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Oxygen supplementation for work in hypoxic environments — a pilot study

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Original article

Abstract

Objective: To investigate at what level of isobaric hypoxia a clinically significant decrease of PO_2 (in the blood, noted as SpO_2) occurs when non-acclimatized humans enter a hypoxic environment, and what amount of supplemental oxygen, if any, is necessary to keep SpO_2 within an acceptable range when operating in a low-oxygen environment.

Material and methods: 6 volunteers were exposed to 20.9% (sea level), 19.0% (800 m / 2,620 ft), 15.5% (2,400m / 7,870 ft), 13.5% (3,400 m / 11,150 ft), and 11% (5,200 m / 17,060 ft) atmospheric oxygen saturation at rest and with 80W workload, without and with supplemental oxygen via nasal cannula and a demand system. Pulse rate and SpO_2 were measured.

Results: At 15.5% oxygen or higher, participants stabilized SpO_2 above 90%. At 13.5% oxygen, participants had oxygen saturation values between 80 and 89% at rest without supplemental oxygen. At 11.0% oxygen, many participants had SpO_2 values ≤80%, but 3 of 6 showed SpO_2 values between 80 and 89%. An additional workload of 80W caused only small changes in SpO_2. An immediate and significant increase in SpO_2 was observed after supplemental oxygen administration, both at rest and during exercise. Data from isobaric hypoxia correlate well with those in hypobaric conditions.

Conclusion: Working in a reduced-oxygen environment at 15% oxygen is well tolerated, with no adverse physiological or clinical effects. At ambient oxygen levels of 13.5% or lower, supplemental oxygen may be required in some individuals to maintain an acceptable blood oxygen saturation.

Keywords

- isobaric hypoxia
- oxygen saturation
- supplemental oxygen
- workload

Contribution

A – Preparation of the research project
B – Assembly of data
C – Conducting of statistical analysis
D – Interpretation of results
E – Manuscript preparation
F – Literature review
G – Revising the manuscript

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Introduction

While extensive literature spanning more than a century documents the decline in maximal aerobic exercise and arterial oxygen saturation (SpO_2) with increasing altitude.[1-12] data on work in isobaric hypoxia and the potential need for supplemental oxygen in such environments are limited (survey in Küpper[13]). Some studies have shown significant but minor differences in certain aspects of breathing and exercise physiology, but they are too small to have clinical relevance.[14,15] Despite our knowledge of the physiology of isobaric and hypobaric hypoxia, the governments of several countries assume there is an increased risk for employees when oxygen concentration is below 19.5% (OSHA, USA), or 16% (U.K., Confined Space Regulations[16]). On the other hand, oxygen concentrations of 14%–16% (usually 15.0%–15.5%) are used for fire suppression in various environments. These result in an oxygen partial pressure equivalent to an altitude of about 2,500 m (8,200 ft), the same conditions as a commercial aircraft cabin at cruising altitude. More than 5 billion passengers worldwide prove annually that this is not a problem. Some countries follow a differentiated risk management according to UIAA MedCom Recommendations (e.g. Germany with 4 risk classes,[17-19] Austria with 3 risk categories,[20] or Switzerland with 3 risk categories and free access to atmospheres with more than 17% O_2).[21]

The partial pressure of oxygen is the product of the atmospheric pressure and the percentage of oxygen ($P_{atm} \times O_2\%$). Thus, a low concentration of oxygen at sea level can have the same PO_2 as at a higher altitude. Conversely, enriching the air with oxygen at high altitude can result in the same PO_2 as at lower altitudes, including to sea level values. Therefore, simply specifying the oxygen percentage (% O_2) for safety is not particularly useful from a life sciences perspective. In this realm, any discussion about risk and risk management should be based on oxygen partial pressure, not percentage (concentration). Figure 1 illustrates the relationship between atmospheric pressure, oxygen partial pressure, and oxygen concentration under isobaric conditions as well as at high altitude.

A healthy environment will always have a satisfactory PO_2. The question then becomes: what is satisfactory to avoid poor physical performance and any threat to health? To enable risk management based on data, the study presented here focuses on the following questions:

1. At what level of isobaric hypoxia will a clinically significant decrease of PO_2 (in the blood, noted as SpO_2) occur when humans enter such an environment?
2. What amount of supplemental oxygen, if any, is necessary to keep SpO_2 within an acceptable range when operating in a low-oxygen environment?

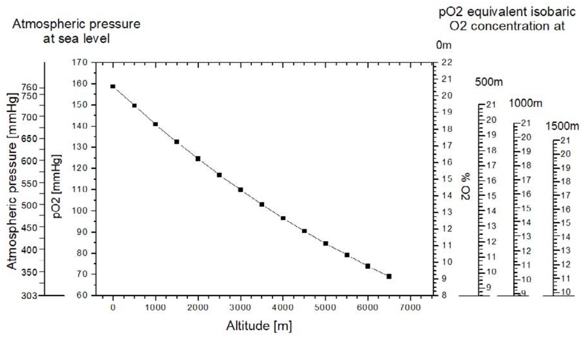


Figure 1. Relationship between pressure, oxygen concentration under isobaric conditions and altitude:[19] Total atmospheric and O_2 partial pressure which correspond to the altitude (X-axis) are given at the left Y-axis. The right Y-axis indicates the oxygen concentration at sea level and three higher locations necessary to simulate the equivalent altitude (X-axis)

This pilot study was intended to indicate whether additional research with larger numbers is necessary to determine when supplemental oxygen should be used for non-acclimatized persons working in a hypoxic environment.

Material and methods

The pilot study was conducted as a self-experiment involving members of our research group (N = 6; 5 males, 1 female; 35 to 61 years), all non-acclimatized, healthy Caucasians with normal body weight. Any medication that might influence breathing or cardiac efficiency and any pulmonary or cardiac disease were exclusion criterions. All participants were well hydrated recreational athletes who did not train hard at least for 24 hours before the measurements.

During exposure in a hypoxic chamber, each participant was continuously monitored by a physician specializing in altitude medicine. SpO_2 and pulse rate were recorded (Beurer Pulsoximeter PO 80, Beurer GmbH, Ulm, Germany). Hypoxia exposure was performed at 40m above sea level with oxygen concentrations as follows (equivalent altitude in brackets): 20.9% (sea level), 19.0% (800 m / 2,620 ft), 15.5% (2,400 m / 7,870 ft), 13.5% (3,400 m / 11,150 ft), and 11% (5,200 m / 17,060 ft). The total duration of the exposure varied from 1.25 to 4 hours.

Measurements with supplemental oxygen were conducted at an ambient oxygen concentration of 15.5%, 13.5%, and 11.0%. Since no significant changes were observed at 19%, and supplemental oxygen under normal atmospheric conditions (20.9% O_2) was unnecessary, these concentrations were investigated without supplemental oxygen. All exposures were performed at rest and at an 80W workload (ET 6 cycling ergometer, Sports Gilles GmbH, Velbert, Germany). An overview of the different exposure situations is given in Table 1.

Table 1. Overview of the exposure and stress factors

Duration [min.]	Oxygen concentration [%]	Workload [W]	Supplemental oxygen [l]
3	20.9	–	–
3	20.9	80	–
3	19.0	–	–
3	19.0	80	–
	Pause >1 h		
3	15.5	–	–
3	15.5	–	2
3	15.5	–	6
3	15.5	–	–
3	15.5	80	–
3	15.5	80	2
3	15.5	80	6
	Pause >1 h		
3	13.5	–	–
3	13.5	–	2
3	13.5	–	6
3	13.5	–	–
3	13.5	80	–
3	13.5	80	2
3	13.5	80	6
	Pause >1 h		
3	11.0	–	–
3	11.0	–	2
3	11.0	–	6
3	11.0	–	–
3	11.0	80	–
3	11.0	80	2
3	11.0	80	6

We categorized SpO_2 into three risk classes:

- normal saturation (“green zone”): >90%;
- mild to moderate decrease (“attention” = “yellow zone”): 80% to 89%;
- severe decrease (“warning” = “red zone”): <80%.

These categories follow generally accepted standard medical recommendations, with perhaps one small difference: based on the fact that we were exposing healthy individuals, and that exposure could be stopped immediately, we set the “critical” range at <80%, rather than <85%, as is clinically standard for seriously ill patients.

If SpO_2 levels fell below 80%, individuals were advised to increase their oxygen supplementation. For supplementation, the demand system OM-824 Oxygen Conserving Device (Drive, Inovo, Inc., N Lehigh Acres, FL 33971) was used (Figure 2, Table 2). Oxygen was administered via a nasal cannula (Figure 3).

Figure 2. OM-824 Oxygen Conserving Device, the switch (scale 1 to 6) regulates the amount of oxygen applied to every breath (for details see Table 2)

Table 2. Oxygen supply by OM-824 Oxygen Conserving Device (based on data from the manufacturer)

Switch position	Flow equivalent [l/min]	ml oxygen per breath
Off	Off	0
1	1	6–20
2	2	15–29
3	3	25–39
4	4	32–46
5	5	39–53
6	6	45–59
7	7	51–65
CF (continuous flow)	2	1.75–2.75 l/min

Figure 3. Oxygen administration via a nasal cannula during work at 5,650 m (Fred Young Telescope, Cerro Cajnantor, Chile)

Study data were collected in an Excel spreadsheet. Descriptive statistics, including mean, standard deviation, median, and range, were calculated. Group differences were analyzed using non-parametric tests (Mann-Whitney U-Test) using Origin 2023 (OriginLab, Northampton, Massachusetts). $P < 0.05$ was considered statistically significant.

Results

The participants were exposed for 1.25 hours, with two of them exposed for up to 4 hours. No subject felt unwell at any time, and there were no dropouts. As expected by the limited time at altitude there were no subjects who were at risk for AMS, HAPE, or HACE. One person showed mild dizziness at 11% oxygen after about 30 minutes. Exposure was continued under physician supervision, and the symptom resolved completely within approximately 10 minutes.

Without oxygen supplementation, SpO_2 decreased with lower oxygen concentration (Figure 4, red dots). The effect is practically identical to the decrease observed with ascent to real altitude (hypobaric hypoxia, Figure 4, black dots). Looking at all the data from the several studies together, it becomes clear that some individuals can maintain an impressive oxygen saturation of approximately 95% even at extreme altitude (>5,000 m / 16,400 ft / 11% O_2). At 15.5% oxygen, most participants (62.5%) maintained SpO_2 above 90%, while 37.5% had values in the upper range of the "yellow zone" (81%–90%), with the lowest SpO_2 recorded at 87% which means that this person was just below the limit defined as the 'physiological normal range', but well above a dangerous level. At 13.5% oxygen, most participants (70.8%) had oxygen saturation values in the "yellow zone" at rest. 25.0% were in the "green zone" (>90%), and 4.2% were marginally in the "red zone" at 80%. At 11.0% oxygen, 41.7% of participants had SpO_2 values in the "red zone (≤80%), with the lowest saturation measured at 65%. 58.3% had SpO_2 values between 81% and 90%, and no one had a saturation above 90%.

The correlation (ambient oxygen concentration vs. SpO_2) of the different data sets is shown in Figures 5a-c.

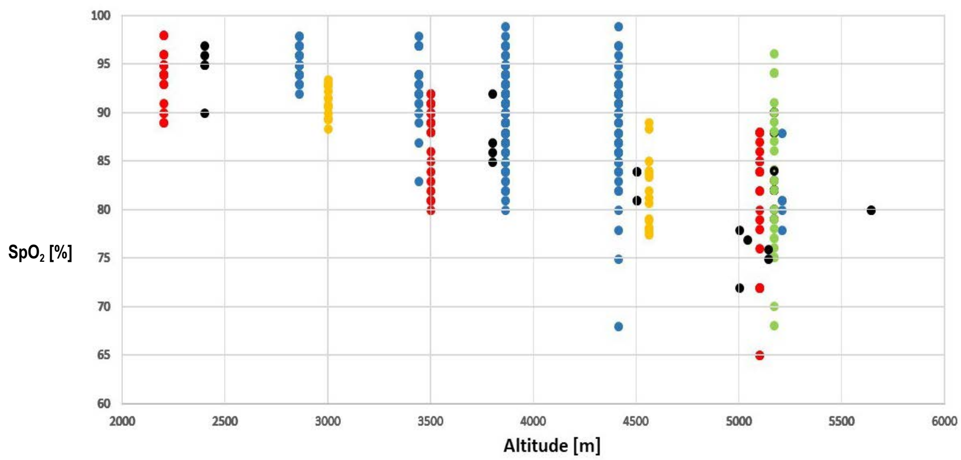


Figure 4. Decrease of oxygen saturation with altitude: actual study in isobaric hypoxia (red dots). For comparison data in hypobaric hypoxia (altitude) are added: Atacama region (Chile, up to 5,640 m, black dots), Solo Khumbu (blue dots)[25,26] at Gorak Shep (Mt. Everest region, Nepal, green dots),[27] and from Margherita Project (3,000 m and 4,560 m, orange dots)[28]

The decrease in SpO_2 in the present study is nearly identical to that in other datasets (Figure 5b,c). It was similar in both acclimatized and non-acclimatized individuals at high altitude (hypobaric hypoxia). Mean values were as follows:

1. At 20.9% oxygen (sea level), the mean SpO_2 at rest was 96.6% (SD 2.2; median 97; range 92–99).
2. At 19.0% oxygen (800 m / 2,620 ft altitude), SpO_2 did not significantly decrease, averaging 96.0% (SD 2.3; median 96; range 92–99; $p = 0.314$).
3. At 15.5% oxygen (2,400 m / 7,870 ft altitude), there was a significant decrease to 93.8% (SD 2.4; median 94; range 89–98; $p = 0.0069$).

4. At 13.5% oxygen (3,400 m / 11,150 ft altitude), SpO_2 further decreased to 87.6% (SD 3.8; median 89; range 80–92; p = 0.0013).
5. At 11.0% oxygen (5,200 m / 17,060 ft altitude), the mean SpO2 was 80.3% (SD 4.5; median 83; range 65-88; p = 0.009).

An additional workload of 80W caused only small changes in SpO_2 (Table 3, Figure 6). It must be noted that down to 15.5% oxygen, no person was in the "red zone" as defined above.

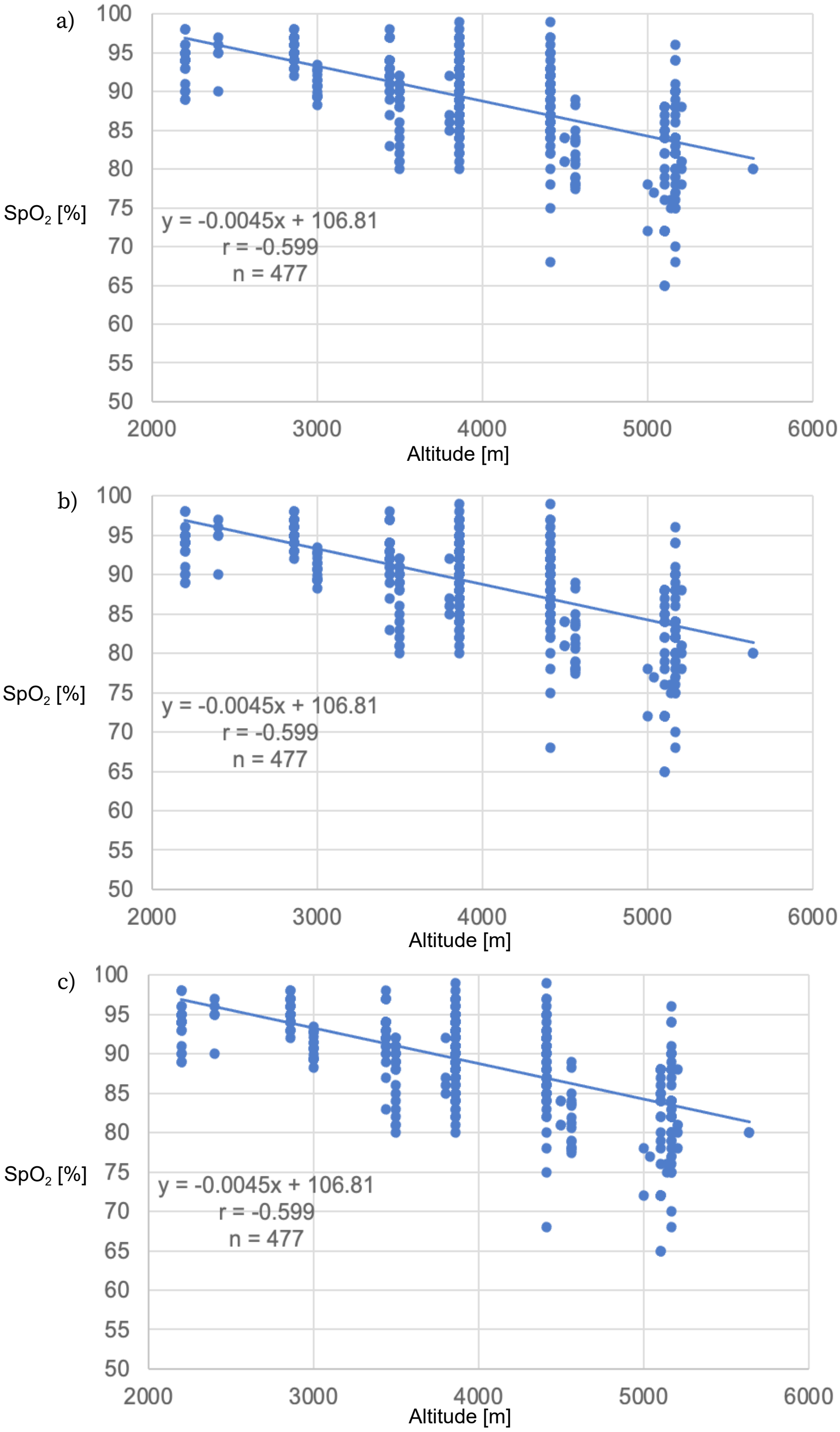


Figure 5. Correlation analysis of the decrease of oxygen saturation with altitude: a) all data from Figure 4; b) data of the actual study (red and black dots in Figure 4); c) data from other studies (blue, green, and orange dots in Figure 4

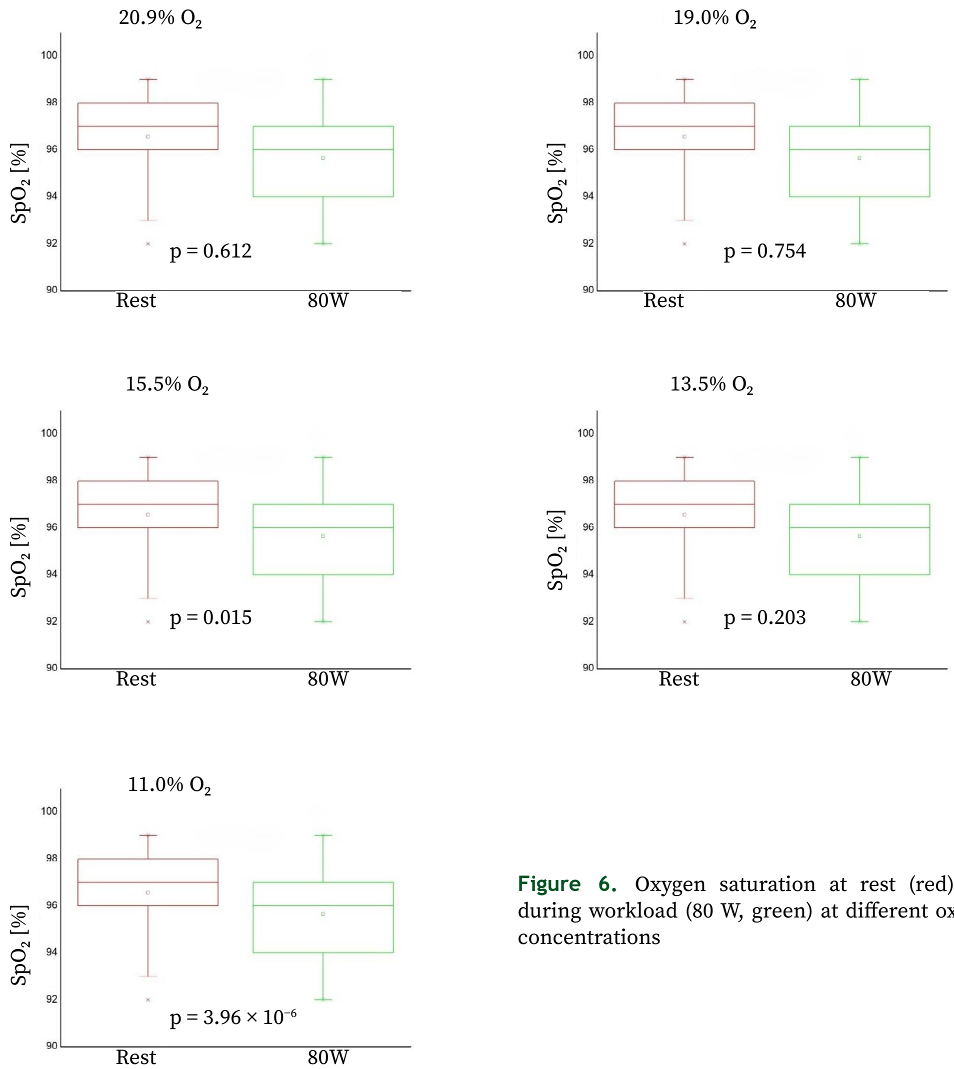


Figure 6. Oxygen saturation at rest (red) and during workload (80 W, green) at different oxygen concentrations

Table 3. Oxygen saturation at different oxygen concentrations with additional workload (80 W, cycling ergometer) but without supplemental oxygen

Oxygen concentration [%]	Equivalent altitude [m]	Mean SpO_2 [%]	SD	Median	Range
20.9	0	95.7[1]	1.8	96	92–99
19.0	800	96.2[2]	2.3	96	91–99
15.5	2400	91.5[3]	3.3	92	87–97
13.5	3400	86.0[4]	6.3	85.5	74–97
11.0	5200	80.3[5]	4.5	83	65–88

Significance levels vs. SpO_2 at rest: 1: $p = 0.6124$; 2: $p = 0.7546$; 3: $p = 0,0155$; 4: $p = 0.203$; 5: $p = 3.96 \times 10^{-6}$.

At ambient oxygen concentrations of 15.5%, 13.5%, and 11.0%, respectively, an immediate and significant increase in SpO_2 was observed after supplemental oxygen administration, both at rest and during exercise (Figure 7, Tables 4 and 5). Pulse rates and the respective statistical data under the investigated conditions are shown in Tables 6 and 7. As expected, the overall heart rate increased with hypoxia and with workload.

Table 4. SpO_2 at different ambient oxygen levels at rest without and with 2 or 6 liters supplemental oxygen

Condition	Mean SpO_2	SD	Range
15.5%	93.8	2.4	89–98
15.5% + 2 l/min O_2	96.3[1]	1.9	92–98
15.5% + 6 l/min O_2	97.5[2]	0.9	95–99
13.5%	87.6	3.8	80–92
13.5% + 2 l/min O_2	91.8[3]	3.1	83–97
13.5% + 6 l/min O_2	95.4[4]	2.2	90–99
11.0%	80.3	7.2	65–88
11.0% + 2 l/min O_2	87.2[5]	4.5	80–94
11.0% + 6 l/min O_2	92.1[6]	5.7	80–98

Significance levels 2 l/min vs. 0 l/min and 6 l/min vs. 2 l/min: 1: $p = 4.53 \times 10^{-4}$; 2: $p = 0.0161$; 3: $p = 4.607 \times 10^{-5}$; 4: $p = 4.399 \times 10^{-5}$; 5: $p = 0.0016$; 6: $p = 0.0012$.

Table 5. SpO_2 at different ambient oxygen levels with an additional workload of 80 W without and with 2 resp. 6 liters supplemental oxygen

Condition	Mean SpO_2	SD	Range
15.5%	91.5	3.3	87–97
15.5% + 2 l/min O_2	93.5[1]	1.8	90–96
15.5% + 6 l/min O_2	91.2[2]	19.5	96–97
13.5%	88.0	6.3	74–97
13.5% + 2 l/min O_2	87.3[3]	3.5	80–92
13.5% + 6 l/min O_2	92.8[4]	2.5	88–96
11.0%	72.3	5.1	64–83
11.0% + 2 l/min O_2	76.8[5]	5.5	69–87
11.0% + 6 l/min O_2	84.6[6]	7.2	72–94

Significance levels 2 l/min vs. 0 l/min and 6 l/min vs 2 l/min: 1: $p = 0.0332$; 2: $p = 5.357 \times 10^{-4}$; 3: $p = 0.282$; 4: $p = 2.796 \times 10^{-6}$; 5: $p = 0.167$; 6: $p = 0.354 \times 10^{-4}$.

In the field, the workload is slightly higher than in the study because workers must carry their oxygen tank, which is transported in a shoulder bag provided by the manufacturer. The total weight of the 2 L system at 200 bar is approximately 4.5 kg. Another additional weight may be caused by more clothing when the system is used at an extreme altitude. However, these factors should not put the user at risk.

Data from "real" altitude (hypobaric hypoxia) show a similar pattern to that from isobaric hypoxia. Two datasets were from studies conducted in the Solo Khumbu Valley (N = 350) and Gorak Shep (N = 44), both in the Mt. Everest region of Nepal. Another observational study was carried out at the Chajnantor Plateau telescope site (5,040–5,100 m / 16,540–17,730 ft / ~11% O_2) and at the construction site of the new Fred Young Telescope at the summit of Cerro Chajnantor (5,650 m / 18,540 ft / ~10.2% O_2). These data align well with the data from isobaric hypoxia, although the individuals from the Himalayas were acclimatized, whereas the Atacama group was not.

Some observations from the Submillimeter Telescope CCAT are noteworthy: During brisk walking at 5,640 m (18,540 ft), oxygen saturation remained stable at 88% with the oxygen demand system set to "5". When carrying very heavy loads at the same setting, saturation briefly dropped to 72%–74% but returned to the initial values within one minute after the load was removed. A similar observation was made at an altitude of 5,140 m (16,860 ft): without supplemental oxygen, saturation at rest was 80%. During walking, it fell to 77%, and during a 50-meter run, it dropped to 68%. Corresponding heart rates were 82, 84 and 120 bpm, respectively. Again, SpO_2 returned to 80% within 1–2 minutes after exercise cessation. With additional oxygen (setting at "5"), SpO_2 increased further to 84%. These data show that even significant physical exertion for a limited period reduces SpO_2, which recovers very quickly after the exertion, and that supplemental oxygen readily stabilizes SpO_2 under such conditions. All subjects felt well. It can be concluded that activity in such extent of hypoxia does not pose a risk to a person who has been advised on how to manage oxygen supply, according to the workload.

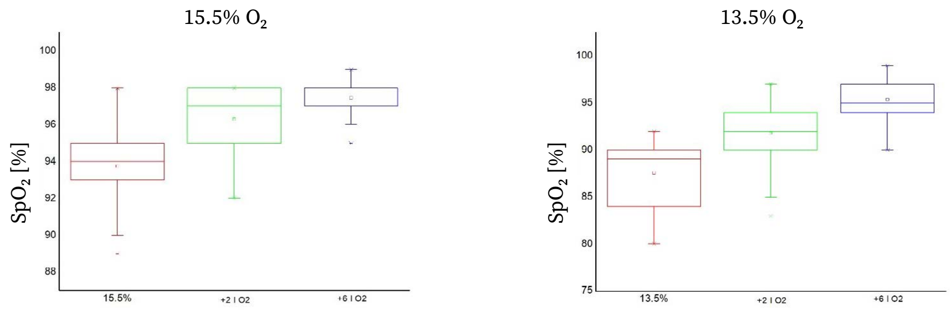
Discussion

The main finding of this study was that at ambient oxygen concentrations of 15% and higher, the decrease in blood oxygen levels (SpO_2) with decreasing oxygen concentration was not clinically relevant, even during modest workloads. At ambient oxygen levels of 13.5% or lower, supplemental oxygen was required in some individuals to maintain an acceptable blood oxygen level. A surprising result was that many individuals maintained a stable SpO_2 even at extreme altitude.

All studies, both those conducted in isobaric hypoxia and at extreme altitude, such as Cerro Chajnantor (5,650 m / 18,540 ft), report a decrease in SpO_2 with increasing altitude, despite some variability in the data. This finding aligns with over a century of research.[4,7] Additionally, a further decrease in SpO_2 is observed during physical exertion, a typical physiological response also seen at sea level with 20.9% oxygen.

The comparison between hypobaric and isobaric hypoxia revealed no significant differences. Savourey noted that up to about 5,500 meters (18,040 ft), or the equivalent isobaric oxygen concentration of approximately 10.4% O_2, the differences in SpO_2 and heart rate are minor and not clinically relevant.[14,15]

Interestingly, data on the effects of supplemental oxygen in hypoxic environments are scarce, despite numerous experiments in aviation and high-altitude medicine since the 1920s.[22] The few available studies report mean values that cannot be used for statistical comparison with the data of this study. Most studies focus on oxygen consumption and supply duration, given the contents of the pressurized cylinders. However, it is clear that supplemental oxygen can provide significant benefits in certain situations. The advantages must be weighed against the disadvantages of the oxygen systems, particularly their weight. The additional effort required to carry the system must not consume more oxygen than would be available without it. An impressive example comes from the 1922 British Everest Expedition: Between 7,000 m (22,965 ft, corresponding to ~8.5% O_2 in isobaric conditions



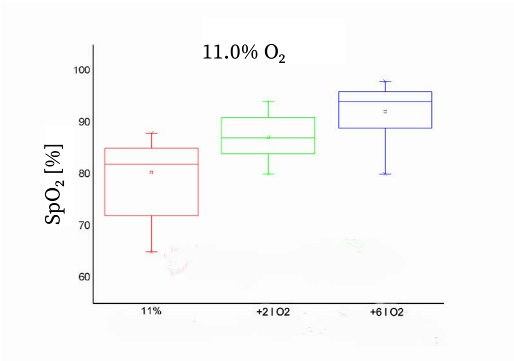


Figure 7. Oxygen saturation at rest without and with 2 l/min and 6 l/min supplemental oxygen. For significance see Table 4

at sea level) and 7,600 m (24,930 ft, ~8% O_2), Finch and Bruce climbed with supplemental oxygen while Mallory, Sommervell, and Norton did not. Finch and Bruce took 3.75 hours with an average ascent rate of 150 m/hour, while the others took 4.5 hours with an average ascent rate of 135 m/hour. Theoretically, Finch and Bruce would have climbed even faster, but the oxygen systems weighed 18.8 kg, thereby significantly slowing them.[23,24] This effect of additional load must be considered when discussing compensation for mild hypoxia. In mild hypoxia (13%–19% O_2), the additional load clearly exceeds the benefit of a slightly higher oxygen partial pressure.

The SCBA used in isobaric hypoxic conditions and at the Chajnantor construction site (5,650 m / 18,540 ft) was equipped with nasal cannulas connected to oxygen cylinders. The system was well tolerated by the study group and by workers during their routine jobs. The results confirmed that oxygen supplementation via nasal cannula maintains acceptable SpO_2, even under working conditions. However, to confirm the results of this pilot study, further research is necessary with a group size that provides adequate power.

Conclusion

Our results show that working in a reduced-oxygen environment at 15% oxygen is well tolerated, with no adverse physiological effects. At ambient oxygen levels of 13.5% or lower, supplemental oxygen may be required in some individuals to maintain an acceptable blood oxygen saturation.

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