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RESEARCH ARTICLE

Altitude-induced central sleep apnea does not affect mean sleep oxygen saturation in young healthy males

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Abstract

At high altitudes, periodic breathing (PB) can occur during sleep in healthy individuals. PB is characterized by a cyclical ventilatory pattern that alternates between central sleep apnea and brief episodes of hyperventilation. The aim of this study was to evaluate the effect of periodic breathing on sleep blood oxygen saturation (Sp_{O_2}). Thirty-six healthy male subjects (median [IQR] age: 26 [24–28] yr old, median [IQR] body mass index: 22.7 [21.1–23.8] kg/m^2) underwent a polysomnography at a simulated altitude of 3,500 m (FI_{O_2}: 13%). Correlations were sought between the apnea-hypopnea index (AHI), oxygen desaturation index (ODI), percentage of sleep time spent in PB (PB), and mean Sp_{O_2} throughout the entire sleep period by calculating the Spearman's rank correlation test. We identified 20 participants who had experienced at least 3 min of periodic breathing adjacent to at least 3 min of regular breathing (RB). We compared the mean Sp_{O_2} between the two respiratory patterns using Wilcoxon signed-rank test. At simulated altitude, the subjects spent a median [IQR] of 43.9 [12.5–79.1]% of sleep time in PB. The median [IQR] AHI was 77.3 [31.4–127.5]/h, and the median [IQR] ODI was 82.6 [52.6–134.0]/h. Median awake and asleep Sp_{O_2} were 75.4 [72.0–77.2]% and 68.5 [66.4–72.5]%, respectively. We found no within-subject difference in mean Sp_{O_2} between RB and PB periods (median [IQR] RB vs. PB: 67.2% [63.8%–74.8%] vs. 67.5% [64.5%–73.9%]; $P = 0.43$). No significant correlation was found between the mean sleep Sp_{O_2} and AHI ($n = 36$, $rs = -0.19$, $P = 0.26$), ODI ($n = 36$, $rs = -0.23$, $P = 0.18$) or PB ($n = 36$, $rs = -0.07$, $P = 0.67$). Awake Sp_{O_2} was correlated with mean Sp_{O_2} during sleep ($n = 36$, $rs = 0.55$, $P = 0.001$). Periodic breathing per se does not have a detrimental effect on mean Sp_{O_2} in young healthy males. Correlation between awake Sp_{O_2} and sleep Sp_{O_2} suggests that sleep Sp_{O_2} at high altitude is primarily determined by baseline oxygen saturation rather than the respiratory pattern developed during sleep.

NEW & NOTEWORTHY Periodic breathing, which occurs during sleep at altitude, causes an oscillation between central apneas and periods of hyperventilation. The overall impact of this breathing pattern on blood oxygen saturation (Sp_{O_2}) remains a topic of debate. We compared the mean Sp_{O_2} between periods of periodic breathing and periods of regular breathing for the same individual. The results suggest that periodic breathing does not affect mean sleep Sp_{O_2}.

blood oxygen saturation; central sleep apnea; high altitude; hypoxia; periodic breathing

INTRODUCTION

At high altitude, periodic breathing occurs during sleep in healthy subjects without sleep-disordered breathing at low altitude (1). Periodic breathing manifests as a cyclical pattern alternating between central sleep apnea (CSA) and brief episodes of hyperventilation. These two phases exert opposing effects on blood oxygen saturation (Sp_{O_2}), with desaturation events occurring during CSA and periods of hyperventilation promoting oxygenation, resulting in increased Sp_{O_2} (Fig. 1). Consequently, the overall impact of this dual-phase phenomenon on mean sleep Sp_{O_2} remains uncertain, contributing to the ongoing discourse regarding the adaptive or maladaptive nature of periodic breathing (2).

Some authors have observed higher mean sleep Sp_{O_2} in subjects who develop periodic breathing at high altitudes (3, 4). They suggested that hyperventilation would overcompensate for apnea-induced desaturation and thus periodic breathing could represent a physiological adaptation to hypoxia. However, other studies did not find this beneficial effect, observing no positive association between the apnea-hypopnea index (AHI) and mean sleep Sp_{O_2} (5–7).

The discrepancy in existing results should be considered in the context of the various methodologies used. Indeed,

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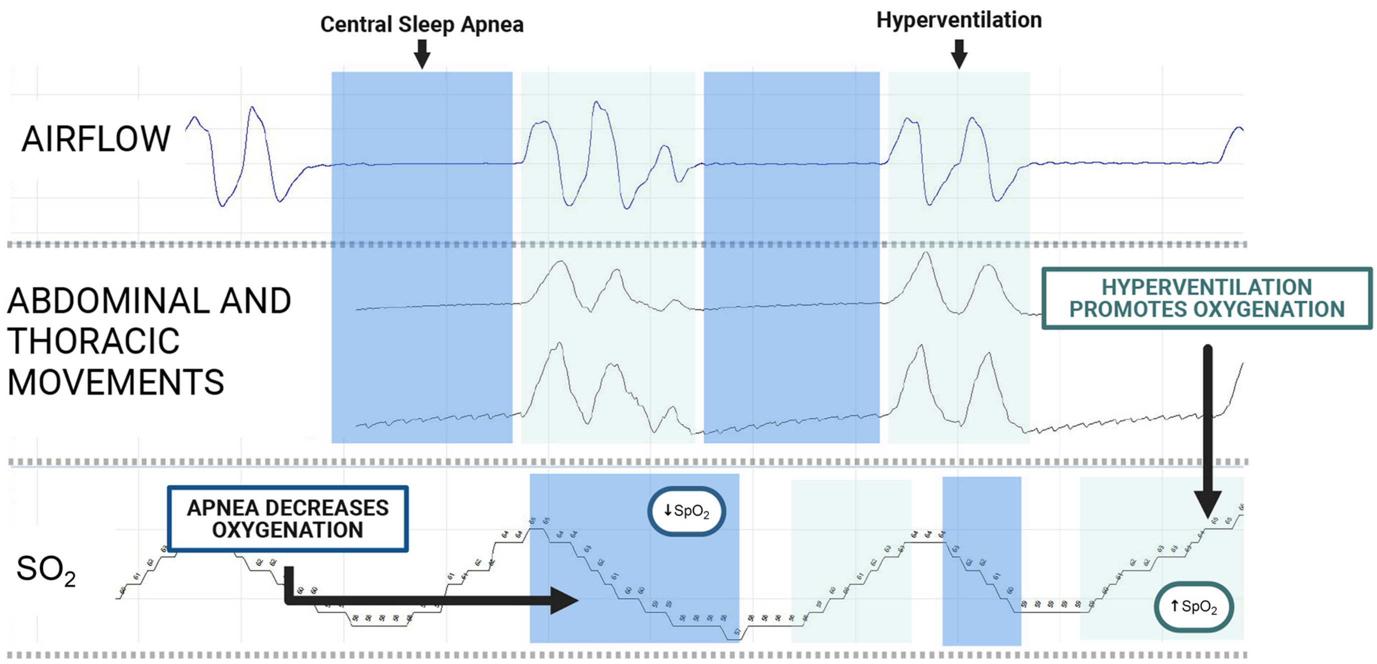

Figure 1. The two phases of periodic breathing (apnea and hyperventilation) have opposite effects on blood oxygen saturation (Sp_{O_2}). Periodic breathing is characterized by a cyclical ventilatory pattern that alternates between central sleep apnea (CSA) and brief episodes of hyperventilation. The two phases of periodic breathing have opposite effects on Sp_{O_2}: central apnea reduces Sp_{O_2} and hyperventilation promotes oxygenation. The overall impact of this dual-phase phenomenon on mean sleep Sp_{O_2} remains uncertain.

Sp_{O_2} measurement in hypoxia can be biased by many factors, including signal instability (8): oxygen saturation in hypoxia is on the steep side of the hemoglobin dissociation curve, making it highly susceptible to variations in ventilation. Therefore, oxygen sleep saturation could be affected by physiological changes in breathing, especially by awakening (7, 9, 10). It has been demonstrated that sleep quality is reduced during sleep in hypoxia with increased arousal and wake (11). Consequently, studies that have not used electroencephalogram (EEG) recordings have likely overestimated the mean sleep Sp_{O_2}, as they probably have included periods of wakefulness in the analysis. The sleep duration in supine position or in rapid eye movement (REM) sleep can influence Sp_{O_2} as a function of airway patency (12, 13) and also require sleep position and EEG sensors to be assessed.

Moreover, studies have demonstrated a wide range in awake Sp_{O_2} level between different individuals measured at the same altitude (14, 15). For example, Kidd et al. (15) observed considerable variability in the measured awake Sp_{O_2} of over 1,500 trekkers who reached an altitude of 4,410 m, with a mean Sp_{O_2} of 87.1%, a standard deviation of 3.76%, and a range of 72%–96%. It is therefore reasonable to anticipate that participants with an awake Sp_{O_2} of 96% in hypoxia will exhibit a higher sleep Sp_{O_2} than subjects with an awake Sp_{O_2} of 72%, irrespective of periodic breathing. Consequently, comparing Sp_{O_2} levels between individuals presents methodological challenges.

The aim of this study was to clarify the determinants of sleep Sp_{O_2} in altitude and in particular the impact of altitude-related periodic breathing by comparing Sp_{O_2} levels during periods of periodic and stable breathing within the same individual, in the same body position, and in the same sleep stage.

MATERIALS AND METHODS

Ethics

The study received approval from the Regional Ethical Committee (Commission cantonale d'éthique de la recherche sur l'être humain, canton de Vaud, Project-ID 2022-00194), and all participants provided written informed consent.

Study Participants

We recruited 55 participants to take part in a study investigating the pathophysiology of periodic breathing and the work of breathing during sleep in hypoxia requiring physiological assessments on different days (data not yet published). Given the tendency of women to be protected against altitude-induced central apnea and the variability of their respiratory drive according to their hormonal cycle, only male subjects were recruited (see study limitations). To ensure a homogeneous sample, only subjects aged between 18 and 30 yr with a body mass index (BMI) of $\leq$30 kg/m^2 and free of cardiac and/or pulmonary pathology were recruited.

Protocol

All participants first underwent baseline polysomnographic recordings (PSG) at home (Nox A1 device, Nox medical, Reykjavik) with a standard American Academy Sleep Medicine (AASM) recommended montage including electrocardiogram, electroencephalogram (EEG) with six electrodes and two mastoid references, electrooculogram, an electromyogram, a pulse oximeter, a nasal cannula, abdominal, and chest motion sensor. Three subjects with an apnea-hypopnea index (AHI) >15/h of sleep at baseline were not included in the study (inclusion criteria). After the baseline recording, three participants decided to drop out of the study.

Forty-nine subjects completed a second polysomnographic recording (Nox A1 device) in a hypoxic chamber (MotionLab sports center, Lausanne) simulating an altitude of 3,500 m [fraction of inspired oxygen (FI_{O_2}): 13%]. The PSG montage was identical to that performed in normoxia in 29 participants. Twenty participants were equipped with a slightly simplified EEG montage (two central electrodes and two mastoid references), an electrooculogram, a pulse oximeter, a nasal cannula, abdominal and chest motion sensors, an esophageal probe (FluxMed device, Buenos Aires), an airflow sensor (FluxMed device, Buenos Aires), and a gas analyzer (METAMAX 3B; CORTEX Biophysik GmbH, Leipzig).

Sp_{O_2} was measured at low and simulated altitude using the NONIN 8000SX sensor (Nonin Medical, Plymouth). This sensor has an accuracy of ±2%, validated over a saturation range of 70%–100%.

Analysis

Sleep stages and respiratory events were scored according to the 2017 American Association Sleep Medicine (AASM) manual (16). The scoring was conducted manually by two trained technicians using Noxturnal 2.1 software (Nox medical, Reykjavik). Sleep positions were measured by a position sensor integrated into the NOX A1 box and were automatically analyzed by the Noxturnal software.

Periodic breathing was defined as the succession of at least three central sleep apneas separated by short periods of hyperventilation. The percentage of total sleep time (TST) spent in periodic breathing (PB) was calculated in addition to the AHI. Regular breathing (RB) was defined as breathing in the absence of respiratory events, including central apneas, obstructive apneas, mixed apneas, and central or obstructive hypopneas.

Given a high number of short-duration respiratory events that did not fulfill the AASM criteria for respiratory events, we additionally scored “atypical central sleep apneas” using previously defined criteria (17), that is, >90% decrease in airflow without thoracoabdominal movement lasting 5–10 s, at least 3% desaturation and the event must be included in a periodic breathing pattern (Fig. 2). As we measured the duration of each respiratory event, we were able to calculate the percentage of the total sleep time (TST) spent in hypopnea and apnea.

Only subjects with more than 120 min of sleep with an artifact-free oximetry signal were included in the Sp_{O_2} analysis. Awake oxygen saturation was calculated as the mean Sp_{O_2} during at least 5 min of artifact-free signal before the first sleep period. We computed the correlation of mean sleep Sp_{O_2} with AHI, oxygen desaturation index (ODI), and PB using Spearman’s rank correlation test. The percentage of total sleep time spent with saturation below 70% (T70) and 65% (T65) was calculated. We analyzed the correlation of T70 and T65 with AHI, ODI, and PB using Spearman’s rank correlation test.

Participants with at least 3 min of periodic breathing preceded or followed by at least 3 min of regular breathing were manually identified. To be included in our analysis, these two periods had to occur within the same sleep stage and in the same position (supine or nonsupine). Mean pulse oximetry saturation level (4 Hz sampling frequency) was then compared between the two periods using the Wilcoxon signed-

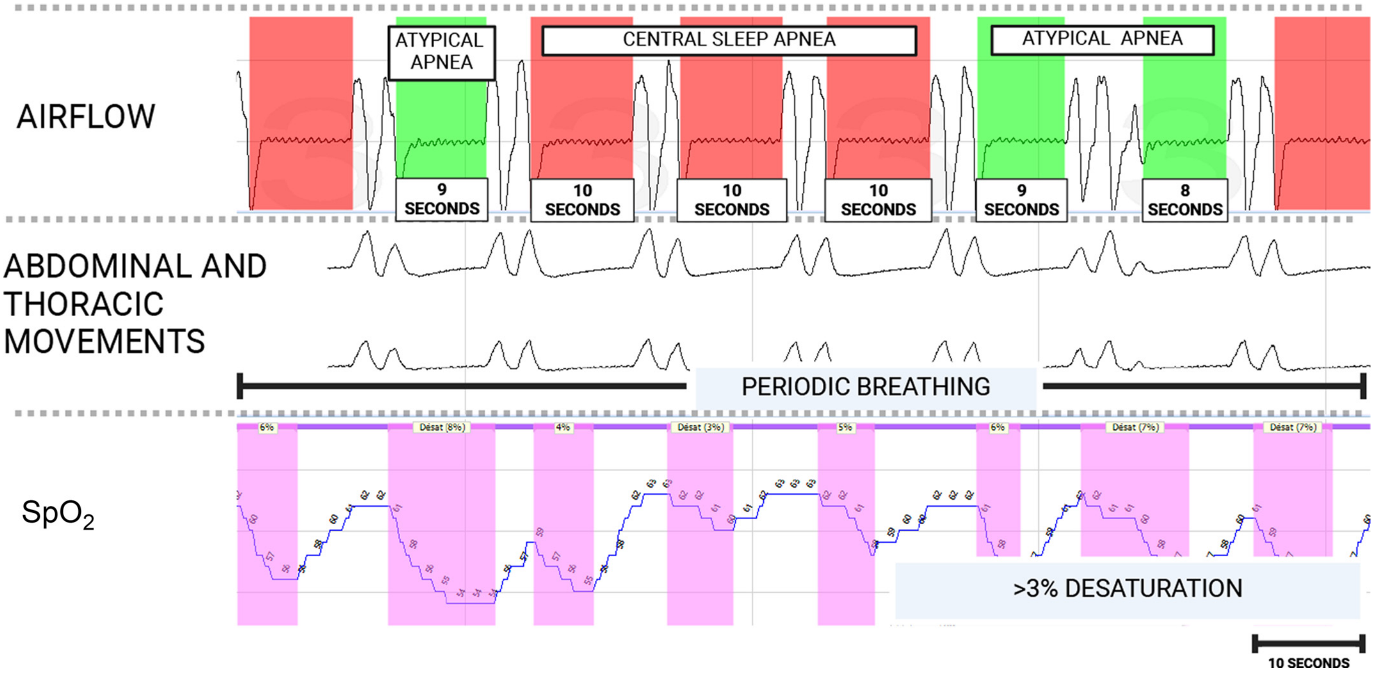

Figure 2. Example of atypical central sleep apnea. Given a high number of short duration respiratory events that did not fulfill the American Association Sleep Medicine criteria for respiratory events, we additionally scored “atypical central sleep apneas.” Atypical events must meet the following criteria: a >90% decrease in airflow without thoracoabdominal movement lasting 5–10 s, at least 3% desaturation and the event must be included in a periodic breathing pattern. Sp_{O_2}, blood oxygen saturation (%).

rank test. The duration of each adjacent epoch was matched based on the shorter of the two periods.

Statistical analyses were performed using GraphPad Prism software (GraphPad Software, Boston). A P value < 0.05 was considered statistically significant.

RESULTS

In accordance with the established inclusion criteria, 49 subjects completed the protocol (Fig. 3). Thirteen subjects were excluded from the analyses due to a sleep time with an artifact-free oximetry signal below 120 min (exclusion criteria). Ultimately, a total of 36 subjects whose recordings met the quality criteria for Sp_{O_2} were included in the analysis (Table 1).

During hypoxia recording, we found large variations between participants in AHI and ODI (Table 2). Both parameters showed a highly positive correlation with the percentage of sleep spent in periodic breathing as determined by Spearman's rank correlation test (AHI: $r = 0.97$, $P < 0.0001$; ODI: $r = 0.95$, $P < 0.0001$).

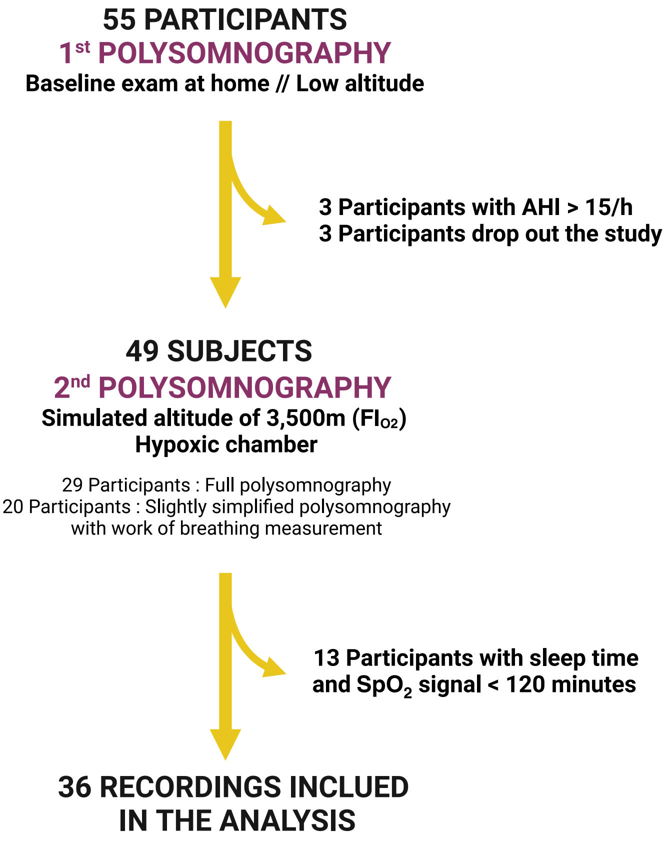

Figure 3. Flowchart of the study. A total of 55 participants underwent the initial polysomnography at low altitude. Three subjects exhibited an apnea-hypopnea index (AHI) > 15/h and were thus excluded from the study. In addition, three other subjects chose not to participate in the subsequent stage of the study. Consequently, 49 subjects underwent the hypoxic chamber examination. The PSG montage was identical to that performed in normoxia in 29 participants. Twenty participants were equipped with a slightly simplified polysomnography montage including a work of breathing assessment. A total of 13 subjects were excluded from the analysis due to a sleep time with a blood oxygen saturation (Sp_{O_2}) signal of <120 min. Thus, 36 recordings were included in the Sp_{O_2} analysis. PSG, polysomnographic recordings.

Table 1. *Characteristics and baseline sleep measurements*

Parameter	Median [IQR]	Range [Min;Max]
Age, yr	26 [24–28]	16 [18;34]
Height, cm	178.5 [172.5–184.0]	36 [160.0;196.0]
Weight, kg	72.0 [68.2–79.0]	39 [57.0;96.0]
BMI, kg/m^2	22.7 [21.1–23.8]	11.3 [19.0;30.3]
AHI/h at low altitude	3.4 [1.7–4.8]	12.0 [0.3;12.3]
ODI/h at low altitude	3.5 [2.5–6.4]	9.7 [0.7;10.4]
Mean sleep Sp_{O_2} at low altitude, %	94.9 [94.0–95.5]	4.8 [92.0;96.8]

$n = 36$ subjects. AHI, apnea-hypopnea index per hour; BMI, body mass index; IQR, interquartile range; Max, maximum; Min, minimum; ODI, oxygen desaturation index per hour; Sp_{O_2}, pulse oxygen saturation (%).

Awake oxygen saturation was significantly correlated with mean sleep Sp_{O_2} ($r = 0.547$; $P = 0.001$), T70% ($r = -0.615$; $P < 0.001$), and T65% ($r = -0.584$; $P < 0.001$) in hypoxic condition.

However, there was no statistically significant correlation between mean sleep Sp_{O_2} and AHI, ODI, PB, or the percentage of total sleep time spent in apnea or hypopnea (Fig. 4).

We found no statistically significant correlation between the percentage of total sleep time spent with saturation below 70% and AHI ($r = 0.214$; $P = 0.210$), ODI ($r = 0.244$; $P = 0.152$), or PB ($r = 0.093$; $P = 0.588$). Similar results were found between T65% and AHI ($r = 0.232$; $P = 0.172$), ODI ($r = 0.271$; $P = 0.109$), or PB ($r = 0.121$; $P = 0.483$).

We identified 20 subjects with at least 3 min of periodic breathing preceded or followed by at least 3 min of regular breathing. To be included in our analysis, these two periods had to occur in the same stage of sleep and in the same position (supine or nonsupine). Five subjects presented multiple sequences corresponding to our criteria, allowing us to select 31 sequences of periodic breathing preceded or followed by an equivalent period of regular breathing. No statistically significant differences were identified between the mean Sp_{O_2} in periodic breathing and the Sp_{O_2} in regular breathing (see Fig. 5). However, there were statistically significant differences in the standard deviation of the mean Sp_{O_2} signal, the Sp_{O_2} signal range, and the minimal and maximal Sp_{O_2} values between periodic and regular breathing (see Table 3).

Table 2. *Polysomnographic data in hypoxia*

Parameter	Median [IQR]	Range [Min;Max]
Awake Sp_{O_2}, %	75.4 [24–28]	20 [66.9;86.9]
Sp_{O_2} sleep time, min	291 [208.8–255.3]	241 [166.5;407.5]
AHI/h	77.3 [31.4–127.5]	183.2 [7.4;190.6]
ODI/h	82.6 [52.6–134.0]	170.5 [13.7;184.2]
PB, %	43.9 [12.5–79.1]	92.2 [0;92.2]
% of sleep in AH	26.7 [11.5–45.5]	59.1 [2.5;61.6]
Mean sleep Sp_{O_2}, %	68.5 [66.4–72.5]	19.4 [61.6;81]
T70, %	63.8 [19.4–81.3]	96.7 [0;96.7]
T65, %	18.9 [0.3–33.6]	83.4 [0;83.4]

$n = 36$ subjects. % of sleep in AH, percentage of sleep spent in apnea and hypopnea; AHI, apnea-hypopnea index per hour; IQR, interquartile range; ODI, oxygen desaturation index per hour; Max, Maximum; Min, minimum; PB, percentage of sleep in periodic breathing; Sp_{O_2}, pulse oxygen saturation (%); Sp_{O_2} sleep time, time of Sp_{O_2} during sleep with no-artifact; T65, percentage of sleep spent with saturation below 65%; T70, percentage of sleep spent with saturation below 70%.

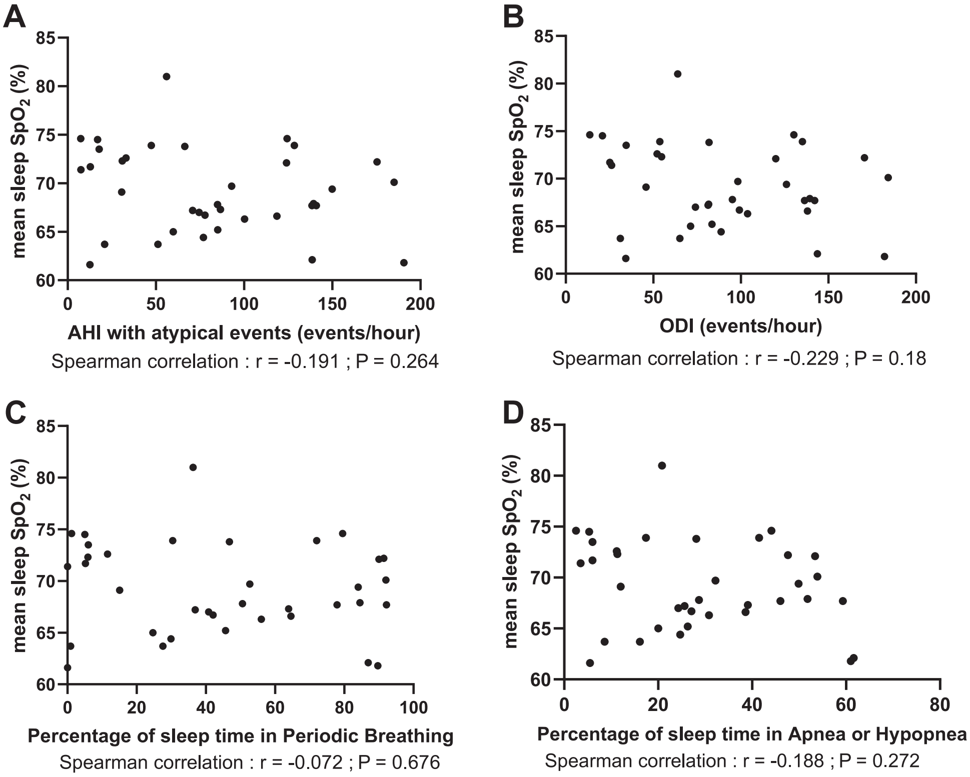

Figure 4. Correlation of mean sleep Sp_{O_2} with AHI, ODI, PB, and the percentage of sleep time in apnea or hypopnea. *A*: correlation between mean sleep Sp_{O_2} and AHI. *B*: correlation between mean sleep Sp_{O_2} and ODI. *C*: correlation between mean sleep Sp_{O_2} and percentage of sleep time in periodic breathing. *D*: correlation between mean sleep Sp_{O_2} and percentage of sleep time in apnea or hypopnea, $n = 36$. We found no statistically significant correlation between mean sleep Sp_{O_2} and AHI, ODI, percentage of sleep time in periodic breathing, or percentage of sleep time in apnea or hypopnea as determined by Spearman's rank correlation test. AHI, apnea-hypopnea index per hour; ODI, oxygen desaturation index per hour; PB, periodic breathing; Sp_{O_2}, pulse oxygen saturation.

Similar results were observed when comparing only sequences taking place in N2 stage ($n = 20$; BP vs. RB; 67.67% [64.74–73.76] vs. 69.05% [65.13–75.61]; $P = 0.1536$) or in the supine position ($n = 18$; PB vs. RB; 66.84% [64.24–73.24] vs. 67.10% [64.75–74.20]; $P = 0.1964$).

DISCUSSION

This study compared the effect of periodic to regular breathing during sleep on mean Sp_{O_2} in the same participants, while minimizing the impact of sleep stage and position. Although periodic breathing is associated with a high number of oxygen desaturation events (intermittent hypoxia), there was no significant difference in mean sleep Sp_{O_2} between both breathing patterns. There was also no association between mean sleep Sp_{O_2} and the proportion of total sleep time spent in periodic breathing, the apnea-hypopnea index, or the oxygen desaturation index. These results support that periodic breathing, despite the presence of numerous desaturation events, does not have a detrimental effect on mean sleep Sp_{O_2}.

This absence of detrimental effect of periodic breathing on Sp_{O_2} may be explained by the positive impact of short periods of hyperventilation, which promote oxygenation and compensate for apnea-induced desaturations. Due to hypoxia, Sp_{O_2} values lie on the steep portion of the hemoglobin dissociation curve (18). Therefore, periods of hyperventilation lead to large fluctuations in oxygen.

The occurrence of periodic breathing is characterized by a higher frequency of oscillation in Sp_{O_2} values, as evidenced by the strong positive correlation between PB and ODI. Furthermore, the range of these oscillations is approximately twice as wide as that observed during regular breathing (see Table 3). It is therefore possible that PB may generate a greater oxidative stress than regular breathing due to larger variations in Sp_{O_2}. Given that the mean sleep Sp_{O_2} value is identical for both breathing patterns, it may be anticipated that individuals with a high percentage of sleep in periodic breathing would spend a greater proportion of time with lower saturations following breathing cessation than individuals with regular breathing. However, no correlation was found between T70 or T65 and AHI, ODI or PB, which challenges this hypothesis. It was the awake Sp_{O_2} that was found to be significantly correlated with the mean sleep saturation, T70 and T65. This can be explained by the impact of the chemical respiratory drive, which plays a significant role in the control of breathing during wakefulness in hypoxic conditions. Therefore, a high ventilatory response to hypoxia will tend to elevate Sp_{O_2} during wakefulness (8). Once asleep, the chemical respiratory drive is the main controller of breathing following the loss of the awake respiratory drive, which explains the correlation between awake and asleep Sp_{O_2}.

In summary, an individual's saturation oscillates within a specific Sp_{O_2} range, with the amplitude and frequency of oscillation dependent on the respiratory pattern. However, the position of this range on the hemoglobin dissociation curve is associated with awake Sp_{O_2}, which is a surrogate of the ventilatory response to hypoxia. This suggests that saturation during sleep is primarily determined by an individual's adaptation and tolerance to hypoxia, rather than the number of desaturations or the respiratory pattern developed during sleep.

This finding may explain the contradictory results of Nespoulet et al. (3), who suggested that periodic breathing was associated with higher Sp_{O_2}. The authors demonstrated that a group of subjects not susceptible to acute mountain sickness (AMS−) had a higher AHI and a higher mean sleep

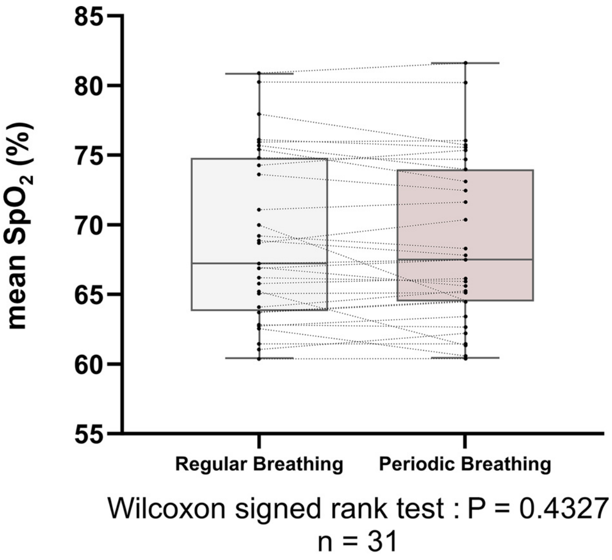

Figure 5. Comparison of mean sleep saturation between each breathing pattern for the same individual, in the same position and in the same sleep stage. We identified 20 subjects with at least 3 min of periodic breathing preceded or followed by at least 3 min of regular breathing. To be included in our analysis, these two periods had to occur in the same stage of sleep and in the same position (supine or nonsupine). Five subjects presented multiple sequences corresponding to our criteria, allowing us to select 31 sequences of periodic breathing preceded or followed by an equivalent period of regular breathing. Mean pulse oximetry saturation level (4 Hz sampling frequency) was then compared between the two periods using the Wilcoxon matched-pairs signed-rank test. In the graphs, the middle line of each box shows the median, the *bottom*/*top* lines of each box show the first/third quartiles, the whiskers the 1.5 interquartile range value (Tukey's). The dots represent the individual data connected for each intraindividual comparison. Sp_{O_2}, pulse oxygen saturation.

Sp_{O_2} than a group of participants susceptible to acute mountain sickness (AMS +). However, AMS− subjects also had a significantly greater ventilatory response to hypoxia during wakefulness than AMS + subjects. Following our hypothesis that mean sleep saturation is primarily influenced by adaptation to hypoxia of which awake Sp_{O_2} is an indicator, AMS− subjects will be more likely to have a higher mean sleep Sp_{O_2} than AMS + subjects. Thus, the higher mean sleep Sp_{O_2} that Nespoulet et al. (3) found in the AMS− group could be caused by the greater ventilatory response to hypoxia rather than by the higher AHI.

Our study supports that periodic breathing does not negatively impact mean oxygenation. These results suggest that periodic breathing is not a maladaptive process to hypoxia in terms of oxygenation. The clinical significance of altitude-related periodic breathing is still debated (2, 6). Some authors suggest that periodic breathing could be an optimization of respiratory work (19, 20), as hypoxia-induced hyperventilation represents a significant energy consumption (21). If periodic breathing can achieve the same Sp_{O_2} levels as regular breathing with fewer hyperpnea and resting (apnea) periods, it could improve the efficiency of the respiratory system by reducing the work of breathing through lower respiratory rates and ventilation of the dead space.

This study has limitations that must be mentioned. First, the recordings were made in normobaric hypoxia, which differs from the conditions experienced by residents or sojourners at high altitudes (hypobaric hypoxia). A previous study conducted by our research group demonstrated that there was an increase in the AHI and a decrease in mean Sp_{O_2} in hypobaric hypoxia compared with normobaric hypoxia (22). It is hypothesized that these differences may be linked to a decrease in nitric oxide (NO) bioavailability (23), which may lead to vasoconstriction in the pulmonary capillaries, hinder alveolar-capillary gas exchange, and disrupt oxygen diffusion due to a reduced pressure gradient (22). Furthermore, barometric pressure may influence fluid dynamics and the flux across the transalveolar capillary membrane (24). Consequently, the findings presented in this paper cannot be directly applied to hypobaric hypoxia. However, Bird et al. (5) observed comparable results at 3,800 m and 5,160 m, indicating that despite an increased AHI in hypobaric hypoxia compared to normobaric hypoxia, the periodic breathing pattern maintains this neutral effect on oxygenation. Second, the study protocol did not include a period of acclimatization before sleep. This could have induced a greater severity of central sleep apneas compared with a longer stay at high altitude. Furthermore, these analyses were conducted as part of a study investigating the pathophysiology of periodic breathing and the work of breathing during sleep in hypoxia (not yet published). Given that the study protocol required respiratory assessments on different days and that women's respiratory physiology varies according to their hormonal cycle, this study exclusively recruited male subjects to prevent the influence of fluctuating female hormones on respiratory control. This limits the generalizability of the findings to women. It is also important to consider the accuracy of oximetry sensors in hypoxic conditions (25), as minor changes in sensor position could produce fluctuations in the oximetry range. For instance, the NONIN 8000SX sensor (Nonin Medical, Plymouth) used in our study has an accuracy of ±2%. It seems that this accuracy is further reduced for values below 75% (26). However, in the present study, we compared the impact of the two breathing patterns in the same subjects over two adjacent periods, without artifacts, in the same sleep stage and body position, which limits the impact of potential measurement inaccuracy.

Conclusions

This study shows that there is no significant difference in mean sleep Sp_{O_2} between regular and periodic breathing in hypoxic conditions within the same subject, in the same sleep stage and body position. In addition, AHI, PB, and ODI

Table 3. *Comparison of mean sleep saturation between each breathing pattern for the same individual, in the same position, and in the same sleep stage*

	Regular Breathing	Periodic Breathing	*P* Value
Mean Sp_{O_2}, %	67.2 [63.8–74.8]	67.5 [64.5–74.5]	0.4327
Sp_{O_2}-SD, %	0.78 [0.71–0.92]	1.9 [1.7–2.3]	<0.001
Sp_{O_2} range, %	4.0 [3.0–5.0]	7.0 [7.0–11.0]	<0.001
Min Sp_{O_2}, %	65.0 [61.0–73.0]	64.0 [60.0–71.0]	<0.001
Max Sp_{O_2}, %	70.0 [66.0–76.0]	71.0 [68.0–78.0]	<0.001

$n = 31$ sequences of periodic breathing adjacent to regular breathing in the same body position and in the same sleep stage. Values are expressed as median-interquartile range. Max Sp_{O_2}, maximal pulse oximetry saturation level; Mean Sp_{O_2}, mean pulse oximetry saturation level; Min Sp_{O_2}, minimal pulse oximetry saturation level; Sp_{O_2}-SD, standard deviation of mean pulse oximetry saturation level.

at simulated high altitudes are not associated with lower mean sleep Sp_{O_2}. These results indicate that altitude-induced periodic breathing, despite the presence of numerous desaturation events, does not have a detrimental effect on the mean nocturnal Sp_{O_2} in young healthy males. Furthermore, we found a strong correlation between awake Sp_{O_2} and mean sleep Sp_{O_2}, suggesting that sleep Sp_{O_2} is primarily determined by baseline oxygen saturation rather than the respiratory pattern developed during sleep.

DATA AVAILABILITY

The source data for this study are not publicly available due to ethical restrictions. The consent form signed by the participants did not include the option of publishing the data on an online database. The source data are available to verified researchers upon request by contacting the corresponding author.

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GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

G.H., F.R., and R.H. conceived and designed research; G.H., F.R., B.B., and G.L. performed experiments; G.H., F.R., B.B., G.L., and R.H. analyzed data; G.S., T.I., A.W., and R.H. interpreted results of experiments; G.H. and F.R. prepared figures; G.H., F.R., and R.H. drafted manuscript; G.S., T.I., A.W., K.L., F.D., and R.H. edited and revised manuscript; G.H., F.R., and R.H. approved final version of manuscript.

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