BRIEF REPORT

Polygraphy of Sleep at Altitudes Between 5300 m and 7500 m During an Expedition to Mt. Everest (MedEx 2006)

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Objectives.—Sleep at extreme altitudes is characterized by the repetitive occurrence of central apneas that in some cases may lead to a marked decrease in arterial oxygen saturation. During the Ludwig Maximilians University Expedition to Mt. Everest (MedEx 2006), nocturnal polygraphic recordings were made at different altitudes and included the first recordings ever made at 7500 m, which were completed on 8 separate occasions during the expedition.

Methods.—The study was performed on the author (K.M., 58 years, 181 cm, 75 kg), who is an experienced high-altitude mountaineer. The standard polygraphic parameters, such as nasal and oral airflow, thoracic and abdominal effort, oxygen saturation, heart rate, body position, movement, and snoring, were collected with a portable sleep recording device (AlphaScreen, SensorMedics, Germany, Hochberg) at different altitudes between 5300 m and 7500 m, and were compared with baseline assessments made in Munich, Germany (altitude 508 m). The daytime value of oxygen saturation at rest was measured at South Col (8000 m) and at the South Summit (8763 m) without breathing supplemental oxygen for at least 10 minutes.

Results.—The number of apneas and hypopneas of central origin increased up to a maximum of 148/h with a minimal blood oxygen saturation of 48% at 7500 m, compared with <5/h at Munich. After 11 days of acclimatization, data recorded at 5300 m showed a marked reduction of disturbed sleep. The Apnea-Hypopnea-Index dropped from 138/h to 51/h, and the minimal blood oxygen saturation rose from 57% to 67%. At South Col (8000 m), the daytime value of oxygen saturation at rest ranged between 53% and 55%, and on South Summit (8763 m) without breathing supplemental oxygen for at least 10 minutes, it fluctuated around 50%.

Conclusions.—These data correlate well compared with those obtained in hypobaric chamber studies and show that regardless of physiologic adjustment to low oxygen conditions at Base Camp altitude, during the final summit attempt oxygen saturation drops further to 55% and even less. Thus recordings of nocturnal oxygen saturation at Camp 3 (7500 m) on Everest, where the night is spent before the summit attempt, may help to show the actual efficiency of hypoxic ventilatory response and to detect the individual hypoxic tolerance to altitudes above 8000 m.

Key words: sleep, high altitude, apneas, Mount Everest, MedEx 2006, acclimatization, hypoxia

Introduction

High-altitude sleep is characterized by repetitive cycles of fast (undisturbed) breathing followed by slow or shallow breathing and apneas (Cheyne-Stokes) resulting in

blood oxygen desaturation and disturbed sleep. Many field and hypobaric chamber studies have investigated this phenomenon,^{1–6} but few were conducted in hypobaric hypoxia at extreme altitudes above 5300 m. John B. West of the United States and James S. Milledge of the UK were the first to conduct such studies on the American Medical Research Expedition to Mt. Everest in 1981.⁷ To better understand the characteristics and risks from nocturnal periodic breathing as a result of hypoxia at extreme altitudes, they conducted polysom-

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nographic studies, including tidal volumes by inductance plethysmography, eye movements by electrooculography, cardiac function by electrocardiography, and arterial oxygen saturation by pulse oximetry. The studies were performed in a rugged tent constructed of a high-tech nylon covering stretched over a durable metal frame with headroom and permanent heating, similar to the tents now used for temporary residency in polar regions. Interesting details of high-altitude sleep, such as the cycle length of periodic breathing, apneic periods, and corresponding arterial oxygen saturation, could be monitored for the first time.

In 1985, "Operation Everest II," a very elaborate and complex scientific project was undertaken to provide more information on sleep and arterial oxygen saturation at even higher altitudes.⁸ An ascent as high as to South Col (8000 m) was simulated in a hypobaric chamber, where all "climbers" were continuously exposed to an increasing hypoxia but apart from that were not exposed to the adverse climatic conditions found at high altitude. Since these studies were carried out, we know much more about sleep quality and arterial oxygen desaturation at extreme altitude, but we still do not know exactly to what extent these results are similar to those obtained under a realistic expeditional approach to extreme altitudes. In particular, the permanent moving up and down in contrast to a slow but steady ascent, the physical strain due to temperatures as low as -30°C to -40°C and excessively low air humidity may have an influence on sleep and breathing parameters.

For this purpose, nocturnal polygraphic measurements were performed during the Ludwig Maximilians University Medical Expedition to Mount Everest in April and May 2006 at altitudes up to 7500 m (Camp III) by the first author without the use of supplemental oxygen or medication, such as acetazolamide. To our knowledge, this was the first time that such measurements were performed at this altitude.

Methods

After a flight from Kathmandu to Lukla (2800 m) and a 10-day walk, the Everest Base Camp (BC) was reached. Two additional days of acclimatization were spent on the way in Namche Bazaar (3450 m) and Lobuche (4900 m).

Within the following 2 weeks, all of the measurements were taken while traversing (repeated ascent and descent) the mountain to acclimatize to different altitudes (5300–7500 m). The weather conditions were fine, with an average temperature varying between $+12^{\circ}\text{C}$ during the day and -21°C during the night. The standard polygraphic parameters, such as nasal and oral airflow, tho-

Figure 1. Equipment as worn by climber after all sensors and the head-box have been fixed and the data recorder (Alpha Screen) programmed to activate.

racic and abdominal effort, oxygen saturation, heart rate, body position, movement, and snoring, were collected with the AlphaScreen (SensorMedics, Höchberg, Germany), a portable sleep recording device (Figure 1). Baseline assessments were made in Munich, Germany (508 m), and follow-up recordings while climbing Everest at BC (5300 m) and all high camps in which nights were spent: Camp I above Khumbu Ice Fall (6000 m), Camp II at Western Cwm (6600 m), and Camp III at the Lhotse Face (7500 m) (Figure 2). The AlphaScreen was programmed to activate half an hour after all sensors had been placed and to terminate data collection another 7 hours later. For the recording of oxygen saturation and heart rate, a finger sensor was used. All sensors, the head-box, and the recording device itself were kept warm in the sleeping bag. The thermistor for measuring nasal and oral air flow during a previous expedition to Mount Vinson (4892 m) in Antarctica had proved to be robust and particularly resistant to temperatures as low as -28°C . At no time did the temperatures drop that low

Figure 2. Picture of the author's ascent route to Mt. Everest via Khumbu Ice Fall showing the location of Base Camp and High Camps.

in the tent at any Everest high camps. A total of 8 nocturnal measurements were made, 3 at BC, 2 each at Camps I and II, and 1 at Camp III during a period of 14 days. In addition, 2 daytime values of oxygen saturation at rest were obtained at South Col (8000 m) and on the South Summit (8763 m) without breathing supplemental oxygen for at least 10 minutes. No acetazolamide or any other medication for acute mountain sickness prevention was taken.

Data analysis was performed by manual scoring after returning to Munich. According to the literature,⁹ an apnea was defined as a cessation of airflow for at least 10 seconds with a drop of oxygen saturation of $>2\%$. A reduction of airflow of $>50\%$ lasting more than 10 seconds with a drop of oxygen saturation of $>2\%$ was scored as hypopnea. The number of apneas per hour (Apnea-Index, AI) and hypopneas per hour (Hypopnea-Index, HI) were combined as Apnea-Hypopnea-Index (AHI). An Institutional Review Boards approval was not necessary for this data collection.

Results

At baseline (Munich, Germany, 508 m), an AHI of $<5/h$ was recorded. During the first night after arriving

at BC (5300 m), the AHI went up to 138/h, while basal oxygen saturation (BOS) dropped from 94% (Munich) to 71% (BC) and nocturnal heart rate changed from 47/min (Munich) to 56/min (BC). Only central apneas and hypopneas were observed, often embedded in periods of periodic breathing. After 10 days of acclimatization at BC, the AHI had dropped from 138/h to 51/h, while changes in BOS (71%–73%) and heart rate (56/min to 55/min) were less marked. At 7500 m, the AHI rose again to 148/h, as did basal heart rate from 55/min to 68/min, while BOS dropped from 75% to 58% (Figures 3 and 4). The mean duration of apneas from 5300 m to 7500 m ranged from 11 to 14 seconds. The longest apnea was monitored during the first night after arriving at BC and lasted 44 seconds; the longest hypopnea (60 seconds) was also found on day 1 at BC. During sleep, the BOS dropped further by about 10% at all altitudes. The lowest nocturnal oxygen saturation (48%) was measured at 7500 m. At South Col (8000 m), the daytime value of oxygen saturation at rest ranged between 53% and 55%, and on South Summit (8763 m) without breathing supplemental oxygen for at least 10 minutes, it fluctuated around 50% (Figure 4).

Nocturnal apneas and hypopneas occurred more frequently during the initial acclimatization. Breathing was

Figure 3. Indices of disturbed nocturnal breathing at different altitudes and on different days (AI indicates Apnea-Index; HI, Hypopnea-Index; AHI, Apnea-Hypopnea-Index).

disturbed most during the first night after arriving at BC. During that night, more than 90% of the time (381 minutes), breathing was disturbed by apneas or hypopneas. Ten days later after acclimatization, only 20% of the night time breathing (83 minutes) was disturbed by apneas or hypopneas. Breathing also became more and more disturbed at increasing altitudes (Figure 5).

In spite of the low nocturnal oxygen saturations, in particular above 6500 m, the first author did not report any fatigue, mental dysfunction, or acute mountain sickness, although these parameters were not specifically measured.

Discussion

Many studies on sleep disturbances and nocturnal oxygen saturation have been performed, but until the present study only one has been carried out above 6500 m.⁸ Data in this previous study (Operation Everest II) were collected at simulated altitudes in a hypobaric chamber, however. Thus, we do not know if and how these data correspond to those recorded under real and unsimulated conditions, particularly with regard to physical exertion and mental stress and to a differing form of acclimatization. During altitude expeditions, acclimatization is achieved by frequent ascent and descent, not by continuous ascent. Environmental conditions also contribute to acclimatization on Everest: climbers are confronted with temperatures down to -40°C and even lower in high winds and storms with the risk of frostbite, hypothermia, exhaustion, and potentially fatal high-altitude disease.

Despite these factors, our data, which were collected at slightly different altitudes, are in fact very similar to those collected in the hypobaric chamber of Operation Everest II by Anholm et al.⁸ At an atmospheric pressure of 347 mm Hg, corresponding to an altitude of about 6500 m from the model atmosphere,¹⁰ Anholm et al re-

Figure 4. Basal (mean) oxygen saturation and minimal oxygen saturation.

cord a mean SaO_2 of $66 \pm 6\%$,⁹ whereas our SaO_2 at 6600 m was 66% (Day 5) and 62% (Day 12). Chamber AI and AHI showed a wide individual range of $69 \pm 49/\text{h}$ and $146 \pm 38/\text{h}$, respectively, but were similar to our values of 51 to 66/h (AI) and 124 to 144/h (AHI). Up to 7500 m (Camp III), basal oxygen saturation dropped further to 58%, and the AI rose to 72/h and the AHI to 148/h. When compared with the data collected at an atmospheric chamber pressure of 282 mm Hg, equivalent to an altitude of almost 8000 m (SaO_2 : $52 \pm 2\%$, AI: $75 \pm 38/\text{h}$, AHI: $254 \pm 108/\text{h}$), they also correlate well.

The present study shows that periodic breathing with central breathing disturbances at 5300 m becomes less severe during acclimatization. Although after arrival at BC and during the following night less than 10% of nocturnal breathing was undisturbed, 10 days later it was 80%. At the same time, BOS went up from 71% to 73%.

Figure 5. The ratio of disturbed to undisturbed nocturnal breathing.

By 5300 m, sleep can normalize gradually, because humans are able to acclimatize permanently to that altitude. Beyond this altitude, however, acclimatization may not be achieved entirely and when the ascent is continued, sleep disturbances and oxygen desaturation may increase. Frequent arousals could feasibly cause disruption of sleep, and, as a consequence, one's daytime performance could be impaired because of fatigue and diurnal sleepiness. In addition, oxygen desaturation during sleep may result in the development of high-altitude disease.^{11–13}

For a successful ascent to the summit of Mt. Everest, it is necessary, according to the American Medical Research Expedition to Mt. Everest (1981), to have not only an excellent physical condition, but as West stated a good tolerance to hypoxia.⁷ West hypothesised that the individual tolerance for high altitude may be dependent on the severity of the hypoxemia experienced during sleep. However, it remains largely unknown to what precise extent the human brain can tolerate hypoxemia and how extreme hypoxia is compensated individually. In this study, low oxygen saturations during the night were tolerated by the author and did not lead to any heavy daytime complaints of increased tiredness or high-altitude disease.

The number of climbers that attempt Everest without supplemental oxygen has not been documented, only the number of those that have reached the summit. Less than 5% (155 of 3678) of the ascents up to the present¹⁴ were attained without supplemental oxygen. Because of the increasing numbers of commercial and less experienced climbers, the percentage of ascents without supplemental oxygen is much lower, approximately 1% to 2%.¹⁴ It is assumed that at least the same percentage of climbers start without oxygen but never reach the summit, because they are not able to tolerate extreme hypoxemia.

Further studies are needed to fully understand the significance of disturbed sleep and decreased nocturnal oxygen saturation for an adequate physical performance and successful ascent to extreme altitudes.

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