Respiratory events and periodic breathing in cyclists sleeping at 2,650-m simulated altitude

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Kinsman, Tahnee A., Allan G. Hahn, Christopher J. Gore, Bradley R. Wilsmore, David T. Martin, and Chin-Moi Chow. Respiratory events and periodic breathing in cyclists sleeping at 2,650-m simulated altitude. J Appl Physiol 92: 2114–2118, 2002.—We examined the initial effect of sleeping at a simulated moderate altitude of 2,650 m on the frequency of apneas and hypopneas, as well as on the heart rate and blood oxygen saturation from pulse oximetry (SpO2) during rapid eye movement (REM) and non-rapid eye movement (NREM) sleep of 17 trained cyclists. Pulse oximetry revealed that sleeping at simulated altitude significantly increased heart rate (317 trained cyclists. Pulse oximetry revealed that sleeping at simulated altitude significantly increased heart rate (3 ± 1 beats/min; means ± SE) and decreased SpO2 (−6 ± 1%) compared with baseline data collected near sea level. In response to simulated altitude, 15 of the 17 subjects increased the combined frequency of apneas plus hypopneas from baseline levels. On exposure to simulated altitude, the increase in apnea was significant from baseline for both sleep states (2.0 ± 1.3 events/h for REM, 9.9 ± 6.2 events/h for NREM), but the difference between the two states was not significantly different. Hypopnea frequency was significantly elevated from baseline to simulated altitude exposure in both sleep states, and under hypoxic conditions it was greater in REM than in NREM sleep (7.9 ± 1.8 vs. 4.2 ± 1.3 events/h, respectively). Periodic breathing episodes during sleep were identified in four subjects, making this the first study to show periodic breathing in healthy adults at a level of hypoxia equivalent to 2,650-m altitude. These results indicate that simulated moderate hypoxia of a level typically chosen by coaches and elite athletes for simulated altitude programs can cause substantial respiratory events during sleep.

RECENT STUDIES ON THE USE of altitude by athletes suggest that the best effect on subsequent physical performances may be gained by sleeping in a moderately hypoxic condition (equivalent to altitudes of ~2,200–3,000 m) while training close to sea level (21, 22). The response to this “live high, train low” approach varies widely between individuals, with some athletes showing substantial performance gains and others showing no effect or even a negative outcome (7). Athletes spend a substantial amount of time asleep while exposed to the live high, train low stimulus (3), and the respiratory events during their sleep time increase as altitude increases (28). However, substantial differences appear to exist between individuals in both the magnitude of this effect and the altitude of onset (2, 8, 39). Although sleep disturbance has been shown to decrease subsequent physical work capacity and increase the self-perception of fatigue (1), no studies have monitored the sleep physiology of athletes undergoing a live high, train low program.

Hyperventilation is among the first physiological adjustments to an acute increase in altitude in an attempt to compensate for the reduced PO2 (10, 30). Episodes of hyperventilation may be separated by intervals of hypopnea or apnea. When respiratory events are cyclic and contain apneic episodes, this is known as periodic breathing (19). Periodic breathing has been observed during sleep in mountaineers, high-altitude residents, and sedentary sojourners from sea level during sleep at altitudes between 3,200 and 7,167 m (24, 29, 35). Periodic breathing has also been documented in awake individuals exposed to short-term hypoxia equivalent to 2,440 m (33).

The respiratory oscillations associated with periodic breathing reflect respiratory instability caused by hypoxia (6). A vigorous hypoxic ventilatory response is a key element in destabilizing the control system at altitude (6, 23). Hypoxic ventilatory response is highly variable between individuals (4, 8, 12) and is depressed during sleep (11, 13, 34). Because a depressed hypoxic response has been associated with exercise training (5, 18, 25), we hypothesized that, although live high, train low athletes may exhibit some respiratory events during sleep, periodic breathing, per se, would not occur under moderate hypoxia (equivalent to an altitude of 2,650 m), given that this altitude is well below the minimum at which periodic breathing during sleep has been previously reported.

To test these hypotheses, we monitored the incidence and severity of sleep respiratory events, as well as the blood oxygen saturation from pulse oximetry (SpO2)
and heart rate of cyclists participating in a live high, train low program.

METHODS

Subjects. Eight male and nine female trained cyclists (26.4 ± 4.7 yr and 66.9 ± 8.4 kg; means ± SE) participated in the study. No subject had a history of any sleep disorder, and each was free of respiratory infection at the start of the study. The study was approved by the Australian Institute of Sport and the Sydney University Ethics Committees, and all cyclists gave written, informed consent. Subjects were encouraged to maintain their normal training programs throughout the study.

Data collection. Subject's sleep was monitored during two consecutive nights of sleep in normoxic conditions (natural altitude of 600 m) and once during the first or second night of exposure to a simulated moderate altitude of 2,650 m. Two to three subjects were studied each night, and the study design was repeated five times, such that each subject underwent a total of three nights of sleep study. For baseline data collection under normoxic conditions, subjects slept in either their normal sleep environment or a room provided within the residence halls of the Australian Institute of Sport (Canberra, Australia).

Altitude simulation. A normobaric, hypoxic environment equivalent to 2,650 m was created by using a nitrogen-enriched facility at the Australian Institute of Sport (3). On all study nights, the fraction of inspired CO2 was maintained below 1.0%.

Nocturnal polysomnography. Standard polygraphic sleep recordings were obtained, including submental electromyogram, electrooculogram, electroencephalogram (C3/A2 or O2/A1), and electrocardiogram recorded on a portable sleep monitor unit (model PS2+, Compumedics Sleep Systems, Melbourne, Australia). The same monitoring system was used to record thoracic effort, nasal and oral airflow, SpO2, and heart rate. Thoracic effort was measured with a piezoelectric band and nasal/oral airflow was measured with a thermistor. SpO2 and heart rate were determined via pulse oximetry.

Sleep quality. For the analysis in which normoxia was compared with simulated moderate altitude, only the second night of baseline sleep data was included. Increased sleep latencies subsequent to awakenings, which often result in a greater time spent in the sleep-onset stage and greater number of respiratory events (32), were accounted for by disregarding the data from the first night of baseline data collection. The first night of baseline data was used from only one subject, as it showed substantially less awakenings than the second night.

Data analysis: sleep and respiratory variables. All sleep studies were staged by using the standard clinical staging technique to identify stages and establish rapid eye movement (REM) and non–rapid eye movement (NREM) sleep time (27). The standard clinical criteria for scoring respiratory events (14) were applied to establish apneas and hypopneas and identify periodic breathing episodes. An apnea-hypopnea index (AHI) was calculated as a rate of respiratory events from the combined number of apneas and hypopneas per hour. We have defined a periodic breathing episode as a minimum of four consecutive respiratory waxing and waning patterns, over an interval ≥100 s. These episodes were manually marked and recorded for duration, and number and the overall percentage of the night's sleep spent in periodic breathing were calculated.

The sleeping heart rate and SpO2 data were collected at a sampling rate of 1 Hz, and these data were manually filtered to discard obvious signal artifacts. Compumedics Replay software (Compumedics, Melbourne, Australia) then provided individual average nightly heart rate and SpO2, values for REM and NREM sleep.

Statistical analysis. Data are expressed as means ± SE. All variables were tested for distribution normality using the Shapiro-Wilks normality test. Post hoc nonparametric analysis was performed by using Wilcoxon's matched-pairs test for AHI, apnea, and hypopnea. All analyses were performed with the use of Statistica (Statsoft, Tulsa, OK, version 5.5) with an α-level of 0.05.

In addition, as a basis for identifying individuals who were particularly affected by hypoxia, typical error of measurement (TEM) (17) was determined from the two baseline studies on all subjects. Subsequently, any individual change that exceeded the 95% confidence interval (CI) of the TEM (1.96 × √2 × TEM) for a specific sleep parameter was deemed likely to be the result of the hypoxic stimulus rather than measurement variability.

![Fig. 1. Effect of exposure to simulated moderate altitude on apnea-hypopnea index (AHI) (P < 0.05), which is calculated as the sum of apneas and hypopneas (top) (see METHODS for details), O2 saturation from pulse oximetry (middle), and heart rate (bottom), for the entire group. Values are means + SE, (n = 17). *Significantly different from baseline, P < 0.05.](http://jap.physiology.org/)
RESULTS

AHI. The AHI while sleeping at simulated altitude was significantly greater than at baseline (13.1 ± 6.0 vs. 0.3 ± 0.1 events/h, respectively; P < 0.01, Fig. 1). During simulated altitude exposure, all 17 cyclists recorded AHI values greater than those observed during baseline studies; in 15 cases, the increase was greater than the 95% CI for this variable.

Oxygen saturation and heart rate. Simulated altitude significantly reduced the average Sp O₂ by 6 ± 1% and increased average heart rate by 3 ± 1 beats/min compared with the baseline levels (Fig. 1). The reductions in Sp O₂ and increases in heart rate were similar during REM and NREM sleep.

Periodic breathing. There was considerable interindividual variation in the magnitude of the breathing response to simulated altitude during sleep (Table 1). Four subjects exhibited periodic breathing (Fig. 2), and two subjects with the highest AHI values had periodic breathing episodes throughout all sleep stages, whereas those with lower AHI had periodic breathing episodes only during stage 2 and REM sleep.

There was no difference between the periodic breathing subjects and other subjects in the average nightly Sp O₂ or heart rate at simulated altitude exposure (Table 1).

Apnea, hypopnea, and sleep state. Although the effect of simulated altitude on AHI was not significantly different between REM and NREM sleep (P = 0.52), the frequency of apneas and hypopneas varied with sleep state. At baseline, the few episodes of apnea were not significantly different between REM (0.16 ± 0.16 events/h) and NREM (0.04 ± 0.03 events/h) sleep. On exposure to simulated altitude, apnea incidence increased significantly from baseline for both sleep states (2.0 ± 1.3 events/h for REM and 9.9 ± 6.2 events/h for NREM), but the difference between the two states was not significant (P = 0.18). Although relatively few hypopneas were observed at baseline, a greater rate was found in REM (0.6 ± 0.2 events/h) than NREM (0.12 ± 0.04 events/h) sleep (P = 0.01). Hypopnea frequency increased significantly from baseline to simulated altitude exposure in both sleep states and was significantly higher in REM (7.9 ± 1.8 events/h) than in NREM (4.2 ± 1.3 events/h) sleep (P = 0.03).

DISCUSSION

The present study investigated the sleep respiratory events in training cyclists on exposure to the simulated altitude of a live high, train low regimen. The major and novel finding of this study is that simulated mod-

### Table 1. Variation in the NREM and REM sleep respiratory events, total AHI, %PB, SpO₂, and heart rate for periodic and nonperiodic breathers on exposure to simulated moderate altitude (2,650 m)

<table>
<thead>
<tr>
<th></th>
<th>NREM Sleep, events/h</th>
<th>REM Sleep, events/h</th>
<th>Heart Rate, beats/min</th>
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<tbody>
<tr>
<td></td>
<td>Hypopnea</td>
<td>Apnea</td>
<td>%PB</td>
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<tr>
<td>Periodic breathers (n = 4)</td>
<td>12.7 ± 4.8</td>
<td>39.5 ± 39.2</td>
<td>17.3 ± 1.9</td>
</tr>
<tr>
<td>Nonperiodic breathers (n = 13)</td>
<td>1.6 ± 0.4</td>
<td>0.1 ± 0.05</td>
<td>5.8 ± 1.3</td>
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Values are means ± SD with range shown in parentheses; n = no. of subjects. AHI, apnea-hypopnea index; %PB, percentage of night spent periodic breathing; SpO₂, blood O₂ saturation from pulse oximetry; NREM, non-rapid eye movement; REM, rapid eye movement.

Fig. 2. Two minutes of a periodic breathing episode in stage 2 (non-rapid eye movement sleep). This subject had the greatest percentage of time spent periodically breathing at simulated moderate altitude. SpO₂, O₂ saturation from pulse oximetry; THOR, thoracic effort.
erate altitude (2,650 m) can cause apneic and hypopneic respiratory events during sleep. Although the AHI was highly variable between individuals, exposure to simulated altitude increased AHI by >95% of the CI for this variable in 15 of the 17 cyclists. Our data confirm the variability of interindividual breathing patterns during sleep (31) and mild hypoxia (8) but also are the first to demonstrate these results in a trained group of individuals at this level of hypoxia. Whereas 2 of the 17 subjects did not show any respiratory events, 4 exhibited periodic breathing at a level of simulated altitude 550 m lower than the minimum natural altitude previously reported to induce periodic breathing during sleep in a healthy population (35).

Periodic breathing. For some athletes in the present study, respiratory events at 2,650-m simulated altitude were profound and gave rise to nocturnal periodic breathing as previously documented at much higher levels of natural or simulated altitude (35). Although we were unable to measure hypoxic ventilatory response because of a technical limitation, it is still worth noting that three of the four periodic breathers were men, which is consistent with earlier research indicating that men tend to have a higher hypoxic ventilatory response (34) and that a high response predisposes one to periodic breathing (23). It is noteworthy that periodic breathing was seen in all stages of sleep in the two periodic breathers with high AHI but only in stage 2 and REM sleep in periodic breathers with a low AHI. A differential influence of hypoxia on sleep respiratory characteristics may be explained by the variation in respiratory sensitivity between sleep stages, with the hypoxic ventilatory drive being more depressed during REM than during NREM sleep (16). Our results contrast with other studies (24, 34) that reported periodic breathing only in NREM sleep, although respiratory instability and oscillations are not uncommon in REM sleep (20). In the study by White and colleagues (34), the appearance of periodic breathing in REM sleep may have been concealed by the frequency of hypoxic and hypercapnic ventilatory response tests in isolated sleep stages of NREM and REM.

Pulse oximetry. An increase in heart rate from baseline to simulated altitude exposure was expected and has been previously reported (9). This significant heart rate increase represents a circulatory compensatory adjustment in response to hypoxia. Because bradycardia is associated with apnea (27), we might have expected the average heart rate to be lower in the periodic breathers, but this was not the case. However, our result may merely reflect the low statistical power of an analysis conducted with only four subjects who were periodic breathers.

It has been observed that periodic breathing during sleep has minimal affect at altitudes of 3,800 and 5,050 m on mean nightly SpO2 (24, 33). Although our individual data (Fig. 2) illustrate substantial desaturation during periodic breathing (91 → 83%), our results also support the finding that periodic breathing has minimal affect on the mean nightly SpO2. The relatively low frequency of these events compared with the total time spent sleeping yield no significant affect on mean nightly SpO2. Importantly, the findings suggest that the mean peak SpO2, which has been used routinely to monitor O2 desaturation in athletes exposed to simulated altitude (15, 26), may be inadequately sensitive to detect the prevalence of respiratory events. Therefore, measurements of nocturnal respiratory parameters of thoracic effort and nasal and oral airflow are required to effectively monitor acclimation and accurately characterize the sleep responses to simulated moderate altitude.

In conclusion, this study has established that nocturnal hypoxia simulating an altitude of 2,650 m is likely to have acute effects on breathing during sleep of most athletes and that the magnitude of these effects varies widely between individuals. Our findings reject the original hypothesis that periodic breathing would not be found in the athlete population at this altitude because it occurred in nearly 25% of our subjects. Given that the number of respiratory events is known to decrease with long-term hypoxic exposure, the observed prevalence of respiratory events at simulated moderate altitude in the present study suggest that further studies to monitor acclimation are recommended.

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REFERENCES


