Oxygen enrichment and its application to life support systems for workers in high-altitude areas

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Background: Workers coming from lowland regions are at risk of developing acute mountain sickness (AMS) when working in low oxygen high-altitude areas.

Objectives: The aim of this study was to improve the conditions that lead to hypoxia and ensure the safety of the high-altitude workers. We analyzed the influence of low atmospheric pressure on the oxygen enrichment process in high-altitude areas using an engineering method called low-pressure swing adsorption (LPSA).

Methods: Fourteen male subjects were screened and divided into three groups by type of oxygen supply system used: (1) oxygen cylinder group; (2) LPSA oxygen dispersal group; and (3) control group. These tests included arterial oxygen saturation (SaO₂), pulse rate (PR), breaths per minute (BPM), and blood pressure (BP).

Results: The results showed that after supplying oxygen using the LPSA method at the tunnel face, the SaO₂ of workers increased; the incidence of acute mountain sickness, PR, and BPM significantly decreased.

Conclusions: The LPSA life support system was found to be a simple, convenient, efficient, reliable, and applicable approach to ensure proper working conditions at construction sites in high-altitude areas.

Keywords: High altitude, Hypoxia, Low-pressure swing adsorption, Oxygen supply, Life support system, Acute mountain sickness

Introduction

Each year, workers from the lowland regions of China are at risk of developing acute mountain sickness (AMS) in high-altitude areas. The primary cause of AMS is atmospheric hypoxia, or a low oxygen level in the organs and tissues due to low partial pressure of oxygen (PAO₂) in air.^{1–3} Hypoxia is involved the major biological pathways that contribute to human pathogenesis of the cardiovascular system, the respiratory system, neurophysiology, oncology, transplantation, and infectious diseases.⁴ When the PAO₂ of air is less than 8 kPa (60 mmHg), the arterial oxygen content (CaO₂) and the arterial oxygen saturation (SaO₂) can significantly decrease and cause hypotonic hypoxemia (low arterial oxygen pressure, low saturation of hemoglobin by oxygen, and high hematocrit and hemoglobin concentrations).⁵ This most commonly occurs at high altitudes because both the atmospheric pressure and the PAO₂ of air decreases with increased elevation. Generally, hypoxemia occurs in humans at an altitude of 2000 m

or above. The PAO₂ of air at 4905 m is nearly half of air at sea level. At this high elevation, the PAO₂ may be as low as 6.7 kPa (50 mmHg).^{6,7} Without assistance, such as the use of oxygen cylinders, humans cannot survive for an extended period at altitudes above 5500 m.

The health hazards of an environment conducive to hypoxia in high-altitude workers include:^{8,9}

1. Elevation disease: high-altitude analogues to diseases such as pulmonary edema, cerebral edema, and heart disease. These are life-threatening diseases.
2. Elevation deterioration: the exhibition of mental deterioration because of hypoxia-induced injury, such as anorexia, physical decline, weight loss, hypomnesia, and somnopathy. Elevation deterioration can negatively affect attention span and cause accidents.
3. Work ability decline: medical research indicates that human work ability decreases 15% with elevation increases of 1000 m. A hypoxic environment not only affects health, but also influences the productivity and rate of work.

The harsh environmental conditions found at high altitudes, such as low temperature and lack of oxygen, are a challenge to occupational safety and production efficiency. However, improving the conditions that

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lead to hypoxia at high elevations is a challenge, especially in tunnels and mines. In China, the majority of the Qinghai–Tibet railway tunnels are in areas above 4000 m, and most high-altitude mines are between 3000 and 3500 m. Therefore, addressing the low-oxygen concentration in air is crucial for the development of tunnels and mines.^{10–13}

In addition, the technology for oxygen enrichment in high-altitude areas over 4000 m has rarely been researched. In the past, high-altitude workers were required to use oxygen cylinders, as was the case during the construction of the Qinghai–Tibet highway. However, there are several limitations to using oxygen cylinders. They are difficult to transport, expensive, and not very effective. Therefore, an alternative to oxygen cylinders is required for use in tunnel construction and mine excavation. One possible means of alleviating hypoxia in these high-altitude work areas is to increase the flow of oxygen in tunnels and/or mines.

The aim of this study was to improve the conditions that lead to hypoxia and ensure the safety of the high-altitude workers. We analyzed the influence of low atmospheric pressure on the oxygen enrichment process in high-altitude areas using an engineering method called low-pressure swing adsorption (LPSA). This is the first study of its kind to research the physiological effects of a life support system with oxygen supply for workers in high-altitude areas based on the LPSA. We hypothesized that the life support system with using LPSA would improve working conditions at high-altitude construction sites, thereby decreasing the likelihood of experiencing high-altitude related diseases.

Methods

Study on LPSA in high-altitude areas

To address hypoxia in high-altitude workers, we proposed a new cycle of LPSA. In high altitude areas, the environmental pressure is lower than one atmospheric pressure. Therefore, the desorption process of the cycle directly utilizes the low pressure in high-altitude areas instead of using a vacuum system to create low-pressure, which can save energy consumption and guarantee increased oxygen concentration and production efficiency when compared with Pressure Swing Absorption (PSA) and Vacuum Pressure Swing Absorption (VPSA).

The LPSA cycle involves relatively high-pressure adsorption, pressure equalization at the top and bottom of the adsorption column, and purge and desorption processes. The last step utilizes the low atmospheric pressure in high-altitude areas. First, the pressure of the feed air is enhanced to 0.2–0.4 MPa by the air compressor. Then, nitrogen is absorbed by the sorbent and after desorption at the local atmospheric

pressure (approximately 0.05 MPa), oxygen with over 90% concentration is obtained. In this cycle, an efficiency similar to VPSA is obtained without the use of a vacuum system.

A schematic diagram of the two-bed LPSA experimental system is shown in Fig. 1.¹⁴ The feed air is cleaned by passing through the dust and oil–water filters and is subsequently compressed. After the compressed air has been cooled, it enters the mass flow meter where air flux can be obtained. Valves A and B work alternately: the compressed air enters column 1 when valve A works; otherwise, it enters column 2. A fraction of the product oxygen purges one column from another column via valve E and the throttle valve, and the remaining fraction enters the oxygen container. The oxygen flux is controlled by a needle valve and measured by the flow meter, located after the needle valve, and the oxygen purity is measured using the oxygen analyzer. The desorbed gas is discharged alternatively from valves C and D and enters the atmosphere.

As a result of the low pressure in high-altitude areas, the displacement of the air compressor is reduced and the air content required in oxygen production is severely insufficient, reducing the oxygen concentration and production efficiency. Therefore, in order to ensure the stable and reliable operation of the oxygen supply system with LPSA, it is necessary to experimentally study the influence of plateau environment on the oxygen supply system.

The experimental system was integrated into an oxygen concentrating apparatus with dimensions of 400 × 300 × 650 mm and a weight of 30 kg. This apparatus is compact and light, facilitating easy movement for testing in multiple locations.

Using this experimental apparatus, oxygen concentration experiments were conducted in Beijing (76 m), Nachitai (3835 m), Xiushuihe (4546 m), and Fenghuoshan (4905 m). The product flux using the LPSA oxygen enrichment system with oxygen purity of 90% was obtained, the LPSA cycle parameters were determined, and the air compressor capacity for oxygen flow rates at different high-altitude areas was quantified.

Owing to the low pressure in high-altitude areas, the ratio of compressor output pressure to environmental pressure increases, causing the compressor's volumetric coefficient and air output to decrease. Therefore, in order to ensure the safe operation of compressor and oxygen production efficiency for the stable and reliable operation of the oxygen supply system with LPSA, it is necessary to experimentally study the influence of plateau environment on the oxygen supply system. The matching air content required in LPSA at different elevations was determined from the experimental data on the air

Figure 1 Schematic diagram of the LPSA experimental system.

compressor capacity for a certain oxygen flux rate at different high-altitude areas, as well as the relationship between oxygen concentration, oxygen production rate, and production efficiency for different heights above sea level.

Life support systems for workers in high-altitude areas

The primary working region for the workers in tunnels and mines is in the tunnel face. However, in high-altitude areas, the ventilation in the tunnel face is not sufficient. Furthermore, the oxygen concentration in the tunnel face is usually lower than the oxygen concentration outside the tunnel because of oxygen consumption from workers and equipment. To solve hypoxic problems and ensure worker safety, we designed a life safety system with an oxygen supply based on LPSA and the experimental data. The system utilizes two new methods for supplying

oxygen that directly integrates dispersed high-purity oxygen at the tunnel face and an oxygen cabin near the workplace to satisfy the oxygen requirements of tunnel workers.¹⁵

Oxygen dispersal system at the tunnel face

The oxygen dispersal system diffuses oxygen to the tunnel face to increase the oxygen concentration in the air around the tunnel face. It is composed of an oxygen pipeline, valves, and an oxygen-distributing apparatus. An illustration of the system is shown in Fig. 2. The oxygen-distributing apparatus includes two symmetrically installed oxygen distributors with flexible tubes. One side of the oxygen distributor consists of uniformly small holes where oxygen is ejected similar to an atomized jet. The small jets of oxygen from these tiny holes interfere with one other, which can form an oxygen curtain and contribute to a sectional oxygen-enriched area in order to provide

Figure 2 Schematic diagram of the oxygen dispersal supply system.

sufficient oxygen to workers. Moreover, the height of the oxygen-distributing apparatus and the distance between them can be adjusted to satisfy the requirements of varying high-altitude workplaces.

In order to verify the effectiveness of the LPSA oxygen dispersal system, we implemented it in the development of the Qinghai–Tibet railway engineering project. In addition, we performed a comparison of physiological responses of miners in the Western Mining’s lead-zinc mine at Xitieshan (3064 m) before and after the oxygen supply by the LPSA system. All the laboratory studies, including SaO_2 , pulse rate (PR), breaths per minute (BPM), and blood pressure (BP) were measured simultaneously.

Convenience sampling was used to select fourteen male mine workers in three tunnel faces for physiological study. All subjects were healthy with no history of sickness or hypoxemia, altitude fitted, and had been employed for more than 2 years in high-altitude areas. The workers were between the ages of 22 and 40 years. They were divided into three groups by type of oxygen supply system used: (1) the “oxygen cylinder group” was composed of six men who carried 2 L oxygen cylinders for their oxygen supply; (2) the “LPSA oxygen dispersal group” was

composed of five men who used the LPSA oxygen dispersal system for the oxygen supply; and (3) the “control group” was made of three men who did not use any oxygen supply.

Physiological parameters were measured after 1 hour of continuous work in the tunnel face without supplied oxygen and again after 1 hour of continuous work at the tunnel face for all three oxygen supply systems groups. Miners worked normally during measurement collection. Measurements were collected for 15 consecutive days.

Oxygen cabin for high-altitude areas

To satisfy the oxygen requirements of the resting workers in the tunnel, we propose an oxygen cabin with seats and branch oxygen pipes to concurrently serve several miners. Oxygen cabins consist of a compartment with light material and a moveable pedestal. This makes them easily moveable within the tunnel section, as shown in Fig. 3. Cabins are made of aluminum alloy and can be lifted or easily placed into a refuge hole.

The oxygen supply facilities (Fig. 4) transport the oxygen from oxygen stations to oxygen cabins and automatically control the oxygen pressure. They are configured in the oxygen cabin and consist of the

Figure 3 Sketch of the oxygen cabin.

Figure 4 Configuration of the oxygen supply facilities in the oxygen cabin.

Figure 5 Air content curves at different elevations.

main and branch oxygen pipes. The branch oxygen pipes are connected with valves and oxygen tube connectors. The oxygen flow rate can be regulated to satisfy the different requirements of the workers. It can also be used for other tunnel construction sections at high elevations.

Results

Influence of elevation on the matching air content

The relative air content, or the ratio of the air content required in LPSA in Beijing to that in different high-altitude areas, is shown in Fig. 5. Figure 5 also shows that matching air content increases with increases in elevation. Equation (1), determined using the regression analysis method, describes the quantitative relationship.

$$A = 0.99433 + 3.327 \times 10^{-4} \times \exp\left(\frac{H}{653}\right) \quad (1)$$

where A is the relative air content and H is the height above sea level.

Influence of elevation on the oxygen concentration and production rate

Experiments investigating the relationship between oxygen concentration and oxygen production rate were performed at the different occupational elevations. Experimental results from the four different altitude areas, Beijing (76 m), Nachitai (3835 m), Xiushuihe (4546 m), and Fenghuoshan (4905 m), are shown in Fig. 6. In the case of the same oxygen

Figure 6 The relationship between the oxygen concentration and the oxygen production rate at different elevations.

concentration, the oxygen production rate decreased with increasing elevation.

In the oxygen supply system with LPSA, the oxygen concentration decreases with oxygen production rate. This is because the processing capacity of adsorbent increases, but the adsorption capacity is the same, when the oxygen production rate increases. The oxygen concentration should be more than 90% in the oxygen supply system with LPSA, making it necessary to control the appropriate oxygen production rate.

Influence of elevation on the oxygen production efficiency

The oxygen production efficiency (η) is defined as the ratio of oxygen production measured in high-altitude areas to oxygen production in Beijing, under the condition that the oxygen production concentration is 90%. Using the experimental data in Fig. 6, the oxygen production rates at different elevations were determined (Table 1). Equation (2), determined using regression analysis, describes the quantitative relationship between the oxygen production efficiency and the height above sea level.

$$\eta = 9.93 \times 10^{-1} + 1.424 \times 10^{-4} \times H - 4.34 \times 10^{-8} H^2 \quad (2)$$

Using equation (2), the oxygen production efficiency curves at different elevations were determined (Fig. 7). As elevation increases, there is lower oxygen

Table 1 Oxygen production rate by elevation

Area	Elevation (m)	Oxygen production rate (l/min)	PAO ₂ (mmHg)	Oxygen volume concentration in air (%)	Operation temperature (°C)	Relative humidity (%)
Beijing	76	3.25	158.02	20.79	10	59
Nachitai	3835	3	113.20	14.81	-2	63
Xiushuihe	4546	2.25	104.67	13.68	-5	78
Fenghuoshan	4905	2.1	100.36	13.10	-15	76

Note: All the data were measured when oxygen production concentration was 90%.

Figure 7 Oxygen production efficiency curves at different elevations.

production efficiency. When the elevation is greater than 3500 m, oxygen production efficiency decreases by 25% with each elevation increase of 1000 m. For example, the oxygen production efficiency (η) is only 60% in Fenghuoshan (4905 m).

Application of the oxygen dispersal system at the Qinghai–Tibet railroad

The implementation of the oxygen dispersal system at the Qinghai–Tibet railroad is described as below.

The oxygen dispersal system has the potential to improve the labor efficiency and accelerate construction progress. When the oxygen dispersal system was used in Fenghuoshan tunnel construction, the PAO_2 was approximately 13.1–14.0 kPa in the tunnel and an additional 2–3 kPa outside the tunnel. After using the oxygen dispersal system, the tunneling advance rate was 5–8 m/day compared to 2–3 m/day before use of the system, suggesting an increase in the working efficiency.

The oxygen dispersal system may increase the safety of workers. The incidence of AMS decreased significantly from 2.40% (24/1000) to 0.24% (10/4189) after

using the oxygen dispersal system in the Fenghuoshan tunnel, and the number of outpatients decreased from 59 persons/day to 33 persons/day ($P < 0.05$).

Results show that the incidence of AMS decreased significantly, blood oxygen saturation increased, and there was improved sleeping quantity. No deaths have occurred in the Fenghuoshan tunnel since construction began in 2001.

Application effect of the oxygen dispersal system at Western Mining's lead–zinc mine in Xitianshan

We tested the physiological parameters of workers on Western Mining's lead–zinc mine in Xitianshan. Physiological parameters for the three groups are provided in Table 2.

Although 14 subjects worked continuously with supplied oxygen for 1 hour, the SaO_2 measured after using oxygen supply was 3%–6% higher compared to before using the oxygen supply. Table 2 shows that PR and BPM both decreased by more than 10%. We found that oxygen supply can decrease the miners PR remarkably, helping to alleviate the heart burden caused by manual work. The oxygen supply also can increase the oxygen quantity at every breath, which can compensate the oxygen consumption caused by manual work and decrease the BPM.

Oxygen supply was significant for elevated SaO_2 when proceeding the manual intensive work, however, the SaO_2 of miners who did not take oxygen supply decreased markedly due to the high altitude and manual work. As a result of the high intensity physical labor, the SaO_2 in the “control group” decreased about 3.5%, and their PR and BPM both increased more than 10%. For all three groups of miners, a short period of oxygen supply would not cause a significant impact to BP.

Conclusions

In high-altitude areas, the environmental pressure is less than one atmospheric pressure, which prevents

Table 2 Physiological parameters of workers in Western Mining's lead–zinc mine in Xitianshan

Groups	Physiological parameters	Before	After	Degree
Oxygen cylinder group	SaO_2 (%)	89.52	94.79	5.89%
	PR (min)	88.44	82.13	–7.13%
	BPM	24.90	21.81	–12.43%
	BP (mmHg)			
	Systolic pressure	115.10	113.37	–1.28%
LPSA oxygen dispersal group	Diastolic pressure	80.06	79.90	0.23%
	Differential pressure	35.04	33.46	–1.84%
	SaO_2 (%)	90.44	93.51	3.40%
	PR (min)	97.28	83.15	–14.52%
	BPM	21.72	19.26	–11.33%
	BP (mmHg)			
	Systolic pressure	97.82	97.85	0.30%
Control group	Diastolic pressure	58.36	62.54	9.46%
	Differential pressure	39.46	35.31	–6.47%
	SaO_2 (%)	93.52	90.24	–3.51%
	PR (min)	86.36	95.8	10.93%
	BPM	17.8	20.28	13.93%
	BP (mmHg)			
	Systolic pressure	110.91	108.83	–1.50%
	Diastolic pressure	77.70	76.30	–1.01%
	Differential pressure	33.22	32.52	–1.13%

conventional oxygen supply systems, such as the PSA, from being effective. The LPSA oxygen enrichment method described in this study utilizes the low pressure of high-altitude areas, instead of using a vacuum system, to create low-pressure during the desorption process. This method decreases energy consumption and increases the concentration and efficiency of oxygen production.

Owing to the low pressure in high-altitude areas, the compressor's volumetric coefficient reduces, leading to the reduction of the oxygen concentration and production efficiency. Therefore, in order to ensure the stable and reliable operation of the oxygen supply system with LPSA, it is necessary to experimentally study the influence of plateau environment on the oxygen supply system. This paper presents preliminary data using the LPSA system, including the relationship between oxygen concentration and oxygen production rate and the corresponding air content curves for different heights above sea level. These data provide information for the application of an oxygen enrichment system in high-altitude areas.

Two oxygen supplying life support systems for workers in high-altitude areas were proposed: an oxygen dispersal system at the tunnel face and an oxygen cabin. The oxygen dispersal system directly integrates dispersed high-purity oxygen at the workplace with a system of oxygen supply near the tunnel section to satisfy the oxygen requirements of the workers in the tunnel. The method was successfully used in the development of the Qinghai–Tibet railway engineering project. Results indicated that the PAO_2 of the tunnel section was enhanced by 2–3 kPa, and the lack of oxygen in the tunnel construction site was efficiently solved.

We also performed an experimental study on the application of the oxygen dispersal system at Western Mining's lead–zinc mine in Xitieshan. Through the test of oxygen supply in plateau mines, we concluded that the LPSA oxygen dispersal system for miners working in high-altitude tunnels can elevate miners' SAO_2 , decrease their PR and BPM, and improve safety and work efficiency. This suggests that this method of oxygen dispersal should be further implemented during mineral resource exploration in plateau areas.

As shown in Table 2, the increase of SAO_2 in the “oxygen cylinder group” was larger than in the “LPSA oxygen dispersal group.” However, in the production process, working while carrying an oxygen cylinder was not convenient, affecting the workers' labor to some extent. The LPSA oxygen dispersal system is beneficial because it decreases the risk of plateau hypoxia, while meeting the oxygen demand of workers with high-intensity physical labor without affecting the normal work. Therefore we conclude that LPSA oxygen dispersal system is a better oxygen supply

option compared to the oxygen cylinder for high-altitude workers performing intensive work.

Although we introduced the oxygen enrichment technology and its application to life support systems for workers in high-altitude areas, the oxygen supply technology based on LPSA may also be appropriate for the people living, working, and traveling in high-altitude areas. The proposed life support systems with oxygen supply were introduced to verify the feasibility of LPSA applied to workers in high-altitude areas. When used in different high-altitude settings, including apartments, hotels, bars automobiles, and/or hospitals, the dimensions and constructions of these oxygen supply systems should be adjusted according to the local environment (temperature, pressure, PAO_2 , etc.).

While this mechanism of oxygen supply has been gradually adopted in parts of China, its continued promotion will require additional policy support and financial assistance from the Chinese government. Meanwhile, as a result of the difficult and varying climate in high-altitude areas and differences in the meteorological environments, it is difficult to improve, adjust, and implement this technology in different high-altitude areas.

Even so, the life support system using oxygen supplied by LPSA was demonstrated to be a simple, convenient, efficient, reliable, and applicable approach to ensure proper working conditions at construction sites in high-altitude areas. Therefore, this technology warrants further research and active promotion.

The results from this research can provide a basis for the promotion and application of the life support systems with oxygen supply based on LPSA for mineral resources exploration in plateau areas.

Disclaimer statements

Contributors The list of authors includes all those who can legitimately claim authorship. The list of authors played by all contributors as follows: (1) have made a substantial contribution to the concept and design, acquisition of data, or analysis and interpretation of data; (2) drafted the article or revised it critically for important intellectual content; and (3) approved the version to be published.

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