Eur J Appl Physiol (2009) 105:439–444
DOI 10.1007/s00421-008-0921-5

ORIGINAL ARTICLE

The effect of 60-h sleep deprivation on cardiovascular regulation and body temperature

Jani Vaara · Heikki Kyröläinen · Mikko Koivu · Mikko Tulppo · Taija Finni

Accepted: 23 October 2008 / Published online: 12 November 2008

Abstract This study examined cardiovascular regulation and body temperature (BT) during 60 h of sleep deprivation in 20 young healthy cadets. Heart rate variability was measured during an active orthostatic test (AOT). Measurements were performed each day in the morning and evening after 2, 14, 26, 38, 50 and 60 h of sleep deprivation. In AOT, in the sitting and standing positions, heart rate decreased ($P < 0.001$), while high frequency and low frequency power increased ($P < 0.05$–0.001) during sleep deprivation. Body temperature also decreased ($P < 0.001$), but no changes were detected in blood pressure. In conclusion, the accumulation of 60 h of sleep loss resulted in increased vagal outflow, as evidenced by decreased heart rate. In addition, BT decreased during sleep deprivation. Thus, sleep deprivation causes alterations in autonomic regulation of the heart, and in thermoregulation.

Keywords Sleep deprivation · Heart rate variability · Autonomic nervous system · Blood pressure · Body temperature

J. Vaara (✉) · H. Kyröläinen · T. Finni
Department of Biology of Physical Activity,
University of Jyväskylä, 40014 Jyväskylä, Finland
e-mail: jani.vaara@sport.jyu.fi

H. Kyröläinen · M. Koivu
National Defence University, Helsinki, Finland

M. Tulppo
Department of Exercise and Medical Physiology,
Verve, Oulu, Finland

Introduction

Sleep deprivation (SD) is especially common in sustained military operations, and in some sport events (Vanhelder and Randomski 1989). In humans, SD is well known to have negative effects on cognitive and neurobehavioral functions (Harrison et al. 2000; Horne 1993; Pilcher and Huffcutt 1996; Thomas et al. 2000). SD is also associated with alterations of different physiological functions, such as metabolism (Van Cauter et al. 1991; Spiegel et al. 1999; Gonzalez-Ortiz et al. 2000; Knutson et al. 2007), neuroendocrinology (Van Cauter et al. 2007; Lusardi et al. 1999) and inflammation (Dimitrov et al. 2004; Irwin 2002; Meier-Ewert et al. 2004; Shearer et al. 2001; Vgontzas et al. 1999). SD may also compromise cardiovascular regulation, and increase the risk of cardiovascular diseases (Shamsuzzaman et al. 2003; Meier-Ewert et al. 2004).

Heart rate has been reported either to decrease or to be unaffected by SD (Bond et al. 1986; Burgess et al. 1997; Holmes et al. 2002; Chen 1991; Kato et al. 2000; Ogawa et al. 2003; Zhong et al. 2005). However, very few studies have examined the association between SD and cardiovascular regulation. Muscle sympathetic nerve activity (MSNA) has been reported to decrease after an acute SD period of one night (Kato et al. 2000; Ogawa et al. 2003). In addition, 30 h of SD has been shown to decrease sympathetic activity and to have no effect on parasympathetic activity (Holmes et al. 2002). In contrast, 36 h of SD increased sympathetic and decreased parasympathetic cardiac modulation (Zhong et al. 2005). To our knowledge, no study has investigated the effects of SD on cardiovascular regulation over a period of more than 42 h. The aim of the present study was to assess the effect of 60 h of SD on cardiovascular regulation.

Methods

Subjects

Twenty healthy cadets (17 men, 3 women, age 26 ± 3 years) volunteered to participate. Their health and physical activity status were assessed by a questionnaire. All subjects were healthy and physically active, performing moderate intensity exercise 3–5 times per week. Based on a circadian rhythm questionnaire, the subjects were classified as morning types and their daily rhythm of life was regular (Folkard et al. 1979). Body mass was measured before (79.8 ± 11.0 kg) and after (80.3 ± 10.7 kg) the SD period. Subjects kept sleep logs for four nights preceding the study (mean 6:52 ± 2:28 h/night). The study was approved by the Ethical committee of the University of Jyväskylä prior to its initiation. All subjects provided written informed consent. (Table 1)

Sleep deprivation period

During the 60-hour SD period, the subjects were not allowed to drink caffeine containing liquids, but water could be consumed ad libitum. Five of the subjects were habitual smokers, and were allowed to smoke in accordance with their usual daily habits. However, smoking was not allowed within 3 h of the measurements. Subjects had dinner and lunch each day at the same time (11:00 and 17:00), and also ate snacks that were reported in a diary. During SD, physical activity was restricted to a minimum, while subjects performed military tasks related to tactics. The subjects were allowed to engage in various activities such as playing cards, reading books, watching videos, studying or doing job-related work. Throughout the entire SD period, subjects were constantly observed by the research personnel to prevent them from falling asleep.

Study protocol

Subjects were measured twice a day, in the mornings and evenings, resulting in a total of six measurements after 2, 14, 26, 38, 50 and 60 h of SD. Five of the six measurement periods took place in the morning at 08:00 and in the evening at 20:00, except the final evening measurement period, which took place at 18:00. Each measurement period consisted of blood pressure (BP) and body temperature (BT) measurements followed by heart rate variability (HRV) recordings in an active orthostatic test (AOT).

Measurements

Body temperature was measured from the ear (Omron, MC-510-E, Omron Healthcare Co. Ltd, Japan), and BP with an automatic monitor (Omron, HEM-705c, Omron Healthcare Co. Ltd, Japan). BT was measured twice and BP three times in each measurement session. For BT, the average of the two values was used in the statistical analysis. For BP, the average of the two most similar results was used for further analysis. HRV was measured during AOT in a group of five subjects. AOT included 5-min sitting followed by 3-min standing. HRV was measured beat by beat with wrist monitors (T6, Suunto Oy, Finland) and downloaded to a computer for analysis. For AOT, a 2-minute period was analyzed in the sitting position before standing up. In the standing position, the last 2 min were analyzed. All R-R intervals were first edited automatically (Polar Precision Performance SW 4.03.043), and then visually inspected to exclude measurement errors and ectopic heart beats. Each edited R-R interval was replaced with an average value according to the length of the error sequence, taking the previous and next normal R-R interval into account for correction (Jurca et al. 2004). An autoregressive method was used to estimate the power spectrum of HRV by calculating the power of two frequency bands: high frequency (HF) (0.04–0.015 Hz) and low frequency (LF) (0.15–0.40 Hz) power. HF power is predominantly a reflection of vagal activity, whereas LF power is considered to reflect both sympathetic and vagal activity or sympathetic modulation. The LF/HF ratio is suggested to reflect sympathovagal balance or sympathetic modulation (Task Force. 1996). HRV parameters were expressed in natural logarithmic transformed values (ln) (Tables 1, 2).

Statistical analysis

Repeated measures ANOVA was used to identify changes in BT and BP between the measurements by applying Bonferroni post hoc tests. In addition to testing differences between each of the six measurement points (BT and BP), data were compared across the 3 days by treating the morn-

Table 1 Mean ± SE of heart rate variability during the active orthostatic test while sitting

P values indicate statistical significance between the measurements

	Day 1	Day 2	Day 3	*P* (1 versus 3)	*P* (2 versus 3)	*P* (1 versus 2)
HR (b/min)	75 (2)	72 (2)	67 (2)	$P < 0.001$	$P < 0.001$	NS
HF (ln, ms²)	6.1 (0.2)	6.4 (0.1)	7.0 (0.1)	$P < 0.001$	$P < 0.001$	NS
LF (ln, ms²)	6.8 (0.2)	7.2 (0.1)	7.6 (0.2)	$P < 0.001$	NS	NS
LF/HF	2.3 (0.6)	2.5 (0.6)	2,0 (0.4)	NS	NS	NS

Table 2 Mean ± SE of heart rate variability during the active orthostatic test while standing

P values indicate statistical significance between the measurements

	Day 1	Day 2	Day 3	*P* (1 vs. 3)	*P* (2 vs. 3)	*P* (1 vs. 2)
HR (beats/min)	78 (2)	77 (2)	72 (2)	$P < 0.001$	$P < 0.005$	NS
HF (ln, ms^2)	5.5 (0.2)	5.7 (0.2)	6.1 (0.2)	$P < 0.05$	NS	NS
LF (ln, ms^2)	6.5 (0.2)	7.1 (0.2)	7.2 (0.2)	$P < 0.005$	NS	$P < 0.001$
LF/HF	3.3 (0.6)	4.1 (0.8)	3.7 (0.7)	NS	NS	NS

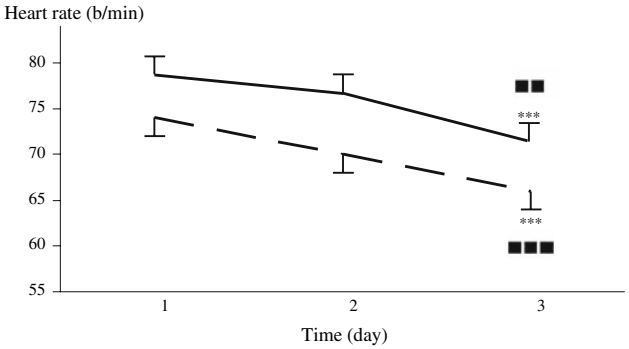

Fig. 1 Changes in HR in the sitting (*dashed line*) and standing positions (*solid line*) in AOT. ***$P < 0.001$ compared to Day 1; ■■■$P < 0.001$ compared to Day 2; ■■$P < 0.005$ compared to Day 2

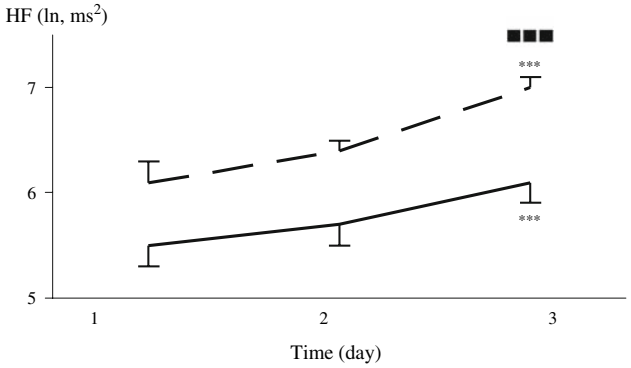

Fig. 2 Changes in HF power in the sitting (*dashed line*) and standing positions (*solid line*) in AOT. ***$P < 0.001$ compared to Day 1; ■■■$P < 0.001$ compared to Day 2

ing and evening measurements as one measurement (HR variables). Sixteen percent of the HRV data contained errors to such an extent that they were excluded from the analysis. This led to an incomplete data set in some subjects. Consequently, HR variables were analyzed using a mixed model approach with compound symmetry to detect changes during SD. The significance level was set to 0.05.

Results

Active orthostatic test

In the sitting position, HR decreased between days 1 and 3 ($P < 0.001$) and between days 2 and 3 ($P < 0.001$) (Fig. 1), while HF power increased ($P < 0.001$) in both intervals (Fig. 2). LF power increased between days 1 and 3 ($P < 0.001$).

In the standing position, HR decreased between days 1 and 3 ($P < 0.001$) and between days 2 and 3 ($P < 0.005$) (Fig. 1). HF and LF power increased between days 1 and 3 ($P < 0.05$ and $P < 0.001$, respectively) (Fig. 2), and LF power also increased between days 1 and 2 ($P < 0.001$).

Body temperature decreased both in the morning (36.3 ± 0.4, 35.9 ± 0.4, 35.7 ± 0.3°C in the three consecutive mornings) and in the evening (36.4 ± 0.4, 36.1 ± 0.3, 35.9 ± 0.4°C) measurements between days 1 and 2 and days 1 and 3 ($P < 0.05$–0.001) (Fig. 3). No changes were detected in BP in the morning (141/79, 139/75, 138/75 mmHg) or evening (146/80, 142/78, 140/80 mmHg) measurements for systolic or diastolic pressure (Fig. 4). Changes in HRV indices and HR were not correlated with the changes in BT during SD.

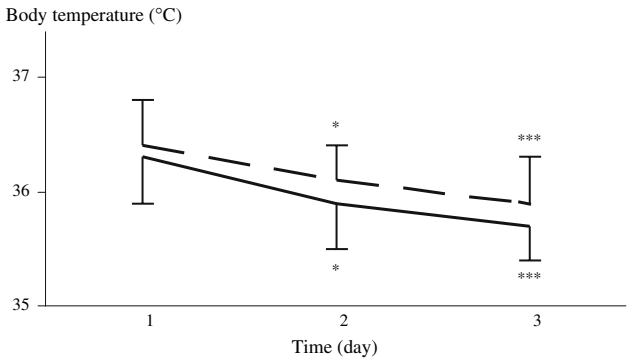

Fig. 3 Changes in BT in the evening (*dashed line*) and morning (*solid line*) measurements. *$P < 0.05$ compared to Day 1; ***$P < 0.001$ compared to Day 1

Discussion

The novel finding of the present study was that 60 h of SD decreased HR and increased vagal activity. SD also resulted in decreased BT, while no changes were observed in BP. These changes were cumulative over the 60-h time period.

Previous studies have reported that HR either decreases or is unaffected by SD (Bond et al. 1986; Burgess et al.

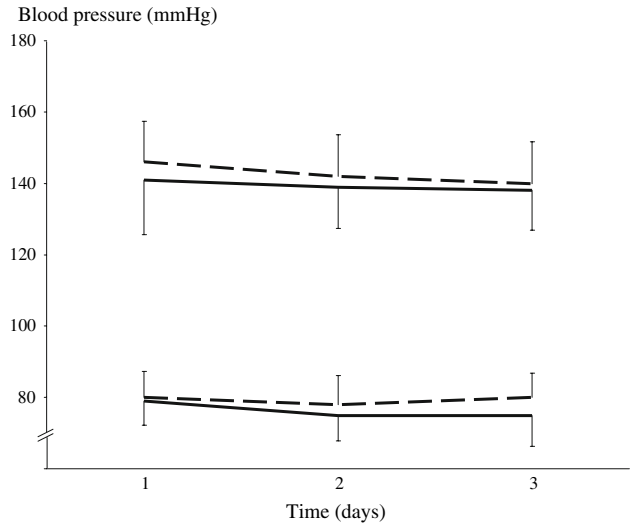

Fig. 4 Changes in BP in the evening (*dashed line*) and morning (*solid line*) measurements

1997; Holmes et al. 2002; Chen 1991; Kato et al. 2000; Ogawa et al. 2003). In the present study, HR decreased during SD. Similarly, Holmes et al. (2002) and Chen (1991) reported a decrease in HR after 30 h of SD, and Bond et al. (1986) after 42 h of SD. Zhong et al. (2005) also reported that HR measured in a supine position decreased after 12 and 36 h of SD, as well as after 24 h in a seated position. However, Kato et al. (2000) and Ogawa et al. (2003) found no change in HR after one night of SD. Based on the results of the present and previous studies, it seems likely that when SD lasts for more than one night, a decrease in HR can be observed (Bond et al. 1986; Chen 1991; Holmes et al. 2002; Zhong et al. 2005), whereas shorter periods of SD (e.g., one night) do not seem to affect HR as consistently (Kato et al. 2000; Ogawa et al. 2003).

In our study, the decreased HR was associated with increased vagal activity, while Holmes et al. (2002) have shown no changes in parasympathetic activity but decreased cardiac sympathetic activity after 30 h of SD. In contrast, Zhong et al. (2005) reported that 36 h of SD lead to increased cardiac sympathetic activity and decreased parasympathetic activity. However, Kato et al. (2000) and Ogawa et al. (2003) showed decreased muscle sympathetic nerve activity using MSNA measurements after one night of SD. It has been shown that SD has a perturbing effect on cardiac sympathovagal balance, although no clear consensus has been reached. Compared to previous studies that have observed a reduction in HR due to SD (Holmes et al. 2002; Zhong et al. 2005), the regulation of sympathetic and parasympathetic branches of the cardiac autonomic nervous system appeared to differ in the present study. The factors responsible for these discrepant findings in cardiovascular parameters are not well known, but may include methodological differences, the duration of SD, body position, physical and psychological activity and isolation from versus interaction with other people during SD.

Blood pressure (BP) has been shown to increase due to SD (Kato et al. 2000; Ogawa et al. 2003). In contrast, BP has also been reported to be unaffected by SD (Zhong et al. 2005). The findings of the present study are in agreement with those of Zhong et al. (2005) after 36 h of SD, but are in contrast to the findings of Kato et al. (2000), who found increased mean arterial pressure, and Ogawa et al. (2003), who observed an increase in diastolic pressure. Both findings were observed after 24 h of SD.

We concur with Holmes et al. (2002), who suggest that the changes in HR and sympathovagal activity after SD may function as a protective mechanism in an acute stress situation like SD. SD can also impose increased demands on cardiac function due to prolonged waking hours. However, SD has been shown to decrease alertness and cognitive function, as well as decreasing brain activity measured by cerebral glucose metabolic rate (CMRglu) in the thalamus, cerebellum, temporal cortex and prefrontal and posterior parietal cortices (Wu et al. 1991; Thomas et al. 2000). In the present study, BT decreased during SD and circadian rhythm was maintained, as shown in previous studies (Ax and Luby 1961; Kolka et al. 1984; Lubin et al. 1976; Horne 1983; Horne and Pettitt 1985). According to the literature, the hypothalamus is involved in the regulation of both body temperature and the autonomic nervous system via descending and ascending pathways from the cerebral cortex or the basal forebrain (Kandel et al. 2000). If reductions in brain activity similar to those reported by Wu et al. (Wu et al. 1991) and Thomas et al. (Thomas et al. 2000) also occurred in the hypothalamus, it could be suggested to have an impact upon down regulative outcomes, such as decreased BT and HR with increased vagal activity. Thus, the main effect of SD would be to alter the function of regulative centers in the brain, which could be seen as reflective to changes in BT, HR and vagal activity.

In the present study, certain limitations have to be considered. We did not include a control group to ensure that SD was primarily responsible for any changes that were observed, although the role of other factors was obviously negligible in the controlled environment of this study. We also did not record respiratory parameters during HRV-measures in AOT. As respiratory frequency affects cardiac autonomic modulation (Eckberg 2003), changes in respiration could have had an effect on the results. However, volunteers were carefully instructed to breathe normally. In addition, SD has been shown to have no effect on basal breathing patterns and resting ventilation (White et al. 1983; Ballard et al. 1990; Neilly et al. 1992; Spengler and Shea, 2000). We detected no changes in BP, although systolic pressure remained relatively high throughout the SD

period considering that the subjects were healthy young cadets. This could largely be due to the restricted time schedule of this study. Subjects were also measured in pairs, and in front of a group of other subjects. This may have caused BP to increase due to nervousness and anxiety. Habitual smokers were allowed to smoke as normal, despite previous evidence suggesting that smoking increases sympathetic and decreases parasympathetic activity at rest (Narkiewicz et al. 1998). Nonetheless, in separate analyses of HRV and BT, no changes were observed after excluding smokers. In addition, smoking was not allowed 3 h before each measurement, and prohibition of smoking could have resulted in significant withdrawal symptoms, which could also have affected sympathovagal balance.

In summary, the accumulation of 60 h of SD resulted in decreased HR regulated by increased vagal outflow, and decreased BT, although circadian variation was maintained. In addition, cardiovascular regulation seems to be modulated differently after sleep deprivation of 2 or 3 days compared to just 1 day.

References

Ax A, Luby ED (1961) Autonomic responses to sleep deprivation. Arch Gen Psychiatry 4:55–59

Ballard RD, Tan WC, Kelly PL, Pak J, Pandey R, Martin RJ (1990) Effect of sleep and sleep deprivation on ventilatory response to bronchoconstriction. J Appl Physiol 69:490–497

Bond V, Balkissoon B, Franks BD, Brwnlow R, Caprarola M, Bartley D, Banks M (1986) Effects of sleep deprivation on performance during submaximal and maximal exercise. J Sports Med Phys Fitness 26:169–174

Chen HI (1991) Effects of 30-h sleep loss on cardiorespiratory functions at rest and in exercise. Med Sci Sports Exerc 23:193–198

Burgess HJ, Trinder J, Kim Y, Luke D (1997) Sleep and circadian influences on cardiac autonomic nervous system activity. Am J Physiol 273:1761–1768

Dimitrov S, Lange T, Tieken S, Fehm HL, Born J (2004) Sleep associated regulation of T helper 1/T helper 2 cytokine balance in humans. Brain Behav Immun 18:341–348

Eckberg DL (2003) The human respiratory gate. J Physiol 15:339–352

Folkard S, Monk TH, Lobban MC (1979) Towards a predictive test of adjustment to shift work. Ergonomics 22:79–91

Gonzalez-Ortiz M, Martinez-Abundis E, Balcazar-Munoz BR, Pascoe-Gonzalez S (2000) Effect of sleep deprivation on insulin sensitivity and cortisol concentration in healthy subjects. Diabetes Nutr Metab 13:80–83

Harrison Y, Horne JA, Rothwell (2000) A prefrontal neuropsychological effects of sleep deprivation in young adults—a model for healthy aging? Sleep 15(23):1067–1073

Holmes AL, Burgess HJ, Dawson D (2002) Effects of sleep pressure on endogenous cardiac autonomic activity and body temperature. J Appl Physiol 92:2578–2584

Horne JA (1983) Human sleep and tissue restitution: some qualifications and doubts. Clin Sci 65:569–577

Horne JA (1993) Human sleep, sleep loss and behaviour implications for the prefrontal cortex and psychiatric disorder. Br J Psychiatry 162:413–419

Horne JA, Pettitt AN (1985) High incentive effects on vigilance performance during 72 hours of total sleep deprivation. Acta Psychol 58:123–139

Irwin M (2002) Effects of sleep and sleep loss on immunity and cytokines. Brain Behav Immun 16:503–512

Jurca R, Church TS, Morss GM, Jordan AN, Earnest CP (2004) Eight weeks of moderate-intensity exercise training increases heart rate variability in sedentary postmenopausal women. Am Heart J 147:21

Kandel ER, Schwartz JH, Jessell TM (2000) Principles of neural science international ed, 4th edn. McGraw-Hill, New York

Kato M, Phillips BG, Sigurdsson G, Narkiewicz K, Pesek CA, Somers VK (2000) Effects of sleep deprivation on neural circulatory control. Hypertension 35:1173–1175

Knutson KL, Spiegel K, Penev P, Van Cauter E (2007) The metabolic consequences of sleep deprivation. Sleep Med Rev 11:163–178

Kolka MA, Martin BJ, Elizondo RS (1984) Exercise in a cold environment after sleep deprivation. Eur J Appl Physiol Occup Physiol 53:282–285

Lubin A, Hord DJ, Tracy ML, Johnson LC (1976) Effects of exercise, bed rest and napping on performance decrement during 40 hours. Psychophysiology 13:334–339

Lusardi P, Zoppi A, Preti P, Pesce RM, Piazza E, Fogari R (1999) Effects of insufficient sleep on blood pressure in hypertensive patients: a 24-h study. Am J Hypertens 12:63–68

Meier-Ewert HK, Ridker PM, Rifai N, Regan MM, Price NJ, Dinges DF, Mullington JM (2004) Effect of sleep loss on C-reactive protein, an inflammatory marker of cardiovascular risk. J Am Coll Cardiol 43:678–683

Narkiewicz K, van de Borne PJ, Hausberg M, Cooley RL, Winniford MD, Davison DE, Somers VK (1998) Cigarette smoking increases sympathetic outflow in humans. Circulation 98:528–534

Neilly JB, Kribbs NB, Maislin G, Pack AI (1992) Effects of selective sleep deprivation on ventilation during recovery sleep in normal humans. J Appl Physiol 72:100–109

Ogawa Y, Kanbayashi T, Saito Y, Takahashi Y, Kitajima T, Takahashi K, Hishikawa Y, Shimizu T (2003) Total sleep deprivation elevates blood pressure through arterial baroreflex resetting: a study with microneurographic technique. Sleep 15:986–989

Pilcher JJ, Huffcutt AI (1996) Effects of sleep deprivation on performance: a meta-analysis. Sleep 19:318–326

Shamsuzzaman AS, Caples SM, Somers VK (2003) Sleep deprivation and circulatory control. Sleep 15:934–936

Shearer WT, Reuben JM, Mullington JM, Price NJ, Lee BN, Smith EO, Szuba MP, Van Dongen HP, Dinges DF (2001) Soluble TNF-alpha receptor 1 and IL-6 plasma levels in humans subjected to the sleep deprivation model of spaceflight. J. Allergy Clin Immunol 107:165–170

Spengler CM, Shea SA (2000) Sleep deprivation per se does not decrease the hypercapnic ventilatory response in humans. Am J Respir Crit Care Med 161:1124–1128

Spiegel K, Leproult R, Van Cauter E (1999) Impact of sleep debt on metabolic and endocrine function. Lancet 23:1435–1439

Thomas M, Sing H, Belenky G (2000) Neuronal basis of alertness and cognitive performance impairments during sleepiness. Effects of 24 h of sleep deprivation on waking human regional brain activity. J Sleep Res 9:335–352

Van Cauter E, Blackman JD, Roland D, Spire JP, Refetoff S, Polonsky KS (1991) Modulation of glucose regulation and insulin secretion by circadian rhythmicity and sleep. J Clin Invest 88:934–942

Van Cauter E, Holmback U, Knutson K, Leproult R, Miller A, Nedeltcheva A, Pannain S, Penev P, Tasali E, Spiegel K (2007) Impact of sleep and sleep loss on neuroendocrine and metabolic function. Horm Res 67(1):2–9

Vanhelder T, Randomski MW (1989) Sleep deprivation and the effect on exercise performance. Sports Med 7:235–247

Vgontzas AN, Papanicolaou DA, Bixler EO, Lotsikas A, Zachman K, Kales A, Prolo P, Wong M-L, Licinio J, Gold PW, Hermida RC, Mastorakos G, Chrousos GP (1999) Circadian interleukin-6 secretion and quantity and depth of sleep. J Clin Endocrinol Metab 84:2603–2607

White DP, Douglas NJ, Pickett CK, Zwillich CW, Weil JV (1983) Sleep deprivation and the control of ventilation. Am Rev Respir 128:984–986

Wu JC, Gillin JC, Buchsbaum MS, Hershey T, Hazlett E, Sicotte N, Bunney WE Jr (1991) The effect of sleep deprivation on cerebral glucose metabolic rate in normal humans assessed with positron emission tomography. Sleep 14:155–162

Zhong X, Hilton HJ, Gates GJ, Jelic S, Stern Y, Bartels MN, Demeersman RE, Basner RC (2005) Increased sympathetic and decreased parasympathetic cardiovascular modulation in normal humans with acute sleep deprivation. J Appl Physiol 98:2024–2032