Sleep architecture, periodic breathing and mood disturbance of expeditioners at Kunlun Station (4087 m) in Antarctica

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Abstract   Several studies have reported the detrimental impacts of hypoxia exposure on sleep. Chinese Kunlun Station (altitude 4087 m) is located at Dome A, the highest point on the Antarctic ice sheet and one of the most extreme environments on Earth. This study investigated alteration of sleep, breathing and mood status in healthy expeditioners at Kunlun Station at Dome A. The study examined 10 male volunteers of the inland transverse party to Kunlun Station during the 31st Chinese National Antarctic Research Expedition, and valid data from eight volunteers were analyzed. Sleep structure, breathing pattern and mood were monitored using portable polysomnography (PSG) and profile of mood state (POMS) at two time points: (1) at Zhongshan Station (10 m) before departure to Kunlun Station; (2) on nights 12−13 of residence at Kunlun Station.

Slow-wave sleep (Stage 3 non-rapid eye movement) was markedly reduced at Kunlun Station ($P < 0.01$). Total sleep time, sleep efficiency and sleep latency showed no significant changes. Total respiratory events ($P < 0.05$), apnea/hypopnea index (AHI) ($P < 0.05$) and hypopnea index ($P < 0.01$) substantially increased at Kunlun Station. The most common respiratory disorder was periodic breathing, occurring almost exclusively during non-rapid eye movement sleep. The oxygen desaturation index increased markedly ($P < 0.05$), while nocturnal oxygen saturation dramatically fell at Kunlun Station ($P < 0.05$). Vigor scores decreased at Kunlun Station ($P < 0.05$). Expeditioners exhibited reduced slow wave sleep, induced periodic breathing, decreased oxygen saturation and decreased vigor at Kunlun Station.

Keywords   sleep, periodic breathing, expeditioner, Kunlun Station, Antarctica

1   Introduction

Sleep disturbances are common in sojourners traveling to high altitude environments. A number of previous field and hypobaric chamber studies have confirmed that ascent to high altitude results in sleep architecture alterations and sleep-related breathing disorders. These alterations are characterized by frequent awakenings, reduced deep slow wave sleep, periodic breathing (PB), and pronounced oxygen desaturation (Weil, 2004; Ainslie et al., 2013; Bloch et al., 2015). Polygraphic sleep assessment on the Antarctic plateau was first reported in a study with two subjects at South Pole Station (SP; 2835 m) (Joern et al., 1970). Researchers discovered increased non-rapid eye movement (NREM) sleep and a near absence of slow wave sleep (SWS). Another sleep study at SP with a larger sample size

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(38 men) suggested unchanged sleep architecture, increased oxygen desaturation and disordered breathing (Anderson et al., 2015). In a study at the Concordia Station (3233 m), Tellez et al. (2014) reported that severe periodic breathing persisted through the year-long campaign. Consistently, people transported rapidly from sea level to SP were found to complain of sleep disorders persistently over 7 d (Anderson et al., 2011). Importantly, Collet et al. (2015) compared sleep-related parameters between two Antarctic stations, Dumont d'Urville Station (sea level) and Concordia Station (corrected [for air temperature] altitude 3800 m). The results revealed decreased total sleep time, longer wakefulness after sleep onset and impaired sleep efficiency at Concordia Station compared with sea level (Collet et al., 2015).

Importantly, sleep disorder induced by hypoxia may affect subjective mood and impair daytime performance. de Aquino Lemos et al. (2012) reported that hypoxic conditions at 4500 m increased depression, anger, and fatigue. Another study suggested an increase in irritability at high altitudes (Bahrke and Shukitt-Hale, 1993). Therefore, exploring disturbances of sleep, breathing and mood of expeditioners on the Antarctic plateau is important for informing the development of suitable medical interventions.

Dome A is the highest point on the Antarctic ice sheet, with an altitude of 4087 m and barometric pressure equivalent to approximately 5000 m above sea level (560–590 hpa from January to April). It is considered one of the most challenging environments on Earth, because of the low oxygen, harsh climate (cold and windy), unpredictable dangers and poor transport accessibility. In 2009, Kunlun Station was established as a summer station at Dome A by the inland transverse party of the 25th Chinese National Antarctic Research Expedition (25th CHINARE), with a capacity to accommodate 20–28 research personnel. Based on previous studies, we predicted that expeditioners at Kunlun Station would also experience sleep problems and mood disturbance. To validate this hypothesis and guarantee the well-being of expeditioners, we monitored nocturnal sleep architecture, breathing patterns and mood

state in healthy expeditioners travelling from Zhongshan Station (10 m) to Kunlun Station (4087 m).

2   Materials and methods

2.1   Participants and procedure

The inland transverse party of the 31st CHINARE consisted of 30 expeditioners. Because we had only five sets of portable polysomnography (PSG) devices, 10 volunteers participated in this study and PSG measurements were carried out on two consecutive nights. Eventually, valid data from eight volunteers were acquired and analyzed; all participants were healthy men aged between 23 and 39 years (mean 27.9 ± 5.5 years), with a mean weight of 70.9 ± 8.4 kg, body mass index of 22.7 ± 2.6 kg·m^{-2}, and normal respiratory function before departure (forced vital capacity [FVC]: 5.4 ± 0.4 L; forced expiratory volume in 1 s [FEV1]: 4.5 ± 0.6 L; FEV1/FVC: 83.2±11.2%). None of the participants had known medical problems or took regular medicine. Participants were asked to refrain from alcohol and caffeine ingestion 24 h before the sleep study. All participants signed informed consent and the study protocol was approved by the ethics committee of Peking Union Medical College (ethics number: 2018004).

Participants reached Zhongshan Station (altitude 10 m) on 1 December 2014 via the R/V *Xuelong* icebreaker, 30 d after leaving from Shanghai on 30 October 2014. After preparing for 15 d, the expeditioners departed for Kunlun Station (altitude 4087 m) on 15 December by snow tractor and arrived on 30 December after a gradual 15-d ascent. After 24 d of scientific exploration, they left Kunlun Station on 23 January 2015. The expeditioners took 15 d to return to Zhongshan Station on 7 February 2015. The itinerary and schedule of sampling and tests is shown in Figure 1.

2.2   PSG Measurements

Sleep patterns were evaluated using portable PSG equipment (Embla X100, USA) at two time points: (1) at Zhongshan Station (10 m) before departure to Kunlun
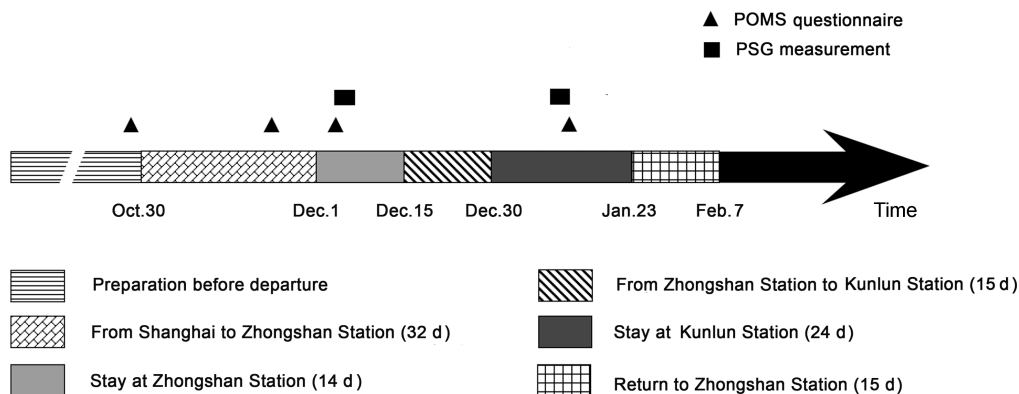
Figure 1   The itinerary and schedule of sampling and tests of the inland transverse party of the 31st CHINAER.

Station; (2) on nights 12–13 at Kunlun Station (4087 m). The recorded channels included: two electroencephalogram (EEG: C3/A2 and O2/A1) channels; chin and tibial electromyogram (EMG) channels; two electro-oculogram (EOG) channels (left and right); thoracic and abdominal effort monitored by inductance plethysmography sensors; oronasal flow evaluated using pressure transducer and oxygen cannula; and nocturnal oxyhemoglobin saturation recording carried out using a finger pulse oximeter.

After returning to China, PSG recordings were analyzed by two qualified sleep technologists manually blinded to subject information according to general criteria (Wolpert, 1969; Berry et al., 2012).

Sleep parameters were defined and analyzed as follows: total sleep time (TST) (min), sleep onset latency (min), sleep efficiency (i.e., total sleep time/time in bed × 100%), wake after sleep onset (min), arousal, percentage of each sleep stage (NREM1, NREM2, NREM3 (SWS), REM sleep) (i.e., time of each sleep stage/total sleep time × 100%).

Apnea was defined as a $\geq 90\%$ drop in the peak signal excursion from baseline by ≥ 10 s. Hypopnea was defined as $\geq 30\%$ drop in the peak signal excursions from baseline by ≥ 10 s accompanied with a decrease from oxygen saturation (SpO_2) by $\geq 4\%$. Central apneas/hypopneas were identified as absent or reduced respiratory effort and airflow for ≥ 10 s. Obstructive apneas and hypopneas were identified as unchanged or increased respiratory effort accompanied with decreased airflow for ≥ 10 s. The apnea/hypopnea index (AHI) measures the number of apneas and hypopneas per hour of TST. Periodic breathing was identified as episodes of ≥ 3 consecutive central apneas/hypopneas separated by a crescendo and decrescendo in breathing amplitude, and an apnea duration of central apneas/hypopneas during periodic breathing having a minimum duration of 5 s (Bloch et al., 2010; Nussbaumer-Ochsner et al., 2012). Hypopnea index, central apnea index, obstructive apnea index and mixed apnea index respectively represent the number of occurrences of hypopnea, central apnea, obstructive apnea and mixed apnea per hour during sleep monitoring.

Measurements of blood oxygenation included SpO_2 measured by pulse oximetry, the desaturation index, and the percentage of time in which SpO_2 was less than 90% (T90%) or 80% (T80%) during sleep.

2.3 Psychological questionnaire

The profile of mood state questionnaire (POMS, 1971 EdiTS/Educational and Industrial Testing Service, San Diego, CA, USA) was given to each expeditioner at Zhongshan Station and on nights 12–13 at Kunlun Station, consistent with the time point of conducting PSG measurements. Scores of tension, anger, depression, vigor, confusion, fatigue and total mood disturbance (TMD) were calculated according to standard scoring methods.

2.4 Statistical analysis

All data were analyzed using IBM SPSS Statistics 21

software (SPSS Inc, Chicago, IL) and expressed as mean ± SEM. Data distribution was evaluated by Shapiro-Wilks statistics. Parameters with normal distributions were analyzed using repeated measures of analysis of variance followed by the Bonferroni method. Parameters with abnormal distributions were analyzed using the Wilcoxon signed rank test. $P < 0.05$ was considered to indicate statistical significance.

3 Results

During the experiment, two respiratory recordings and one EEG recording at 4087 m were not obtained as a result of the sensors failing. As a result, EEG recordings of seven expeditioners and respiratory recordings of six expeditioners were analyzed.

3.1 Reduced slow wave sleep at Kunlun Station (4087 m)

The total sleep time, sleep efficiency, sleep latency, wake after sleep onset and arousal were comparable between different time points (Figures 2a–2e, Table 1). The percentage of SWS exhibited a marked decrease at 4087 m (18.61% ± 2.04% vs. 9.39% ± 3.05%, $P < 0.01$) (Figure 2h, Table 1), although the percentage of light sleep and REM sleep remained unchanged (Figures 2f, 2g, 2i; Table 1).
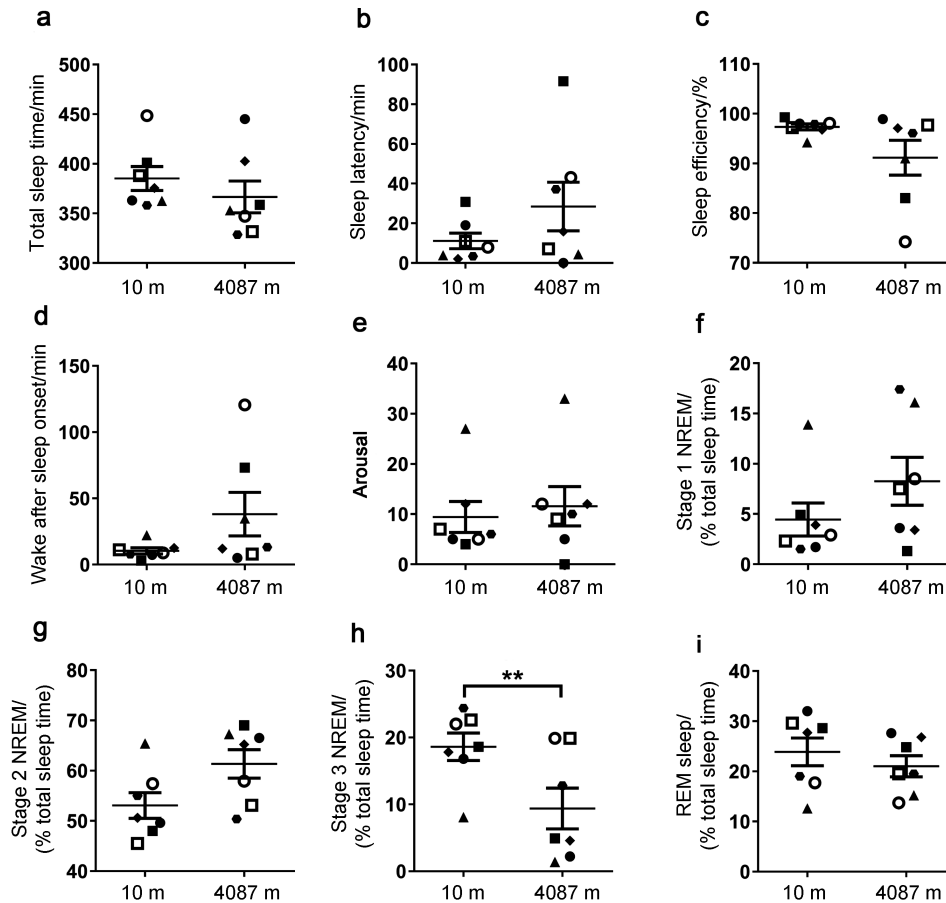
3.2 Induced PB at Kunlun Station (4087 m)

Between 10 m and 4087 m elevation the total respiratory events (48.00 ± 33.33 vs. 338.83 ± 102.69, $P < 0.05$), apnea/hypopnea index (AHI) (7.90 ± 5.57 h^{-1} vs. 55.07 ± 15.38 h^{-1}, $P < 0.05$) and hypopnea index (5.60 ± 4.38 h^{-1} vs. 37.42 ± 7.38 h^{-1}, $P < 0.01$) all significantly increased (Figures 3a–3c, Table 2). Apneas were mostly of the central type occurring during NREM sleep, rather than the obstructive or mixed type (Figures 3d–3f, Table 2). PB was virtually absent at sea level. Exposure to 4087 m resulted in obvious changes in breathing pattern. PB became prevalent, occurring for an average of 38.67% of sleep time (Figure 3g, Table 2). There was substantial variability in PB among the subjects. In three subjects, PB was present in more than 40% of TST, and one subject did not develop PB at 4087 m (Figure 3g). Figure 4 is an example of one expeditioner exhibiting normal breathing and oxygen saturation during sleep at 10 m and severe disordered breathing during sleep at 4087 m.

3.3 Decreased oxygen saturation at Kunlun Station (4087 m)

At 4087 m, the number of events of oxygen desaturation per hour increased dramatically (7.23 ± 4.76 h^{-1} vs. 60.20 ± 15.19 h^{-1}, $P < 0.05$) (Figure 5a, Table 3). The minimum oxygen saturation during sleep fell from 89.67% at sea level

to 72% at 4087 m ($P < 0.01$) (Figure 5b, Table 3). The mean overnight blood saturation fell from 96.17% to 80.85% ($P < 0.05$, Table 3) (Figure 5c). Consistently, mean SpO_2 during NREM and REM sleep dropped at 4087 m by 15.07% and

16.44%, respectively ($P < 0.05$) (Figure 5d, 5e; Table 3). In addition, the time during which SpO_2 was below 90% or 80% increased by 99.72% and 24.17%, respectively ($P < 0.05$) (Figures 5f, 5g; Table 3).


Figure 2 Reduced percentage of NREM3 sleep at Kunlun Station (4087 m). **a**, Total sleep time; **b**, Sleep latency; **c**, Sleep efficiency; **d**, Wake after sleep onset; **e**, Arousal; **f**, Percentage of NREM1 sleep; **g**, Percentage of NREM2 sleep; **h**, Percentage of NREM3 sleep; **i**, Percentage of REM sleep at 10 m and 4087 m. Data were expressed as mean ± SEM; $n = 7$, **$P < 0.01$, 4087 m versus 10 m.

Table 1   Changes of sleep parameters at Zhongshan Station (10 m) and Kunlun Station (4087 m)

Parameters	10 m	4087 m	*P* value
Total sleep time/min	385.21±12.06	366.57±16.00	0.439
Sleep latency/min	11.13±3.95	28.46±12.23	0.176
Sleep efficiency/%	97.36±0.60	91.14±3.51	0.176
Wake after sleep onset/min	10.40±2.29	38.09±16.43	0.176
Arousal	9.43±3.09	11.57±3.92	0.176
Stage 1 NREM/(% total sleep time)	4.44±1.64	8.26±2.39	0.128
Stage 2 NREM/(% total sleep time)	53.07±2.56	61.34±2.82	0.061
Stage 3 NREM/(% total sleep time)	18.61±2.04	9.39±3.05 *	0.004
REM sleep/(% total sleep time)	23.89±2.78	21.01±2.09	0.115

Note: Data were expressed as mean ± SEM, $n = 7$; *$P < 0.05$, 4087 m versus 10 m.
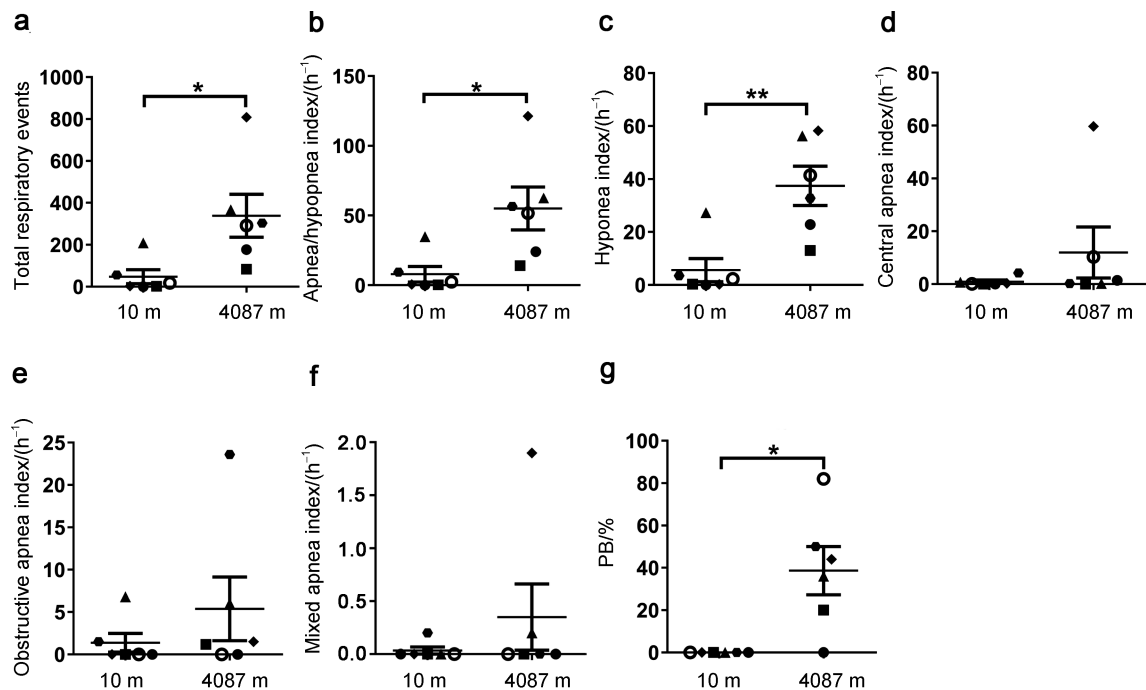
Figure 3 Changes in breathing patterns during sleep at Zhongshan Station (10 m) and Kunlun Station (4087 m). **a**, Total respiratory events; **b**, Apnea/hypopnea index (AHI); **c**, Hypopnea index; **d**, Central apnea index; **e**, Obstructive apnea index; **f**, Mixed apnea index; **g**, PB at 10 m and 4087 m. Data were expressed as mean ± SEM, $n = 6$; *$P < 0.05$, 4087 m versus 10 m; **$P < 0.01$, 4087 m versus 10 m.

Table 2 Changes of respiratory patterns at Zhongshan Station (10 m) and Kunlun Station (4087 m)

Parameters	10 m	4087 m	*P* value
Total respiratory events	48.00±33.33	338.83±102.69*	0.028
Apnea index/(h^{-1})	7.90±5.57	55.07±15.38*	0.028
Hyponea index/(h^{-1})	5.60±4.38	37.42±7.38**	0.004
Central apnea index/(h^{-1})	0.88±0.67	11.97±9.68	0.345
Obstructive apnea index/(h^{-1})	1.38±1.11	5.38±3.75	0.144
Mixed apnea index/(h^{-1})	0.03±0.03	0.35±0.31	0.414
PB/%	0.00±0.00	38.67±11.38*	0.043

Note: Data were expressed as mean ± SEM, $n = 6$; *$P < 0.05$, 4087 m versus 10 m; **$P < 0.01$, 4087 m versus 10 m.

3.4 Reduced vigor at Kunlun Station (4087 m)

The mood states of expeditioners were monitored using the POMS questionnaire. Compared with 10 m, vigor scores decreased markedly at 4087 m (23.13 ± 2.01 vs. 19.13 ± 3.24, $P < 0.05$) (Figure 6a, Table 4), indicating decreased vigor among expeditioners at Kunlun Station. However, no significant differences were found in tension, anger, depression, confusion, fatigue or TMD scores (Figures 6b–6g, Table 4). No significant correlations were observed between vigor and changes in sleep, breathing or oxygen saturation parameters (Supplementary Figure 1).

4 Discussion

The current study examined sleep and breathing alterations in healthy Antarctic expeditioners travelling from sea level to 4087 m at Kunlun Station, in one of the harshest environments on Earth. The current results suggest that even after approximately 2 weeks adaptation, compared with sea level, expeditioners still experienced clear alterations in sleep architecture, breathing patterns and mood states at 4087 m. The current study provides valuable scientific data to inform sleep research and medical interventions at the Antarctic plateau.

Human sleep consists of REM sleep and NREM sleep. Normal sleep structure involves 61% stage 1+2 NREM, 16% SWS (NREM3) and 23% REM for adults (Ohayon et al., 2004), in which SWS is the most important stage with the function of physical recovery and hormone secretion. According to previous studies, loss of SWS would impair cognitive and behavior performance, disrupt glucose metabolism, hormone release and immunity function, as

a

b
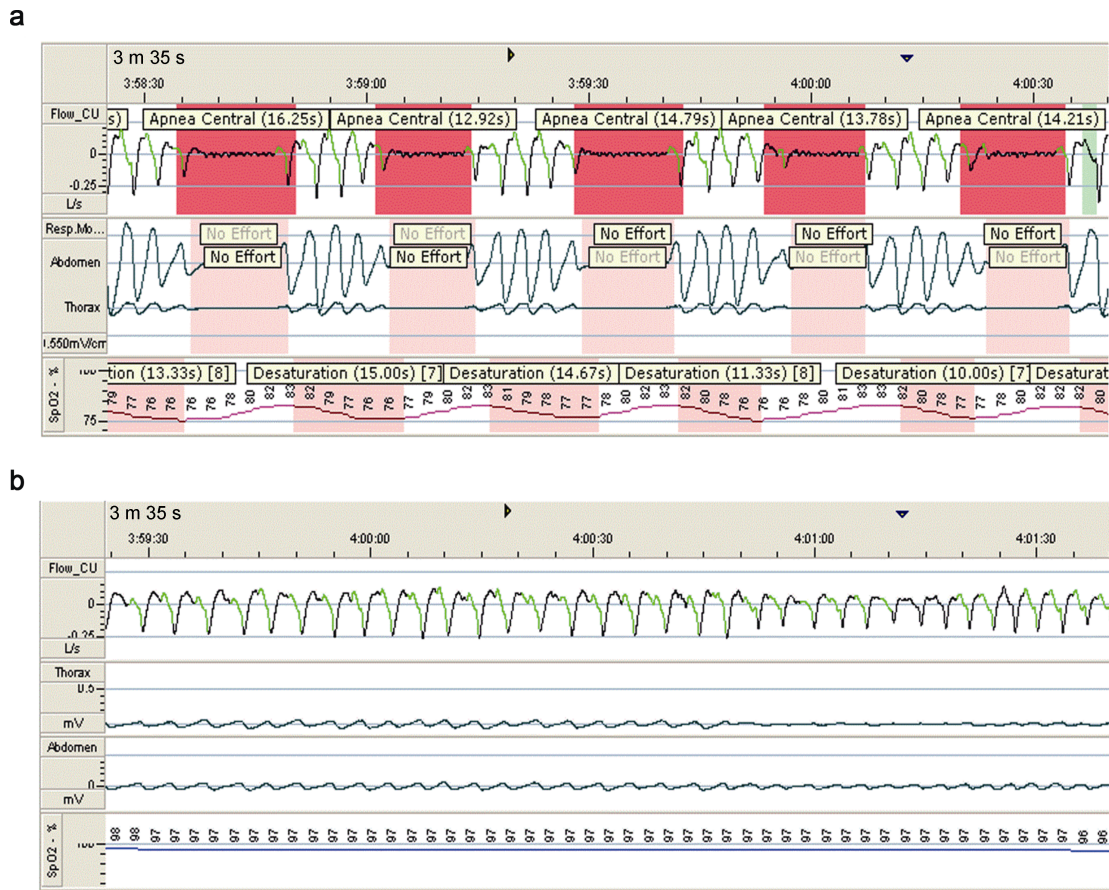
Figure 4 Examples of respiratory patterns during sleep recorded by polysomnography. **a**, One example of an expeditioner who developed central apnea under hypoxic conditions at 4087 m; **b**, Data from the same volunteer at 10 m.
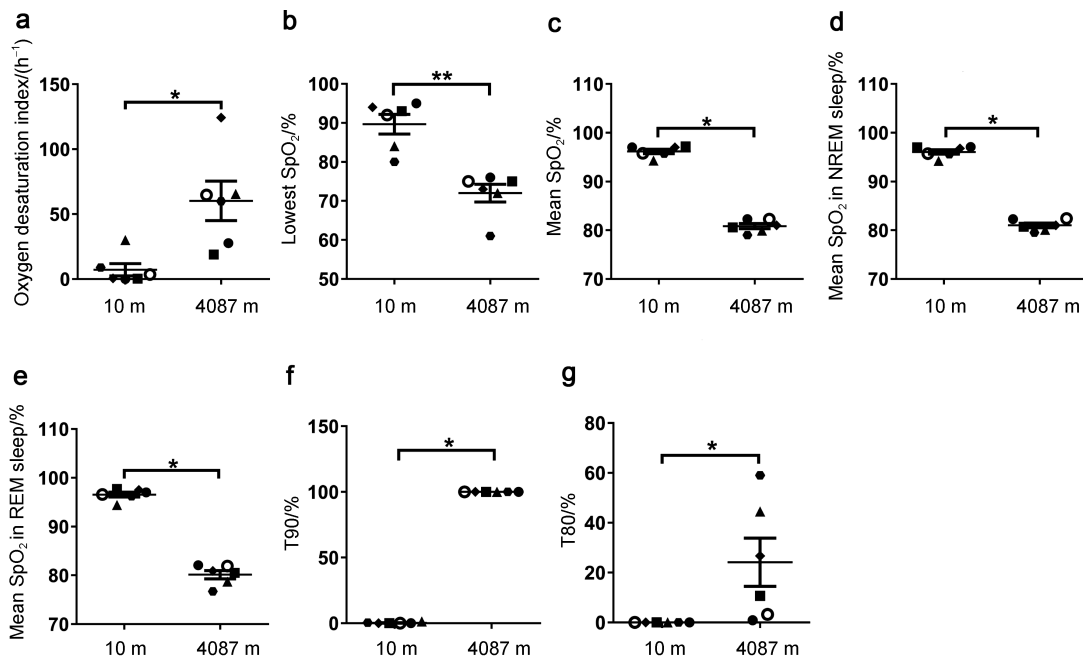
Figure 5 Decreased oxygen saturation at Kunlun Station (4087 m). **a**, Oxygen desaturation index; **b**, Lowest SpO_2; **c**, Mean SpO_2; **d**, Mean SpO_2 during NREM sleep; **e**, Mean SpO_2 during REM sleep; **f**, Percentage of SpO_2 below 90% during sleep; **g**, Percentage of SpO_2 below 80% during sleep at 10 m and 4087 m. Data were expressed as mean ± SEM, n = 6; *P < 0.05, 4087 m versus 10 m; **P < 0.01, 4087 m versus 10 m.

Table 3 Changes of oxygen saturation at Zhongshan Station (10 m) and Kunlun Station (4087 m)

Parameters	10 m	4087 m	P value
Oxygen desaturation index/(h^{-1})	7.23±4.76	60.20±15.19*	0.028
Lowest SpO$_2$/%	89.67±2.51	72.00±2.28**	<0.001
Mean SpO$_2$/%	96.17±0.46	80.85±0.54*	0.028
Mean SpO$_2$ in NREM sleep/%	96.07±0.46	81.00±0.48*	0.028
Mean SpO$_2$ in REM sleep/%	96.57±0.49	80.13±0.85*	0.028
T90/%	0.28±0.21	100.00±0.00*	0.024
T80/%	0.00±0.00	24.17±9.65*	0.028

Note: Data were expressed as mean ± SEM, $n = 6$; *$P < 0.05$, 4087 m versus 10 m; **$P < 0.01$, 4087 m versus 10 m.
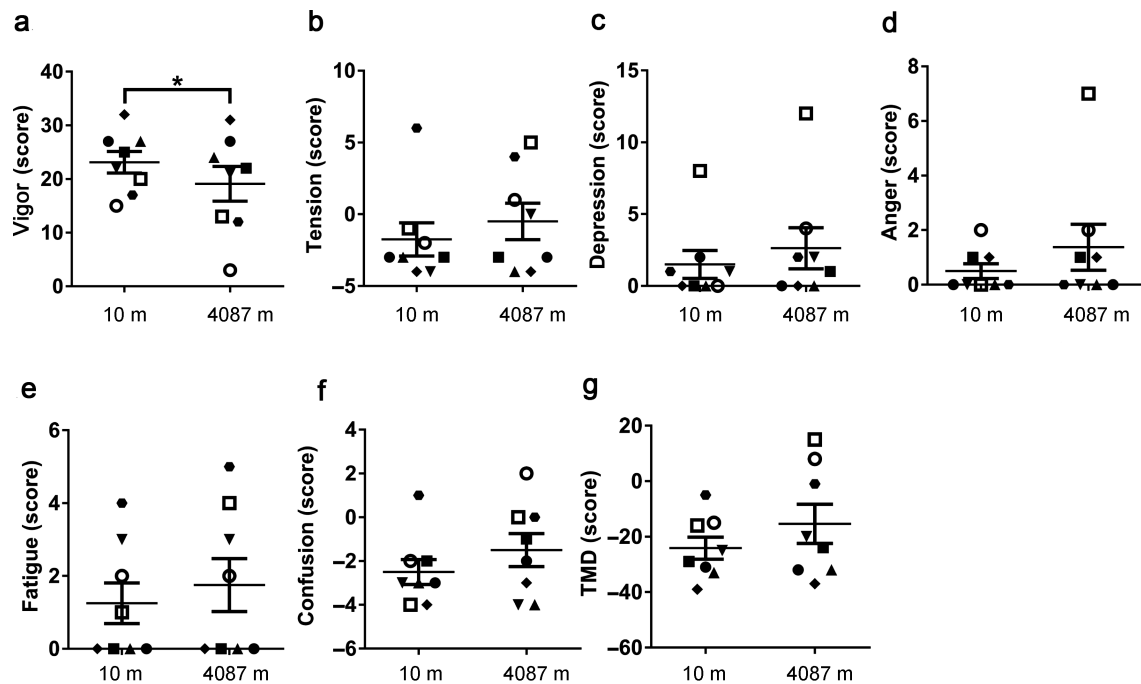
Figure 6 Decreased vigor at Kunlun Station (4087 m). **a**, Vigor; **b**, Tension; **c**, Depression; **d**, Anger; **e**, Fatigue; **f**, Confusion; **g**, TMD scores at 10 m and 4087 m. Data were expressed as mean ± SEM, $n = 8$; *$P < 0.05$, 4087 m versus 10 m.

Table 4 Changes of POMS scores at Zhongshan Station (10 m) and Kunlun Station (4087 m)

POMS scores	10 m	4087 m	P value
Vigor	23.13±2.01	19.13±3.24*	0.025
Tension	−1.75±1.16	−0.50±1.27	0.225
Depression	1.50±0.96	2.63±1.43	0.167
Anger	0.50±0.27	1.38±0.84	0.317
Fatigue	1.25±0.56	1.75±0.73	0.180
Confusion	−2.50±0.57	−0.15±0.76	0.214
TMD	−24.13±3.98	−15.38±7.06	0.071

Note: Data were expressed as mean ± SEM, $n = 8$; *$P < 0.05$, 4087 m versus 10 m.

well as increase the incidence of cardiovascular disease, such as hypertension (Javaheri et al., 2012; Léger et al., 2018). In the current study, we also observed decreased vigor at 4087 m compared with sea level, which may be related to the reduced SWS. A number of studies have indicated that lowlanders commonly experienced reductions

in slow wave sleep after arriving at high altitude, particularly in the first few days. Disruption of sleep could be mainly due to decreased oxygen saturation, which subsequently induced periodic breathing, as reported in this study, and symptoms related to acute mountain sickness (headache, cough, shortness of breath, etc.) (Bloch et al., 2015). Most sleep studies suggested substantial reduction of SWS after acute ascent, nevertheless, after 3 d (Nussbaumer-Ochsner et al., 2012) or 2–4 weeks (Reite et al., 1975; Salvaggio et al., 1998) at high altitude, disturbance of sleep structure could partially recover. In accordance with the work plan of the whole crew in our study, the PSG tests were arranged during nights 12–13 at Kunlun Station. Surprisingly, the reduction of SWS was still obvious at this time. The difference may be attributed to severe ambient factors (cold, wind) and poor living conditions (e.g., noisy, smelly sleeping chamber companions) in the extreme environment we examined.

In the current study, there was a dramatic decrease in SWS in one of the subjects who did not suffer PB, and an increase in SWS was observed in one subject, even though PB predominated his sleep time. These results support the notion that the occurrence of PB is not a major determinant of SWS reduction at high altitude (Salvaggio et al., 1998; Johnson et al., 2010; Sargent et al, 2013).

Previous studies conducted in high-altitude conditions (4000–5000 m) reported that AHI was 34.9 h^{-1} at 4200 m (Moraga et al., 2014), 52 h^{-1} at 4200 m (Johnson et al., 2010), 30.4 h^{-1} (first week) and 71.9 h^{-1} (second week) at 4497 m (Bloch et al., 2010), 34.4 h^{-1} at 4500 m (de Aquino Lemos et al., 2012), 47.1 h^{-1} at 4559 m (Erba et al., 2004), 60.9 h^{-1} (first night) and 86.5 h^{-1} (third night) at 4559 m (Nussbaumer-Ochsner et al., 2012). The percentage of PB during sleep was reported to be 25% at 4200 m (Moraga et al., 2014), 21% (first week) and 56% (second week) at 4497 m (Bloch et al., 2010), 34% at 4559 m (Erba et al., 2004), and 44.6% at 5000 m (Plywaczewski et al., 2003). Differences in study design and setting, acclimatization time, and sample size may have caused variation among these previous studies. Nevertheless, all of these studies consistently suggested a positive correlation between the prevalence/severity of PB and altitude (Ainslie et al., 2013), which was also observed in the current findings. Most previous studies reported that PB does not vanish, but rather persisted or even intensified during prolonged acclimatization (Bloch et al., 2010; Burgess et al., 2013). In accord with this notion, we detected severe PB during sleep after nearly 2 weeks at Kunlun Station.

Previous reports (Kamphuis et al. 2012; Finan et al., 2015) suggested that alterations of sleep patterns may be associated with mood swings. SWS is crucial for physical restoration. Reduction of SWS might negatively affect vigilance, vigor, cognitive and visual-motor performance during the daytime. In accord with this notion, our findings suggested decreased vigor at Kunlun Station. This change may have been caused, at least partially, by reduced SWS

under hypoxic conditions. Our previous reports also suggested mood disturbances of expeditioners while staying at Dome A, including tension, depression, anger and fatigue (Xu et al., 2015). However, these changes were not detected in the current study. Possible explanations include small sample size, individual differences and different work intensity of each team.

The Antarctic plateau involves more intense altitude challenges than would be expected based on physical altitude alone (West, 2001; Anderson et al., 2011). The harsh environment, involving low pressure as well as extremely dry and cold conditions, would be expected to result in higher AMS incidence as well as severity compared with other geographic locations at similar altitudes (Anderson et al., 2011). Thus, strict physical screening and pre-training before traveling to Antarctica is imperative. However, previous evidence indicates that oxygen supplementation of room air during sleep could reduce apneas, ameliorate oxygen saturation, enhance sleep quality and improve day performance (Gerard et al., 2000; Barash et al., 2001; West, 2002). Hence, to improve expeditioners' safety, work productivity and general well-being, oxygen supply equipment is recommended to be installed and used in living chambers or rooms at Kunlun Station.

One limitation of the current study was the small size of the cohort due to the small scale of the expedition team and the limited availability of monitoring devices. Nevertheless, as the first study investigating sleep and breathing pattern alterations at Kunlun Station, the current results make a valuable contribution that can inform further investigations in the field.

In conclusion, the current study reported novel data on sleep architecture, breathing patterns and mood states of Chinese expeditioners after an approximately 2 weeks' stay at Kunlun Station (4087 m) in Antarctica. Compared with a site at 10 m altitude, the expeditioners exhibited reduced SWS and vigor, as well as increased periodic breathing and oxygen desaturation at 4087 m. Although the current study involved several limitations, the results are valuable for expanding knowledge about alterations in sleep and breathing on the Antarctic plateau.

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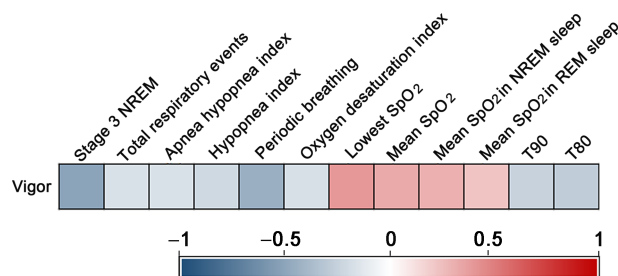
Supplementary Figure 1 Heat map of correlations between vigor and changed sleep, breathing or oxygen saturation parameters.