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Extreme sleep fragmentation for 11 consecutive days and nights does not significantly alter total sleep time, and sleep stage distribution, during the continuous alpine downhill skiing world record

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Original article

Abstract

Introduction: Extreme levels of sleep deprivation, fragmentation and management, are major problems in many sportive disciplines, ultramarathons, polar or extreme altitude expeditions, and in space operations.

Material and methods: Polysomnographic (PSG) data was continuously recorded (total sleep time and sleep stage distribution) in a 34-year-old male whilst performing the new world record in long-term downhill skiing. He napped only during the short ski lift rides for 11 days and nights.

Results: After an initial period of complete sleep deprivation for 24 hours, total sleep time and the total times of non-REM and REM achieved during the lift rides returned to standard values on the second day. PSG data revealed an average sleep time per 24 hours of 6 hours and 6 minutes. During daylight sleep was rarely registered. The subject experienced only two minor falls without injury and immediately resumed skiing.

Conclusion: In a healthy, trained, elite male athlete, sleep fragmentation over 11 consecutive days did not significantly impair the sleep, motor or cognitive skills required to perform a continuous downhill skiing world record after an initial adaptation phase.

Keywords

- continuous exercise
- recovery
- resilience
- sport
- sleep stages
- sleep deprivation
- sleep fragmentation
- expeditions

Contribution

A – preparation of the research project
B – assembly of data
C – conducting of statistical analysis
D – interpretation of results
E – manuscript preparation
F – literature review

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Introduction

Sleep deprivation and fragmented sleep are common problems experienced during prolonged wilderness activities such as expeditions to polar regions, high mountains or very remote regions, global sailing, extreme endurance competitions (i.e. ultramarathons), and other athletic activities.[1-8] Sleep deprivation refers to a significant decrease in the total sleeping time (TST). Sleep fragmentation describes the quality of sleep and frequency of brief arousals or awakenings. Sleep deprivation and fragmented sleep are generally experienced by many athletes, although good data and studies are scarce.[8,9] The three risk factors for sleep disturbance in elite athletes were generally categorized as training, travel and competition.[9] Experiments suggest that individual vulnerability to sleep loss varies significantly.[10,11] Optimizing sleep hygiene during expeditions in extreme or remote environments may be the key to success or failure, and sometimes even survival.[12]

Table 1. Sleep stages according to the American Academy for Sleep Medicine (AASM)[20]

Alert / awake
• EEG: mainly alpha activity
• Share in TST < 5%
Non-REM-Sleep (NREM)
Stage N1: transition phase between awake and sleep ("snoozing")
• EEG: theta activity, vertex waves
• Share in TST about 5%
Stage N2: steady sleep
• EEG: theta activity, k complexes, sleep spindles
• Share in TST 45 to 55%
Stage N3: deep sleep
• EEG: delta activity
• Share in TST 12 to 25%
Stage R: REM sleep
• EEG: mixed frequencies, series of sawtooth waves
• Share in TST about 20%

Involuntary extreme sleep deprivation and fragmentation measured via continuous polysomnography in ICUs led to disrupted sleep and loss of circadian rhythm, but not to a major quantitative change in TST and sleep stage distribution[13] (the sleep stages according to the American Academy of Sleep Medicine (AASM) are illustrated in Table 1). The same is true for voluntary sleep fragmentation and deprivation due to Cheyne Stokes respiration at simulated or real extreme altitude.[14,15] Several publications have shown that the expected impairment of cognitive function and concentration after voluntarily imposing fragmented sleep patterns during extreme physical activities or on space flights, depends on the length of the physical activity, the total amount of sleep fragmentation, and the time point of measurement during or after the extreme activity and sleep fragmentation.[16]

There are very few studies using continuous polysomnography (PSG) in humans with over 24 hours of voluntary extreme sleep fragmentation or deprivation in combination with physical activity.[8] PSG is considered the gold standard of sleep monitoring and allows for the determination of REM and non-REM. In an early 1990 tennis marathon study where two men played continuously for 146 hours or six full days with only a single two-hour nap each day, the authors found no REM sleep occurred, and that slow wave sleep made up around 50% of all sleep.[17] Buguet et al. described the effects of exercise overload in extreme environments resulting in significantly decreased TST, slow-wave sleep and REM sleep, respectively.[7] In a more recent study the authors investigated the performance and sleepiness of sailors just before and during a transatlantic yacht race. Sleep during the physical activity onboard was measured via PSG and assessed in relation to the amount of obtained sleep before the race days.[18] Those who followed the individually best sleep management strategy were the winners of the competition.

The aim of this investigation was to objectively examine the possible quantitative changes of sleep stages during this skiing world record attempt; and to assess any detrimental impact on athletic performance when a heavily fragmented sleep pattern pervaded with sleep or napping occurring only during the short ski lift rides.

Materials and methods

We performed continuous PSG in a healthy, well-trained, athletic 34-year-old man (102 kg, 190 cm) for 11 days and nights (264 hours in total) during his world record in long-term downhill skiing. The subject was a professional downhill skiing athlete, a former member of the German National Ski Team, and the previous title holder of ten Guinness World Records in marathon skiing prior to this study. He was seven times world record holder of ski marathons (1999, 2001, 2002, 2003, 2004, 2005, 2007) and his previous record in ultra-long skiing was 222 hours 22 minutes. He gave written consent permitting electrodes to be placed on his body, and for PSG collection with publication of the data to be carried out during this record.

Prior to this the subject was assessed to exclude any relevant chronic illnesses including a sleep disorder (detailed history and standard PSG in a sleep laboratory). Except from his skiing records his sleep history was normal with 7 to 8 hours of sleep per night. Further testing included exercise spirometry, standard blood sample laboratory analysis, and a full PSG at the Department of Sports Science at the University of Innsbruck.

The active skiing took place on the slopes of Obergurgl in the Austrian Alps of Tyrolia at altitudes between 1,700 m and 3,000 m. The athlete was experienced in sleep deprivation and sleep fragmentation by his previous world records. He started this world record attempt without any specific procedures to increase alertness (e.g. over-sleeping, consuming more caffine than usual, using any drug that would influence sleep or alertness, etc.). Continuous surveillance of the subject was guaranteed by a team of physicians, physiotherapists, a sleep technician, and other trained skiers. The subject never skied alone, especially at night, in order to provide immediate First Aid in case of an accident, and to monitor any significant decrease in skiing technique (exhaustion, decreasing alertness, etc.) should this pose an unacceptable risk. Most of the accompanying skiers were ski coaches or members of the youth national team and with their experience they reported their subjective impression about the ability and the technique of the athlete regularly to the team. Beside of information for the study this was also part of the safety regimen to enable the team to stop skiing in the case that risk increases beyond acceptability e.g. by tiredness to avoid an accident of the athlete.

The usual skiing activity during this world record consisted of 10–20 minutes of fast downhill skiing (speed > 50 km/h) on downhill or Super G (super giant slalom) skis, followed by a 15–20 minutes gondola ride to the top again. The athlete was free to choose the slope at any downhill run. At night only those slopes which were illuminated were allowed. Resting, eating a snack and napping or sleeping was possible only during the gondola ride. Every 48 hours there was a two-hour break for food intake and massage at the base. The high-speed skiing required a relatively high concentration level but was less exhausting on red muscles. Concentration was judged indirectly by observing the athlete (skiing style and technique, safe skiing on the slope with high traffic of other skiers etc. Unfortunately, the rules of the world record did not allow any time for psychological testing. Speed and distances were monitored by GPS.

PSG was carried out using the SomnoScreen™ Plus recorder and the analyzing-software "Domino" (2.2.0–2.5.0) (SOMNOmedics GmbH, D-97236 Randersacker) according to the AASM 2007 guidelines. Data reading was done by a single trained and experienced sleep technician using the AASM 2007 scoring manual.[19-22] Due to the circumstances of the study and the aim of data acquisition, electrodes and sensors for leg EMG, oronasal flow, and respiratory belts were not used, and this data was not collected. The study was approved by the ethical commission at RWTH Aachen Technical University (EK-213-20).

Results

During the entire study, the subject experienced two minor falls (day 3 and 5 due to much traffic on the slope and a near-hit by a recreational skier) without injury and resumed skiing immediately at full ability. Overall, there was no visible lapse in technique, and no drop in performance objectively measured by GPS, specifically skiing speed and kilometers completed. Top speeds ranged between 80 to 100 (+) km/h on all days. Highest speed (about 105 km/h) was regularly reached on the world cup slope for women.

During the PSG recording the weather varied between −20°C to +6°C. During the second half of the record, the weather conditions deteriorated significantly with high wind speeds and gusts up to about 80 km/h, corresponding to Beaufort.[9]

PSG data collection was possible for 254 hours and 50 minutes, which was 96.5% of the entire testing period. This includes 16:22:00 of missing data at day 1 due to technical problems. However, this was without any consequence for the study since the athlete did not sleep at all during this time. A total sleep time of 68 hours and 43 minutes was detected during this time, corresponding to an average sleeping time per 24 hours of 6 hours and 6 minutes.

Sleep was registered for the first time in the early morning at day 2. During the entire recording, sleep stage N1 was reached for 11 hours and 9 minutes (16.2%), sleep stage N2 for 39 hours and 38 minutes (58.2%), sleep stage N3 for 7 hours and 12 minutes (10.5%), and sleep stage R (REM) for 8 hours and 29 minutes (12.4%). The summarized time of the different sleep stages is presented in Table 2 and Table 3.

The first sleep events were limited to short periods of sleep recorded in stage N1 and N2. The structure of the phases of sleep changed over the days. Beginning on the third day the first slow wave sleep and REM sleep were achieved and increased continuously in percentage of TST in the following days. We therefore defined an adaptation phase from the start to the third day. Only during this adaptation phase were there changes in the individual sleep cycles. The sleep cycles adapted to the maximum possible sleep phases or time. The number

Table 2. Registered sleep stages and total recording time

Measurements							
Day	**Missing data**	**Awake**	**N1**	**N2**	**N3**	**REM**	**TST**
1	16:22:00	07:38:00	00:00:00	00:00:00	00:00:00	00:00:00	00:00:00
2	01:02:50	19:56:00	00:37:10	02:06:00	00:18:00	00:00:00	03:01:10
3	00:43:00	17:15:30	00:57:30	04:36:30	00:23:00	00:04:30	06:01:30
4	01:08:30	17:00:30	00:39:00	03:52:30	01:05:00	00:14:30	05:51:00
5	00:04:30	18:36:00	00:16:00	02:47:00	01:32:00	00:44:30	05:19:30
6	00:53:00	18:06:30	00:13:00	02:50:00	01:03:00	00:54:30	05:00:30
7	00:20:00	17:26:00	00:26:00	03:32:30	01:02:30	01:13:00	06:14:00
8	00:28:30	16:28:30	01:24:00	03:55:30	00:46:00	00:57:30	07:03:00
9	00:11:00	14:08:00	02:19:00	05:38:30	00:40:00	01:03:30	09:41:00
10	00:48:30	17:01:30	01:08:00	03:49:30	00:01:30	01:11:00	06:10:00
11	01:49:30	15:31:00	01:40:00	03:49:00	00:01:30	01:09:00	06:39:30
12	08:53:30	09:19:00	01:29:30	03:01:00	00:19:30	00:57:30	05:47:30
	Mean (min.)		55.8	200.0	46.0	42.8	334.3
	SD		41.6	83.8	26.4	26.4	139.4

N1, N2, N3 – sleep stages; REM – REM sleep; TST – total sleeping time.

of sleep cycles (total cycle is reached in stage N3 or R) remained higher than known for normal physiological sleep, even after the adaptation phase.

During daylight, sleep was rarely registered. We observed the maintenance of a regular circadian day and night rhythm with sleep during the lift and gondola rides for approximately 20 minutes every 40 to 50 minutes and during the two hours massage breaks every 48 hours. This resulted in the total sleeping time as given in Table 2, the amount of the sleep stages in % of TST in Table 3.

Table 3. Registered sleep stages in % of total sleep time

Day	N1	N2	N3	REM
1	0.0	0.0	0.0	0.0
2	20.4	69.6	10.0	0.0
3	15.8	76.2	6.5	1.5
4	11.1	66.2	18.4	4.3
5	5.0	52.1	28.8	14.1
6	4.3	56.5	20.9	18.3
7	6.8	57.6	16.4	19,2
8	19.8	55.6	10.9	13.7
9	23.8	58.3	6.9	11.0
10	18.4	62.0	0.5	19.1
11	25.3	56.4	0.5	17.8
12	25.8	51,9	5.7	16.6

Discussion

Generally, there is a difference between sleep fragmentation and sleep deprivation. During this world record there was both, at least at the beginning. While sleep was fragmented over all 11 days, a deprivation was an effect which could be detected during the first days only. To our best knowledge this is the first study with partitioned and deprived sleep during strenuous exercise at moderate altitude (1,700 m to 3,000 m) for such a long period. The results confirm previous observations of studies in ICU patients and in subjects at extreme hypobaric hypoxia that quantitative sleep and sleep stage distribution are not significantly reduced, or changed, when the subjects have the possibility to achieve a substantial amount of sleep through frequent napping throughout the fragmented sleep period.[13-16] This suggests that sleep is a highly maintained, preserved and adaptive body function, and that sleep works as polyphasic sleep even during severe physical stress and extreme fragmentation.

Compare that to the tennis marathon study where sleep was only possible for one part of each day for up to two hours. Here a regular sleep stage distribution and an adequate amount of REM sleep cannot be maintained.[17]

In our case the athlete had to cope with several additional stressors besides the sleep fragmentation, including changing climatic conditions, altitude and other skiers. The expected lack of sleep could be detected in the first 36 hours. Starting on the third day, the total sleep time normalized to seven hours and five minutes in the daily average. The amount of REM normalized on the fourth day of the study.

However, the sleep fragmentation with sleep only was possible for up to 20 minutes followed by physical exercise for another 20 minutes which led to a total sleep deprivation for the first 32 hours. Only after this initial adaptation time did a normal sleep (TST and stages) occur within another 40 hours completely. Interestingly the performance of the athlete did not decrease during these first 32 hours although he reported some tiredness. An explanation could be that with the goal to break the world record with this physically demanding sport, his sympathetic activity was so high that some tiredness had no influence on the physical performance. Another explanation could be a bias by the athlete, perhaps he felt 'normal' because he was experienced in dealing with sleep deficiencies by his previous world records. Although the number of high-quality evidence studies is limited, athletes show a high overall prevalence of insomnia symptoms (longer sleep latencies, greater sleep fragmentation, non-restorative sleep, and excessive daytime fatigue).[8,11] These symptoms show marked inter-sport differences.[11] Laharnar et. al. found that short-term sleep restriction caused a stronger sleep disturbance than sleep fragmentation.[23] As fragmentation was the main problem during the present world record, and deprivation was limited to the first day, it is possible that the athlete investigated was less impaired than expected due to this effect. Since the consequences of sleep restriction are an early effect, which is at least partially balanced after an adjustment period by a more effective sleep with more short wave and REM sleep, this may also have contributed to the athlete's relatively well-rested status.[24]

These findings present important considerations for any work or sport activity involving heavily fragmented sleep portions. Organizers responsible for such activities should be risk aware of all the consequences of failure and accident risk when missing sleep the first few days of such activities with fragmented sleep. Most of the abnormal sleep was observed in the first 3 days. As sleep deprivation has been associated in other studies with drops in performance, this should be monitored closely for the first few days. Perhaps it would be useful to try something like an adaptation, or undertake a special training or receive some education in sleep fragmentation and sleep management strategies some days before starting the respective activity.

In this study featuring continuous sleep fragmentation, even with the initial total sleep deprivation of one and a half days, this did not lead to an obvious cognitive impairment or loss in concentration for a demanding physical activity. The skiing technique of the athlete was always controlled and safe. To the surprise of the whole team speed and performance of the athlete did not decrease with the decreasing weather conditions during the second part of the race. One has to consider, however, that our skier was a highly trained and experienced athlete and the title holder to the previous ten world records in several disciplines (7 in ultramarathon) in this skiing event.

It should be noted that the % of the different sleep stages is quite normal from day 3 or 4 on. Walsh et al. and Ohyon et al. report for an adult at the age of 30 and sleep of 7–9 hours approximately 61% 'light sleep' (obviously corresponding to stages N1 and N2), 16% 'deep sleep' (N3) and 23% REM sleep.[8,25] This is very similar to our data except for a reduced portion of REM sleep. This and the finding that naps may at least partially compensate sleep deficiencies[8,26] may explain that the athlete investigated here did not show a significant decrease in performance during his world record. He had multiple naps over 24 hrs. A nap is called a short sleep – normally at daytime – which causes benefits like improvement of concentration, alertness, motor performance, and mood.[8,26,27] It has been shown that such naps improve sprints and peak jump velocity performance.[8,28] When athletes have a shorter window to nap as it was the case in our study this is of benefit for performance because then they do not suffer from sleep inertia like grogginess from getting into deep sleep stages.[8] It is a limitation of the study that it was not possible to take time out to perform other tasks and cognitive function tests during the awake periods due to the rules of the record, the demanding nature and goal of the ski activity. Such testing may have shown that the sleep fragmentation would have led to fatigue and a reduced performance in other tests than the physical task. However, to the surprise of the whole team, the athlete was less tired on day 11 compared to the rest of the study members. Another limitation is the lack of data at day 1 due to technical reasons. However, as mentioned above this has no consequences for the study since the athlete did not sleep at all at day 1.

The subject was physically very fit. Therefore, we cannot give any conclusions how 'normal' (less trained) people would react in a situation with sleep fragmentation and physical exercise. On the other hand, it would be hard to find arguments why such people should react so significantly different since the mechanisms of sleep are very archaic ones in human evolution.

Altitude – better: hypobaric hypoxia – should also not have a significant influence here since the ski region is located at quite low altitude (800 to 2,000 m a.s.l.) and any decrease of mental or physical performance of healthy persons is limited to altitudes above about 2,000 m when persons stay there at least for some hours which is not the case for a downhill skier.[29,30] However, a recreational skier may have a significant higher risk for accidents (falls) because their skiing technique is not such an automated activity for them as for a professional skier.

Another limitation is that there was only one subject. However, this cannot be avoided when a world record is investigated, but since the quality of recordings was very good for > 90% of the time, we conclude that they are quite reliable. In future, data from other longer duration activities with sleep fragmentation may be compared in a meta-analysis. This will be necessary because it will be impossible to get a larger collective for a study under such extreme conditions.

Conclusion

We conclude that when fragmented sleep is imposed on a healthy adult for many days, provided there was a prior sleep deprivation adaptation period, this should not lead to a significant cognitive impairment in performing a demanding physical task he was proficient in. There must also exist sufficient subsequent opportunities to nap regularly after the initial adaptation phase to achieve adequate TST. The adult was both knowledgeable and practiced in the importance of good sleep hygiene and having a sleep management strategy.

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