Polysomnography in Extreme Environments: the MagIC Wearable System for Monitoring Climbers at Very-High Altitude on Mt. Everest Slopes

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Abstract

Extreme environments such as high altitude represent a challenging testbed for both people and instruments. During a recent expedition to the slopes of Mt. Everest, (Highcare Expedition), we monitored ECG, respiration, oxygen saturation and posture in five climbers during sleep. Data were collected by using a recently developed textile-based wearable system (the MagIC system). The polysomnographic acquisitions were performed at sea level in indoor environment, and at 6000 and 6800 m asl in tents.

The collected data allowed us to investigate performances and usability of MagIC system as a polysomnographic device at very-high altitude.

In this paper we report on the results of this evaluation.

1. Introduction

High altitude is among the most challenging environments on Earth, due to poor oxygen availability, hard weather conditions (cold and windy), dangers related to glaciers and difficult accessibility for transport means. The acquisition and analysis of physiological data during exposure to such environments is essential to monitor their adaptation to the hostile context, and allow an early detection of possible health problems. In this context, it is particularly relevant to investigate about subjects' conditions during sleep, given the severe effects that high-altitude hypoxia produces on sleep quality, breathing patterns and cardiovascular regulation.

However, we have only a limited knowledge about sleep at very-high altitudes, i.e., above 5300m. Indeed, the few available studies have been performed or in a single skilled subject (1), or at simulated high altitudes (2), or by using a subjective qualitative scoring of sleep quality rather than a quantitative measures of physiological parameters (3).

In 2008, in the framework of the Highcare Expedition, one of the largest scientific mission on the Mount Everest, polysomnographic studies were performed at different altitudes, from sea-level to 6800 m asl. A minute fraction (about 25%) of the measurements collected up to the Everest Base Camp (5400 m asl) were acquired by standard portable polysomnographic devices (Embletta, Embla, Broomfield, CO, USA). However, in the extreme conditions of higher camps, standard devices did not appear to be adequate for a series of reasons. First, the size and weight of traditional devices may become critical when they should be carried on at very high altitude. Second, at very high altitude climbers are often alone in their tents and the self-application of sensors and wires is quite complex, also in view of the limited space and the reduced dexterity in performing any motor task caused by the hypoxia (4).

For these reasons, in the frame of Highcare experiments, an innovative monitoring system based on textile technology, called MagIC (5-6), was used for collecting biological data during sleep in 1) most of the subjects participating in the mission at sea-level and at high altitude (up to 5400m), and 2) all the subjects sleeping at higher altitude (5 climbers at 6000 and 6800 m). This system is characterized by low weight and a small footprint. Moreover, having all sensors and wirings embedded into a vest, the climbers are only asked to wear the garment, with only limited additional requirement to connect an external pulseoximeter.

In this study we focused on the sleep data collected in the climbers at sea level and above 6000 m asl., to investigate performances and usability of MagIC system as a polysomnographic device at very-high altitude.

2. Methods

Subjects. Five male professional alpine guides (age 43.4±9.0 yrs, M±SD) were provided with MagIC systems. They were instructed on how to operate them during briefing meetings in Milan, before the expedition, and at Everest Base Camp, before the last stages of the ascent. Climbers reached the Everest Base Camp (5400 m) after a 6 days trekking and remained at the base camp for an acclimation period of 12 days before moving to higher camps.

Figure 1. The MagIC system modified for the Highcare expedition

Monitoring system. The MagIC system (5-6) is composed of a vest made of polypropylene (yarn for thermal underwear which facilitates transpiration) and elastane (known also as Spandex) and a small electronic module. The vest incorporates two woven ECG electrodes, a textile plethysmograph for measuring thorax movements, and electric connections all made of textile conductive fibers. The electronic module, hooked to the vest by a Velcro strip, includes a triaxial accelerometer for movement and posture assessment and receives data from an external finger pulseoximeter (Nonin Xpod®, Nonin Inc.). Data are stored on a memory card and possibly transmitted to a remote computer via a Bluetooth connection.

Figure 1 shows the vest, the electronic unit and the pulseoximeter of the modified MagIC system. Resolution and sampling rate of the signals collected by the system are reported in table 1.

Table 1. Signals acquired by the MagIC system

Signal	Resolution	Sampling rate
ECG (1 lead)	12 bit	200 Hz
Respiration (1 lead)	12 bit	50 Hz
Acceleration (3 axis)	12 bit	50 Hz
Plethysmography	8 bit	75 Hz
Oxygen saturation	8 bit	3 Hz

Data Collection. For each subject a baseline recording was performed at sea-level (SL) in Milan. The original plan of the expedition included the reaching of the summit of Mt Everest, with polysomnographies recorded at different altitudes up to around 8000m (Camp 4) (figure 2). Unfortunately, because of adverse weather conditions, climbers could arrive only at Camp 2 (6800m asl). In this study we focus on data collected at the highest altitudes (6000 and 6800) as compared with the SL data.

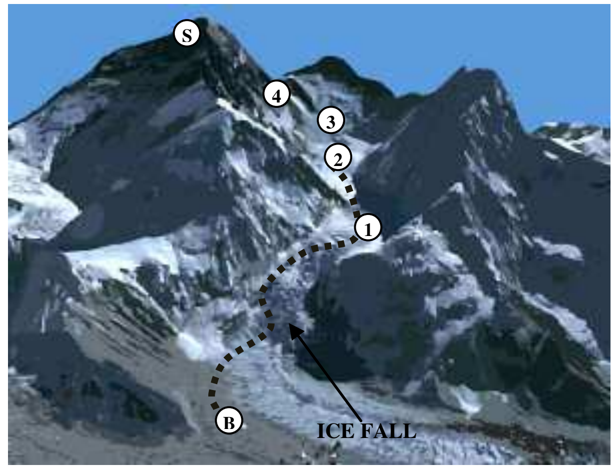

Figure 2. Originally planned stops during the ascent to Mt. Everest (B – Base Camp, 5400; 1 – Camp 1, 6000m; 2 – Camp 2, 6800m; 3 – Camp 3, 7200m; 4 – Camp 4, 8000m; S – Summit); the dotted line indicates the actual route followed by the climbers.

For each sleep study at SL, Camp1 and Camp2, ECG, thorax plethismogram, 3D accelerations, and oxygen saturation were recorded continuously by the MagIC System for more than 10 hours, covering the whole night sleep period. Each polysomnographic recording was stored in a file of about 30-35 MB.

Figure 3. A picture of the Camp 1 showing the environmental conditions of the expedition (Courtesy of INFOkontor GmbH, Köln, Germany, and Istituto Auxologico Italiano, Milano, Italy)

Data Analysis. Each recording was visually inspected to identify artifacts and the occurrence of central sleep apneas. The tachogram was calculated by a derivative-and-threshold ECG algorithm. Premature beats were identified and removed. The average artifact rate was computed for each ECG trace as the ratio between the

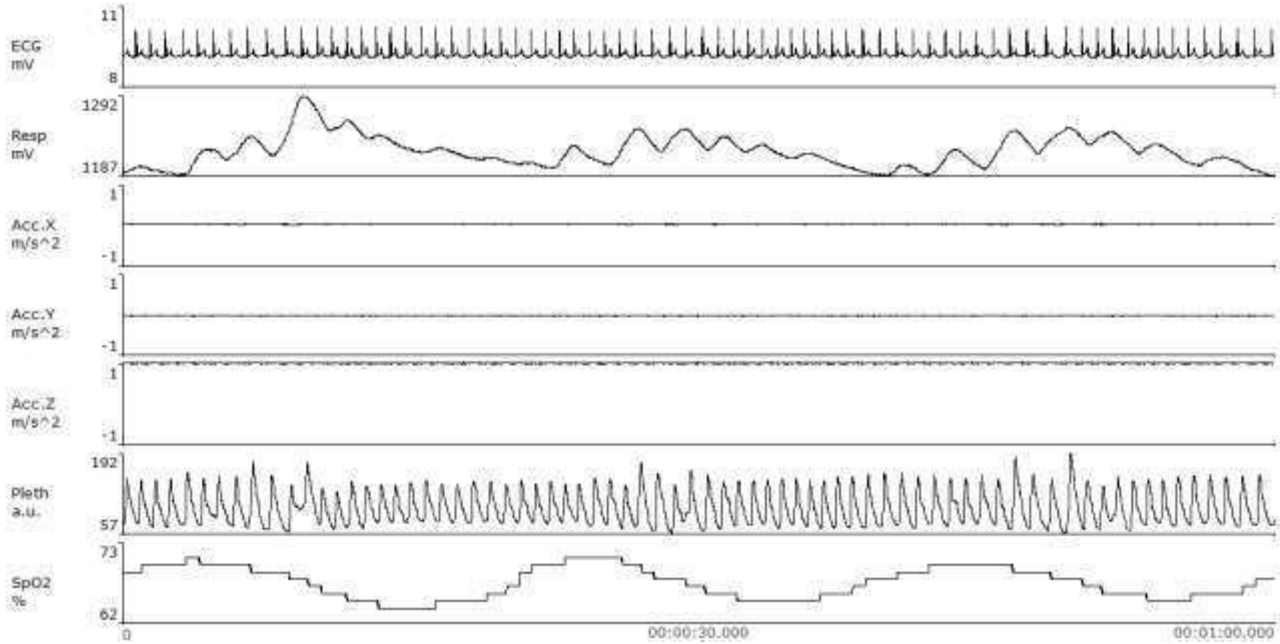

Figure 4. A 60-s segment of data recorded during sleep at 6800m. Plotted signals are (from top) ECG, respiration, three accelerometric components (X,Y,Z), finger pulse and oxygen saturation. Note the presence of central apneas in the respiratory signal. The constant values of the 3 acceleration components indicate that the subject is resting supine**.**

cumulative duration of the artifacts and the length of the whole recording.

The last 4 hours of sleep were selected for the data analyses. From each recording the mean R-R interval, RRI, the standard deviation of normal-to-normal intervals, SDNN, index of overall heart rate variability (HRV) (7), the mean oxygen saturation and the changes in posture (as estimated from the accelerometers) were assessed.

Differences were statistically assessed by repeated measures ANOVA with Newman Keuls post-hoc analysis, setting the threshold for statistical significance at the 5% level.

3. Results

From the usability point of view, each climber found MagIC comfortable to wear, and completed the monitoring set-up without need of help, even in the highly challenging conditions of Camp2.

An example of 1-minute data record obtained in one subject while sleeping at Camp2 is shown in figure 4. Thorax movements and oxygen saturation signals clearly show the occurrence of recurrent central sleep apneas (the so called "periodic breathing" pattern), already described in literature in hypoxic environments (8-9). Modulations of heart rate associated to sleep apneas are clearly visible in the ECG.

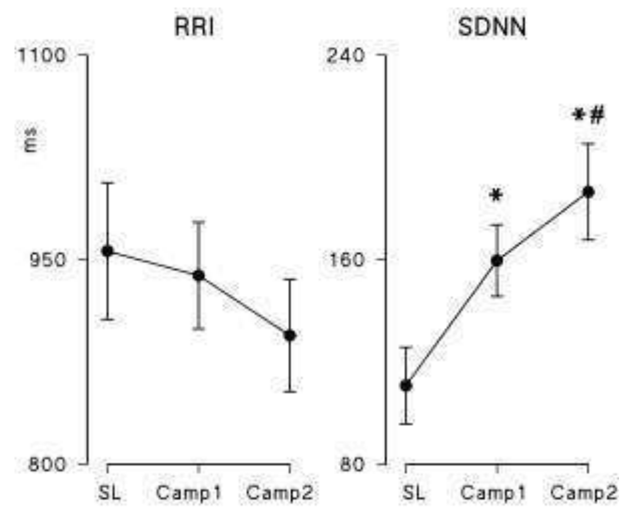

Figure 5. RR Interval and SDNN at different altitudes; * and # indicate significant differences respectively vs. SL and vs. Camp1.

Signal quality resulted to be adequate in all recordings. On average, the artifacts rate was lower than 5%.

RRI tended to decrease from SL to Camp1 and Camp2 while SDNN increased significantly not only from SL to Camp1 but also from Camp1 to Camp2 (figure 5).

Central apneas were absent at SL while occurred frequently during sleep both at Camp1 and at Camp2, As expected, the overall mean oxygen saturation, which was close to 100% at SL, decreased importantly at Camp1 (75%±3%) and reached even lower values at Camp2 (69%±5%).

4. Discussion and conclusions

This study demonstrated that reliable polysomnographic recordings can be achieved in the extremely challenging conditions of very-high altitude camps, thanks to the use of a novel wearable textile based system. In fact, climbers enrolled in our study found the MagIC system easy to carry, set-up and use even in the small room of high-altitude tents. This is an important prerequisite for any monitoring system which should be employed in such extreme conditions. Moreover, the quality of the acquired signals was found to be adequate for the HRV analysis, and to investigate correlations among heart rate, respiratory events and posture changes.

Our study also provides the first description of cardiorespiratory changes during sleep in a group of climbers exposed to hypobaric hypoxia at different very-high altitudes. The preliminary results reported in this study indicate that above 6000 m, even after acclimation, the HRV alterations during sleep (as shown by the significant growth of SDNN values), progressively increase with altitude. These changes seem to be related to the hypoxia-induced periodic breathing. However, further studies are required to properly clarify the issue.

Acknowledgements

The HIGHCARE project was made possible by an unrestricted support by Boehringer Ingelheim (Germany) and Banca Intesa San Paolo (Italy).

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