, J. (1986). Le dosage des catécholamines plasmatiques en biologie clinique. *American Biology Clinical*, **44**, 587–605.

Honda, Y., Takahashi, K. and Takahashi, S. (1969). Growth hormone secretion during nocturnal sleep in normal subjects. *Journal of Clinical Endocrinology*, **29**, 20–29.

Horne, J.A. (1978). A review of the biological effects of total sleep deprivation in man. *Biological Psychology*, **7**, 55–102.

Horne, J.A. and Östberg, O. (1976). A self assessment questionnaire to determine morningness–eveningness in human circadian rhythms. *International Journal of Chronobiology*, **4**, 97–110.

Jarrett, D.B., Greenhous, J.B., Miewald, J.M., Fedorka, I.B. and Kupfer, D.J. (1990). A reexamination of the relationship between growth hormone secretion and slow wave sleep using delta wave analysis. *Biological Psychiatry*, **27**, 497–509.

Karacan, I., Rosenbloom, A.L., Williams, R.L., Finley, W.W. and Hursch, C.J. (1971). Slow wave sleep deprivation in relation to plasma growth hormone concentration. *Behavioral Neuropsychiatry*, **2**, 11–14.

Kindermann, W., Schnabel, A., Schmitt, W.M., Biro, G., Lassens, J. and Weber, F. (1982). Catecholamines, growth hormone, cortisol, insulin and sex hormones in anaerobic and aerobic exercise. *European Journal of Applied Physiology*, **49**, 389–399.

Kostoglou-Athanassiou, I., Treacher, D.F., Wheeler, M.J. and Forsling, M.J. (1998). Bright light exposure and pituitary hormone secretion. *Journal of Clinical Endocrinology*, **48**, 73–79.

Krieger, D.T., Allen, W., Rizzo, F. and Krieger, H.P. (1971). Characterization of the normal temporal pattern of plasma corticosteroid levels. *Journal of Clinical Endocrinology*, **32**, 266–284.

Kupfer, D.J., Bulik, C.M. and Jarrett, D.B. (1983). Night-time plasma cortisol secretion and EEG sleep – are they associated? *Psychiatry Research*, **10**, 191–199.

Lakatua, D.J., Haus, E. and Halberg, F. (1986). Circadian characteristics of urinary epinephrine and norepinephrine from healthy young women in Japan and USA. *Chronobiology International*, **3**, 189–195.

Leproult, R., Copinschi, G., Buxton, O. and Van Cauter, E. (1997). Sleep loss results in an elevation of cortisol levels the next evening. *Sleep*, **20**, 865–870.

Lorizio, A., Terzano, M.G., Parrino, L., Cesana, B.M. and Priore, P. (1990). Zolpidem: A double-blind comparison of the hypnotic activity and safety of a 10-mg versus 20-mg dose. *Therapeutic Research*, **47**, 889–898.

Martin, B.J., Bender, P.R. and Chen, H.I. (1986). Stress hormonal response to exercise after sleep loss. *European Journal of Applied Physiology*, **55**, 210–214.

Mazzeo, R.S. and Marshall, P. (1989). Influence of plasma catecholamines on the lactate threshold during graded exercise. *Journal of Applied Physiology*, **67**, 1319–1322.

Melin, B., Cure, M., Pequignot, J.M. and Bittel, J. (1998). Body temperature and plasma prolactin and norepinephrine relationships during exercise in a warm environment: Effects of dehydration. *European Journal of Applied Physiology*, **58**, 146–151.

Mougin, F., Simon-Rigaud, M.L., Davenne, D., Renaud, A., Garnier, A., Kantelip, J.P. and Magnin, P. (1991). Effects of sleep disturbances on subsequent physical performance. *European Journal of Applied Physiology*, **63**, 77–82.

Murawski, B.J. and Crabbe, J. (1960). Effect of sleep deprivation on plasma 17-hydroxycorticosteroids. *Journal of Applied Physiology*, **15**, 280–282.

Nishihara, K. amd Mori, K. (1988). The relationship between waking time and urinary epinephrine in bed-rested humans under conditions involving minimal stress. *International Journal of Psychophysiology*, **6**, 133–137.

O'Connor, P.J., Morgan, W.P., Koltyn, K.F., Raglin, J.S., Turner, J.G. and Kalin, N.H. (1991). Air travel across four time zones in college swimmers. *Journal of Applied Physiology*, **70**, 756–763.

Opstadt, K., Aakvaag, A. and Rognum, T.O. (1980). Altered hormonal response to short-term bicycle exercise in young men after prolonged physical strain, caloric deficit and sleep deprivation. *European Journal of Applied Physiology*, **45**, 51–62.

Printz, P.N., Weitzman, E.D., Cunningham, G.R. and Kuracan, I. (1983). Plasma growth hormone during sleep in young and aged men. *Journal of Gerontology*, **38**, 519–524.

Rechtschaffen, A. and Kales, A. (1968). *A Manual of Standardised Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects*. Washington, DC: US Government Printing Office.

Sassin, J.F., Parker, D.C., Mace, J.W., Gotlin, R.W., Johnson, L.C. and Rossman, L.G. (1969). Human growth hormone release: Relationship to slow wave sleep and sleep–waking cycles. *Science*, **165**, 513–515.

Sassin, J.F., Frantz, A.G., Kapen, E.D. and Weitzman, E.D. (1973). The nocturnal rise of prolactin is dependent on sleep. *Journal of Clinical Endocrinology and Metabolism*, **37**, 436–440.

Smallridge, R.C., Whorton, N.E., Burman, K.D. and Fergusson, E.N. (1985). Effects of exercise and physical fitness on the pituitary thyroid axis and on prolactin secretion in male runners. *Metabolism*, **34**, 949–954.

Spiegel, K., Follenius, M., Simon, C., Saini, J., Ehrhart, J. and Brandenberger, G. (1994). Prolactin secretion and sleep. *Sleep*, **17**, 20–27.

Spiegel, K., Luthringer, R., Follenius, M., Schaltenbrand, N., Macher, J.P., Muzet, A. and Bradenberger, G. (1995). Temporal relationship between prolactin secretion and slow-wave electroencephalic activity during sleep. *Sleep*, **18**, 543–548.

Steiger, A., Hert, T. and Holsboer, F. (1987). Sleep-electroencephalography and the secretion of cortisol and growth

hormone in normal controls. *Acta Endocrinologica*, **116**, 36–42.

Takahashi, Y., Kipnis, D.M. and Daughaday, W.H. (1968). Growth hormone secretion during sleep. *Journal of Clinical Investigation*, **47**, 2079–2090.

Van Cauter, E., Plat, L. and Copinschi, G. (1998). Interrelations between sleep and the somatotropic axis. *Sleep*, **21**, 553–566.

Weitzman, E.D., Fukushima, D., Nogeire, C., Roffwarg, H., Gallagher, T.F. and Hellman, L. (1971). Twenty four hour pattern of the episodic secretion of cortisol in normal subjects. *Journal of Clinical Endocrinology*, **33**, 14–22.