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High Altitude Sleep Disturbances Monitored by Actigraphy and Polysomnography

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Abstract

Nussbaumer-Ochsner, Nicole Schuepfer, ChristophSiebenmann, Marco Maggiorini, and Konrad E. Bloch.High altitude sleep disturbances monitored by actigraphy and polysomnography. *High. Alt. Med. Biol.* 12:229–236.— ***Aims:*** Data on sleep at altitude are scant due to the limited availability of polysomnography. Therefore, we investigated whether actigraphy might serve as a simple tool for monitoring sleep during altitude field studies. ***Methods:*** Fourteen mountaineers participating in studies on dexamethasone prophylaxis of high altitude pulmonary edema were monitored by actigraphy and polysomnography during 1 night at Zurich (490 m) and 4 nights at the Regina Margherita hut (4559 m). Total sleep time (TST) estimated by actigraphy was compared to polysomnography and subjective sleep quality. ***Results:*** In 64 comparisons, mean differences ± 2SD (bias ± limits of agreement) between actigraphy and polysomnography were 5 ± 35 min for TST and 1 ± 7% for sleep efficiency. Correlations between subjective and polysomnographic estimates of sleep efficiency and sleep latency were nonsignificant. Medians of nocturnal oxygen saturation were 96% at 490 m and 74%–81% during nights 1 to 4 at 4459 m ($p < 0.05$ vs. 490 m). Medians of polysomnographic TST were similar at 490 m (451 min) and 4559 m (377–456 min during nights 1 to 4, p = NS) but the proportions of slow wave and REM sleep were reduced and arousals were more common ($p < 0.05$ all instances). ***Conclusion:*** Actigraphy accurately estimates sleep efficiency and duration. Due to its portability and simple use and the potential application over several weeks, it is a convenient tool for investigating altitude effects on sleep during field studies.

Key words: Actigraphy, sleep disorders, hypobaric hypoxia.

Introduction

During altitude sojourns, travellers commonly perceive a poor sleep quality (Jafarian et al., 2007) which has been related to sleep fragmentation and a reduction of deep sleep (Anholm et al., 1992; Beaumont et al., 1996; Khoo et al., 1996). Insomnia is one of the leading symptoms of acute mountain sickness However, the effects of altitude on sleep are still incompletely understood since the conclusions that can be drawn from earlier studies are hampered by small sample sizes, differences in protocols, settings (field studies vs. simulated altitude), sleeping altitude, and confounding effects of acclimatization and altitude-related illness. Considering the increasing popularity of mountain tourism and the requirements for professional personnel to stay at high altitude during mining operations, working at telescope stations, and other tasks, more scientific data on the effects of altitude on sleep would be desirable. Unfortunately, the technical complexity and logistic demands of polysomnography, the gold standard for investigating sleep, have been major obstacles to a more comprehensive investigation of sleep during altitude field studies. Therefore, a simple technique for the evaluation of sleep in such settings would be desirable. We reasoned that actigraphy might be a useful tool for the evaluation of altitude-related sleep disturbances because it is simple to use and unobtrusive and because actigraphic-derived sleep time strongly correlates with polysomnography in normals and in patients with various sleep

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disorders (Cole et al., 1992, Elbaz et al., 2002, Lichstein et al., 2006). The aim of the current study was therefore to validate actigraphy for the assessment of altitude-related sleep disturbances in comparison to polysomnography. We tested the hypothesis that actigraphy accurately estimates total sleep time, sleep efficiency, and sleep latency in comparison to polysomnography.

Materials and Methods

Participants

This study was part of a research project evaluating dexamethasone for prophylaxis of high altitude pulmonary edema (HAPE). Otherwise healthy mountaineers who had experienced at least one episode of HAPE during earlier altitude sojourns (*i.e.,* HAPE susceptible subjects), were recruited by advertisement. Subjects with chronic or acute medical conditions requiring medical treatment were excluded. Participants gave written informed consent and the study was approved by the institutional ethics committee.

Protocol

Within 1 month after baseline evaluation in Zurich (490 m), participants travelled to Alagna (1170 m), Italy, ascended to Passo Salati (2971 m) by cable car and walked to the Gnifetti hut (3610 m) within 2–3 hours to spend the night there. The following morning, subjects climbed to the Regina Margherita hut (4559 m) within 4–6 hours and stayed there for 4 nights. According to the protocol for the evaluation of dexamathesone prophylaxis on HAPE, subjects were randomized to either receive dexamethasone tablets 4 mg b.i.d. starting 24 hours prior to ascent and during the entire stay at 4559 m, or to receive identically looking placebo tablets 24 hours prior to ascent and dexamethasone starting in the evening of the second day at 4559 m. Actigraphy and polysomnographies were performed during one night in Zurich and during 4 successive nights at 4559 m from approximately 22:00 to 06:00 h.

Measurements

Actigraphy. The actigraph (MSR, Henggart, Switzerland) used in this study was specially designed for high altitude field studies. It is contained within the case of a watch and is worn at the wrist of the nondominant hand (Fig. 1). It incorporates an accelerometer (Type ADXL 202AE, Analogue Devices, Norwood, OH), a barometric pressure sensor for estimation of altitude, and a thermometer for measurement of local skin temperature (or environmental temperature if the device is not worn). Acceleration was recorded at a sampling rate of 256 Hz and with 12 bit resolution over the range of ± 2 *g*. Values averaged over successive 1 min intervals (epochs) were stored in the internal solid state memory along with barometric pressure and temperature.

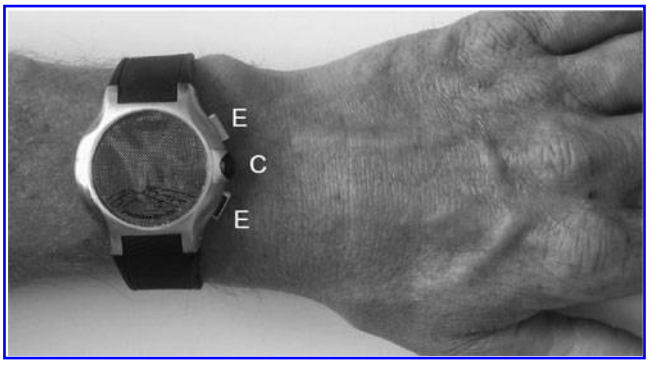

FIG. 1. Actimeter with integrated barometric pressure sensor for estimating altitude. E = event buttons; C = connector for data download to a computer.

Synchronization of actigraphic and polysomnographic recordings were achieved by recording a time stamp via event buttons on both devices at the beginning and the end of the measurement phase (Fig. 1). At the end of the studies, the internal memory of the actigraph was downloaded to a personal computer and processed by specialized software to estimate sleep/wakefulness times. Rest epochs were assumed to represent sleep and identified by an acceleration level below a threshold of 300 arbitrary acceleration units. This level had been found in previous analyses to best separate sleep from wakefulness (unpublished data). Therefore, this threshold was applied as default to all analyses. Visual inspection by an investigator blinded to the polysomnographic data served to verify whether any adjustments were necessary due to potential artefacts or individual differences in activity levels. However, no adjustments to the standard threshold level were required in any of the recordings. For each night, the following measures were determined: time in bed = time from lights-off to lights-on; total sleep time = sum of all epochs with activity below threshold; sleep efficiency = total sleep time/time in bed; sleep latency = time from lights-off to the beginning of the first three consecutive epochs with activity below threshold.

To evaluate whether the actigraph used in the current study (MSR, Henggart, Switzerland) provided activity recordings comparable to recordings by a device from another company (Actiwatch Spectrum, Philips Respironics, Amsterdam, NL), a technical comparison was performed between recordings obtained with the two devices worn simultaneously on the wrist of a volunteer during 72 hours.

To evaluate whether sleep times obtained by the software developed for the current study were comparable to corresponding values obtained by another commercially available software (Actiware 5, Philips Respironics), recordings were analyzed separately by the two softwares and estimated sleep times were compared.

Polysomnography. Polysomnography was performed with a portable, battery driven device (LifeShirt, Vivometrics, Ventura, CA) (Bloch et al., 2010; Brack et al., 2007;Clarenbach et al., 2005). Recordings comprised a central EEG lead (C3A2), EOG, submental EMG, rib cage abdominal motion by calibrated respiratory inductive plethysmography, pulse oximetry, capnography of expired air, ECG, and body position. Sleep stages and arousals were scored according to Rechtschaffen and Kales and the guidelines of the American Academy of Sleep Medicine by an investigator blinded to actigraphy (American Academy of Sleep Medicine, 2007; American American Sleep Disorders Association Task Force, 1992; Rechtschaffen et al., 1968). Apneas/hypopneas were defined as a reduction of the inductive plethysmographic sum volume signal to < 50% of the preceding 2 min baseline during ≥ 10 sec (American Academy of Sleep Medicine Task Force 1999, Thurnheer et al., 2001). Transient reductions in breathing amplitude to < 50% baseline for 5–10 sec were also scored as apneas/hypopneas if they occurred as part of a periodic breathing pattern with hyperventilation alternating with cen-

tral apnea/hypopnea for at least three consecutive cycles (Bloch et al., 2010). Central apneas/hypopneas were distinguished from obstructive apneas/hypopneas by the absence of rib cage-abdominal asynchrony or paradoxical motion. The apnea/hypopnea index (AHI) was computed as the number of events per hour of sleep and the oxygen desaturation index as the number of >3% dips per hour of sleep. Sleep study analysts were blinded to actigraphic and clinical data.

Questionnaire and clinical examination

Each morning subjects were asked to estimate the time spent awake until they fell asleep after lights off (subjective sleep latency). They also estimated the total time spent awake during the entire night for calculation of subjective sleep efficiency as time in bed minus time spent awake/time in bed. Subjective sleep quality was evaluated by visual analogue scales according to the Leeds questionnaire (Parrott et al., 1978, Tarrasch et al., 2003). For each question listed below a vertical mark had to be placed on a line 100 mm in length. If no change was experienced compared to the usual sleep, the mark had to be placed in the centre (at 50 mm). Perceived changes were represented by the distance of the mark from the centre with values <50 mm (left of the center) indicating worse, and >=50 mm (right of the center) indicating better. The following statements were rated: "Sleep was more restlessness than usual/more restful than usual;" "There were more periods of wakefulness than usual/fewer periods of

Table 1. Sleep Studies

		R. Margherita hut, 4559 m				
Polysomnography	*Zurich, 490 m* N=14	*Night 1* N=14	*Night 2* N=14	*Night 3* N=13	*Night 4* N=14	P *ANOVA*
TIB, min	478 (452;500)	494 (487;501)	513 (479;525)	482 (373;499)	480 (464;515)	ns
TST, min	451 (428;459)	442 (440;474)	456 (432;479)	377¶ (357;448)	433 (410;454)	<0.05
SE, %	95 (90;98)	91 (89;93)	95 (88;96)	90* (88;93)	88 (81;94)	ns
Awake, % TIB	4 (2;9)	9 (7;10)	5 (4;11)	10* (6;12)	12 (6;19)	ns
Wake after sleep onset, min	16 (8;35)	27 (9;38)	20 (11;54)	20 (16;46)	35 (8;62)	ns
Sleep latency, min	4 (2;9)	7 (3;28)	6 (3;9)	6 (4;10)	13* (6;27)	ns
Stage 1+2, % TST	66 (57;73)	80* (75;88)	85* (76;88)	70 (69;85)	79* (73;88)	<0.02
Stage 3+4, % TST	18 (13;20)	7* (4;10)	0*# (0;0)	8¶ (6;16)	5*¶ (1;10)	$<10^{-5}$
REM, % TST	10 (7;14)	1* (1;2)	0*# (0;0)	2*¶ (2;4)	1*¶ (1;3)	$<10^{-5}$
Arousal index, 1/h	1.7 (1.0;4.1)	6.9* (4.2;12.3)	4.1* (2.3;9.0)	6.2* (3.0;9.7)	6.0* (2.9;9.2)	$<10^{-3}$
SpO2, %	96 (94;96)	74* (73;78)	79*# (76;80)	79*# (76;82)	81*# (77;83)	$<10^{-5}$
ODI ≥4%, 1/h	0.6 (0.4;1.3)	69.6* (61.5;104.6)	43.2*# (20.4;66.4)	16.2*# (12.2;39.5)	33.3*# (8.4;53.8)	$<10^{-5}$
AHI, 1/h	5.6 (1.3;6.9)	88.1* (84.4;128.5)	61.9*# (24.6;95.9)	32.7*# (9.4;75.6)	42.4*# (14.5;78.3)	$<10^{-5}$
PetCO2, mmHg	36.3 (35;38.1)	26.4* (25.5;28)	24.9* (24.2;26.8)	24.8*#¶ (23.1;25.6)	24.2*# (22.4;26.6)	$<10^{-5}$
Actigraphy	n=14	n=12	n=13	n=12	n=13	
TST, min	464 (435;480)	458 (391;470)	462 (432;490)	415¶ (356;453)	437 (408;456)	ns
SE, %	97 (94;97)	94 (91;96)	95 (88;96)	92* (90;95)	90 (84;97)	ns
Awake, % TIB	4 (3;6)	7* (4;10)	5 (4;12)	9* (5;10)	10* (3;16)	ns
Wake after sleep onset, min§	13† (3;24)	18 (9;31)	21 (14;54)	27 (16;38)	42 (15;78)	ns
Sleep latency, 3 min algorithm	3 (2;5)	7 (4;10)	4 (3;5)	4 (3;7)	3† (3;4)	ns
Sleep latency, 5 min algorithm	6 (4;7)	9 (5;12)	5 (5;10)	7 (5;11)	5 (5;6)	ns

Medians (quartiles). TIB, time in bed; TST, total sleep time; SE, sleep efficiency; *$p<0.05$ vs. 490 m, #$p<0.05$ vs. night 1, ¶ $p<0.05$ vs. night 2, ¥ $p<0.05$ vs. night 3. † $p<0.05$ actigraphy vs. polysomnography. § based on a sleep latency algorithm of 5 minutes.

wakefulness than usual;" "How did you feel on waking (tired/alert)."

Symptoms of acute mountain sickness were assessed by the Lake Louise protocol self report and clinical assessment (Maggiorini et al., 1998). A Lake Louise total score ≥5 was considered to indicate acute mountain sickness.

Data analysis

Data are summarized as medians and quartiles for non-normally distributed data and as means±SD for normally distributed data. Sleep parameters determined by polysomnography and actigraphy were compared graphically and by computing the bias (mean difference) and limits of agreement (±2SD) (Bland et al., 1986). Correlations between the two methods were performed by the Spearman Rank Order testing. The effects of altitude were evaluated by Friedman ANOVA followed by Wilcoxon matched pairs tests as appropriate. A probability of $p<0.05$ was considered significant.

Results

Subjects

Twenty-three subjects were recruited. Two of them cancelled participation after the baseline examination at Zurich, and another 5 during the ascent to the Regina Margherita hut due to symptoms of acute mountain sickness. Three of the remaining 16 subjects (14 men, 2 women) had to spend another night at the Gnifetti hut (3610 m) because of bad weather conditions—of these, only data from the second, the third, and the fourth night at the Regina Margherita hut were available. Median age was 47 (quartile range 40 to 49) years, the body mass index was 24 (22 to 28) kg/m^2. Ten subjects received dexamethasone starting 24 hours prior to ascent and 6 subjects received dexamethasone starting in the evening of the second day at 4559 m.

Sleep studies

From a total of 77 study nights (one at 490 m and four at 4559 m per subject) 64 simultaneous polysomnographic and actigraphic recordings were available for analysis. Thirteen polysomnographies could not be used because of technical failure or poor EEG/EMG signal quality. All actigraphies could be evaluated and used for comparison. Sleep study results are shown in Table 1.

Compared to the night at Zurich, polysomnograms revealed that sleep was significantly impaired at altitude as reflected by a greater time spent awake, a reduced amount of slow wave sleep (NREM stages III and IV) and REM sleep, a reduced sleep efficiency, and an increased arousal index (representative example in Fig. 2). At altitude, there was a significant negative correlation between the arousal index and sleep efficiency measured by actigraphy as well as by polysomnography ($R=-0.5$, $R=-0.4$, respectively; $p<0.05$). Oxygen saturation was significantly reduced at 4559 m and subjects revealed pronounced periodic breathing with a very high central apnea/hypopnea index. Since there were virtually no obstructive events (<5/h in all studies), these are not reported separately.

Comparsion of actigraphy to polysomnography

Actigraphic estimates of total sleep time and sleep efficiency were similar to those of polysomnography (Table 1). Overall median sleep latency by actigraphy did not significantly differ from values assessed by polysomnography. Figure 3 shows identity plots and plots of differences for total sleep time and sleep efficiency estimated by actigraphy and polysomnography. The numerical comparison is presented in Table 2. There was no significant systematic error (bias) for total sleep time, sleep efficiency, and sleep latency, with exception of a minor bias for sleep latency in the fourth night at 4559 m. The limits of agreement indicated that the precision of actigraphy in estimation of total sleep time (±35 min corresponding to±9%) and sleep efficiency (±7%) were high (Table 2). Total sleep time and sleep efficiency from actigraphy were closely correlated with corresponding values by polysomnography ($R=0.92$, $R=0.82$, respectively, $p<0.05$) while the correlation was poor for sleep latency ($R=0.14$, $p=$NS) (Table 2).

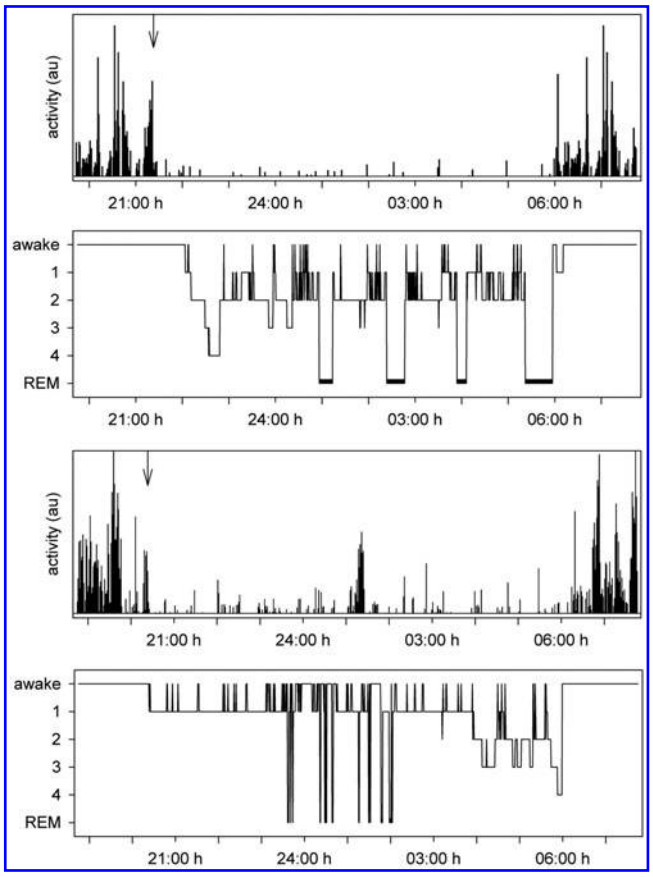

FIG. 2. The actigram obtained in a subject during a night at 490 m (*top panel*) shows very rare spikes with low activity indicating nearly undisturbed sleep. Correspondingly, the hypnogram (*second panel from top*) shows a normal distribution of sleep stages and four NREM/REM cycles. In contrast, the actigram recorded during a night at 4559 m (*third panel from top*) reveals frequent spikes of high activity reflecting movements during the awakenings. The corresponding hypnogram (*lowest panel*) reveals predominantly superficial sleep stages with frequent awakenings, very rare deep sleep stages 3 and 4, and no REM sleep. In addition to the awakenings the subject had a considerable number of arousals (scored according to the ASDA 1992 criteria). Therefore, sleep fragmentation was even more pronounced than what can be appreciated in the hypnogram. X-axis, clock time; y-axis of actigrams, acceleration in arbitrary units; y-axis of hypnograms, NREM stages 1-4 and REM sleep. Lights off is marked by a *vertical arrow*.

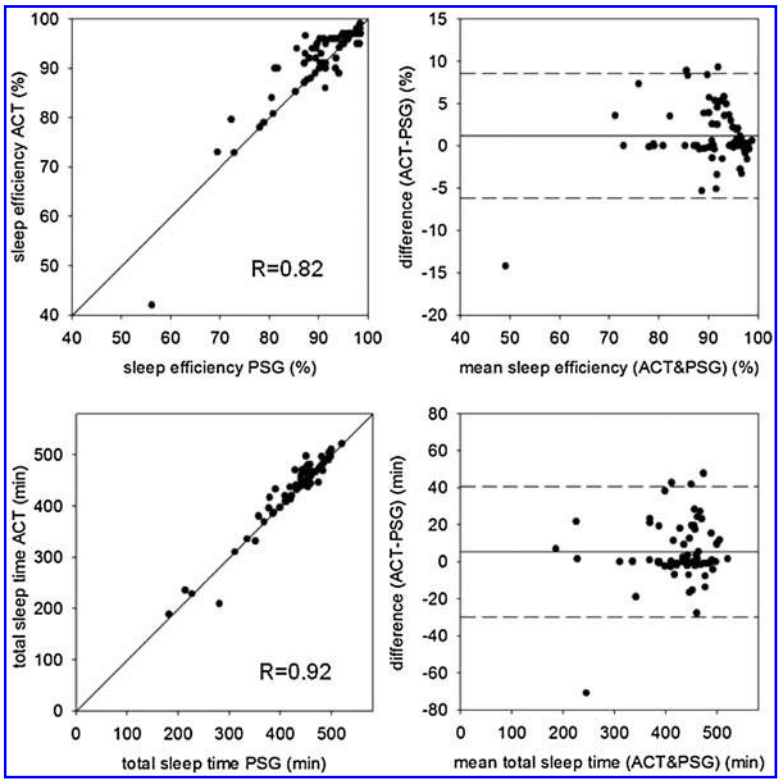

FIG. 3. Identity plots (*left panels*) and plots for differences of actigraphic minus polysomnographic estimates (ACT-PSG) vs. their mean (*right panels*) for sleep efficiency (*upper panels*) and total sleep time (*lower panels*). Mean differences (bias) are represented by a *horizontal line* and the limits of agreement (bias ± 2 SD) by *dashed lines*.

The comparison of accelerations measured in a volunteer during 72 hours by the MSR actigraph used in the current study and the Philips Respironics Actiwatch Spectrum worn at the same wrist revealed a very close correlation ($R = 0.96$, $P < 10^{-6}$). Analysis of activity recordings obtained with the MSR actigraph used in the current study were compared in 9 subjects during 29 nights with the software developed for the current study and a commercially available software (Actiware 5, Philips Respironics,). The results revealed no significant bias in the

Table 2. Comparison of Actigraphy to Polysomnography

		R. Margherita hut 4559 m				*Total*
	Zurich 490 m	*Night 1*	*Night 2*	*Night 3*	*Night 4*	*all nights*
Number of comparisons	14	12	13	12	13	64
Total sleep time (min):						
bias ± limits of agreement	8.6 ± 30.2	−0.4 ± 52.9	3.4 ± 20.3	8.6 ± 34.6	5.5 ± 26.9	5.2 ± 35
Correlation coefficient, R	0.78#	0.77#	0.96#	0.97#	0.96#	0.92#
Sleep efficiency (%):						
bias ± limits of agreement	2 ± 6	0 ± 11	1 ± 4	2 ± 8	1 ± 5	1 ± 7
Correlation coefficient, R	0.75#	0.72#	0.96#	0.33	0.93#	0.82
Sleep latency (min), 3 min immobility:						
median difference (quartiles)	0	−0.5	1	0	−3*¶¥	−1
Correlation coefficient, R	(−7;3)	(−12.5;3)	(−4;2)	(−3;1)	(−23;0)	(−6;1.5)
	−0.29	0.49	0.35	0.53	−0.21	0.14
Sleep latency (min), 5 min immobility:						
median difference (quartiles)	2	1	1	1.5	−1*¶¥	0
Correlation coefficient, R	(−2;5)	(−2.5;5)	(−1;4)	(−1.5;4)	(−21;2)	(−4;4)
	−0.08	0.68#	0.28	0.23	−0.2	0.13

Values represent mean differences (bias) of values by actigraphy minus corresponding values by polysomnography ± 2SD (limits of agreement). Since differences of sleep latency were not normally distributed medians (quartiles) are indicated instead of mean differences and limits of agreement. Correlation analysis was performed using Spearman Rank Order testing. *$p < 0.05$ vs. 490 m, ¶$p < 0.05$ vs. night 2, ¥$p < 0.05$ vs. night 3, #$p < 0.05$ polysomnography vs. actigraphy.

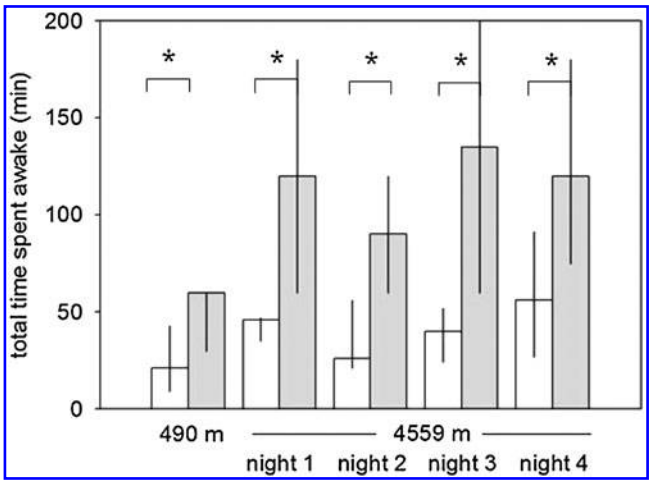

FIG. 4. Total time spent awake estimated subjectively (*gray bars*) significantly exceeds corresponding values measured by polysomnography (*white bars*) (*$p < 0.05$). *Bars* and *vertical lines* represent medians and quartile ranges; the upper quartile in night 3 was 350 min.

estimated sleep time (mean difference of 4.0 min and limits of agreement of ± 24.9 min).

Symptoms and clinical examination

There was no significant overall effect of altitude on subjective sleep quality. Subjective estimates of total time spent awake at low and high altitude were significantly greater and more variable than corresponding values measured by polysomnography (Fig. 4). At altitude, the Lake Louise Score indicated that subjects suffered from mild symptoms of acute mountain sickness (Table 3) but symptoms regressed during prolonged stay. There was no significant correlation of the subjective sleep quality measurement 'restless sleep' compared to the sleep efficiency assessed by polysomnography and actigraphy (R = 0.16 and 0.12, respectively, p = NS). Subjective estimation of 'nocturnal wakefulness' also did not correlate with the time spent awake measured by polysomnography or actigraphy (R = 0.18 and 0.21, respectively, p = NS). However, there was a significant although weak correlation between the arousal index and the Lake Louise Score (R = 0.3, $p < 0.05$).

In two subjects, high altitude pulmonary edema developed during the second night at altitude. They were initially treated with sildenafil 50 mg and oxygen supplementation and recovered quickly with a treatment of sildenafil 25 mg twice daily during the whole stay at altitude. No evacuation was necessary, and sleep studies from these subjects were also included into analysis.

Discussion

Our study validates a novel actimeter specifically designed for field studies at altitude. Compared to polysomnography, the gold standard for measuring sleep, actigraphy accurately estimated the total sleep time and sleep efficiency, and it detected changes in sleep efficiency induced by altitude. Subjective perception of sleep quality and sleep duration did not correlate with objective measures, emphasizing the need for an objective tool assessing sleep at altitude. Since actigraphy is unobtrusive and easily portable, it might serve as a valuable tool for the investigation of the effects of altitude on sleep in field studies over several days and nights.

Sleep studies at altitude can be simulated in pressure chambers or performed under field conditions. Examinations in the field are more realistic but are hampered by demanding logistics, meteorological conditions, and the limited availability of polysomnography. Actigraphy is a simple and convenient technique that allows estimating sleep/wakefulness indirectly by recording movements of the wrist over several months. The validity of actigraphic assessment of sleep is supported by several studies in subjects with and without sleep disturbances. De Souza et al. (2003) compared actigraphy to polysomnography in 21 healthy volunteers. Depending on the analysis algorithm applied, the bias and limits of agreement for total sleep time were 18.5 ± 41.4 min and 8.1 ± 42.0 min, respectively; the bias and limits of agreement for sleep efficiency were 4 ± 8% and 2 ± 9%, respectively. Gagnadoux et al. (2004) evaluated actigraphy in patients with obstructive sleep apnea syndrome during a night in the sleep laboratory without CPAP therapy. The bias of actigraphic compared to polysomnographic estimates of total sleep time was nonsignificant (2.5 min), however the precision was poor as reflected in the very wide limit of agreement of ± 70.6 min. Gagnadoux and co-workers speculated that the poor performance of actigraphy might have been due to the apnea-related sleep fragmentation in obstructive sleep apnea patients (Gagnadoux et al., 1999). In the current study, the precision of actigraphy in terms of total sleep time and sleep efficiency was greater and similar to that reported for normal subjects in previous comparisons (Table 2) (De Souza et al., 2003). In

Table 3. Questionnaire Evaluation

		R. Margherita hut, 4559 m			
	Zurich, 490 m	*Night 1*	*Night 2*	*Night 3*	*Night 4*
Subjective sleep latency (min)	20† (15;45)	30 (20;45)	20 (10;60)	25† (20;90)	30 (12;45)
Subjective time spent awake (min)	60† (30;60)	120*† (60;180)	90† (60;120)	135† (60;350)	120† (75;180)
SEQ 'restless sleep'	35 (24;42)	14 (5;24)	22 (11;38)	19 (6;36)	32 (22;42)
SEQ 'wakefulness'	18 (13;26)	13 (4;21)	20 (9;33)	21 (5;30)	29 (9;37)
SEQ 'tired/alert'	42 (35;49)	26 (15;48)	53# (46;64)	54 (28;63)	47 (40;59)
LLS total	0 (0;1)	4* (3;4)	3* (1;4)	2* (1;4)	2*# (1;3)
LLS question on insomnia	0 (0;0)	2* (1;3)	1* (1;2)	2* (1;2)	2* (1;2)

Medians (quartiles), n = 14. *$p < 0.05$ vs. 490 m, #$p < 0.05$ vs. night 1, ¶$p < 0.05$ vs. night 2, ¥$p < 0.05$ vs. night 3, †$p < 0.05$ vs. results from polysomnography. LLS, Lake Louise score; SEQ, visual analog scores of Leeds Sleep Evaluation Questionnaire items.

contrast to obstructive sleep apneas that commonly trigger arousals, we observed that the proportion of central apneas associated with arousals in high altitude periodic breathing was low (Table 1) (Anholm et al. 1992, Khoo et al., 1996) which might explain the better accuracy of actigraphy in the current study in mountaineers.

Despite a nonsignificant bias, the sleep latency estimated by actigraphy was only loosely correlated with polysomnographic values (Table 2). This has been explained by a period of immobility that precedes falling asleep and that might be erroneously scored as sleep by actigraphy (Pollak et al., 2001). In order to evaluate the potential effect of the analysis algorithm on sleep latency estimated by actigraphy (Chae et al., 2009), we applied a 5 minutes and a 3 minutes immobility rule for sleep onset and found no clinically relevant difference in resulting sleep latencies (Table 1).

The close correlation of acceleration measured by the actigraph used in the current study and another commercially available device, and the lack of a significant bias between estimates of sleep time obtained by our specialized software and a commercially available software suggest that evaluation of sleep time at altitude may be performed by the actigraph and software used in the current study and at least one other type of equipment. We cannot exclude that other actimeters may perform differently or may not be robust enough for field studies at altitude. Therefore, a careful selection and evaluation of the actigraphic equipment is crucial.

We observed that subjects perceived their sleep quality at high altitude as poor and polysomnography revealed a reduced amount of slow wave and REM sleep (Table 1). Only few studies have investigated sleep at altitude using polysomnography and the variety of applied protocols including differences in ascent rate, acclimatization, sleeping altitude, and settings hampers a comparison to the current data. Nevertheless, a reduced deep sleep seems to be a consistent finding (Johnson et al., (2010); Nussbaumer-Ochsner et al., 2010). The arousal indices we measured at low and high altitude were relatively low, in particular considering the high apnea/hypopnea index at 4559 m (Table 1). Since the few published studies on the arousal index in healthy subjects of different age groups reveal a very large normal range (Mathur et al., 1995), it remains open whether our findings are spurious due to the shortcomings of a single central EEG recording, whether arousals defined by the ASDA criteria (American Sleep Disorders Association Task Force, 1992) do not reflect sleep disturbance from high altitude periodic breathing, or whether HAPE-susceptible subjects have an altered arousal response. Finally, we were not able to assess the effects of dexamethasone which may have modified the arousal threshold.

While the current study is the first that validates actigraphy by comparison to polysomnography at altitude, the technique has been employed previously to evaluate the effects of hypoxia, acute mountain sickness, and drugs for treatment of altitude insomnia (Barash et al., 2001; Erba et al., 2004; Nickol et al., 2006) illustrating the role of actigraphy for investigation of sleep and its disturbances at altitude. One study revealed that temazepam induced a reduction in periodic breathing over the course of a trek to 5000 m (Nickol et al., 2006) but there was no change in actigraphic sleep latency or nocturnal restlessness. Another study assessing the effects of zolpidem and zaleplon on sleep at 3613 m (Beaumont et al., 2007) revealed a significant decrease in the number of wrist movements by both drugs compared to placebo. Barash et al. (2001) evaluated the effect of oxygen enrichment on sleep architecture at 3800 m. Compared to ambient air, no significant difference for sleep efficiency, time scored awake and asleep was detected by actigraphy. Polysomnography showed that subjects spent a significantly greater percentage of time in deep sleep stages (slow wave sleep) with oxygen enrichment, while no change in the other sleep variables was detected. In another study at altitude, we compared sleep and nocturnal breathing in subjects with and without acute mountain sickness (Erba et al., 2004). Actigraphic recordings indicated reduced sleep efficiency in subjects suffering from acute mountain sickness consistent with the notion that insomnia and headache are characteristic features of the disease.

The lack of a correlation between subjective estimates of total sleep time and sleep latency with corresponding measurements by polysomnography (Table 3, Fig. 4) may represent a sleep state misperception and emphasizes the important role of objective measurements for assessing sleep at altitude.

Although total sleep time and sleep efficiency estimated by actigraphy and polysomnographic variables reflecting sleep architecture represent useful information for assessment of sleep disturbances at altitude, it is conceivable that multichannel, topographic EEG and other measures yet to be defined by future studies might be more sensitive and specific for assessment of altitude effects on sleep.

Conclusion

Our study demonstrates that actigraphy provides objective estimates of sleep efficiency and total sleep time at low and high altitude which are sufficiently accurate to be of use in research studies. Considering its simple use and robustness and the potential application over several weeks makes the technique a valuable tool for investigation of sleep disturbance during altitude field studies. Actigraphy might be used as an adjunct to questionnaire evaluation and clinical examination in settings were more sophisticated methods such as polysomnography cannot be used.

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