Minimum oxygen concentration in breathing gas: Effects of altitude

Dan Warkander[1,2,*], Richard Arnold[1], Alberto Spasciani[3]

1. Naval Medical Research Unit Dayton, Dayton, OH, USA,
2. Leidos, Reston, VA, USA,
3. Spasciani Spa, Origgio, Italy.

* Corresponding author email: dan.warkander.1.ctr@us.af.mil, dwarkand@buffalo.edu

ABSTRACT

Background. Oxygen is essential for life and a minimum safe level shall be determined before using air purifying respiratory protective devices. However, no consensus among regulatory standards exists on what is a safe low limit of oxygen concentration (O_2%) – the values range from 17% to 19.5%. A person's fundamental need is the partial pressure of oxygen, not the O_2%. The partial pressure of O_2 is proportional to the number of molecules of O_2 in the air. Since the barometric pressure decreases with altitude, the number of O_2 molecules in a breath of air also decreases. Therefore, it makes little sense to express a safe low limit as a concentration, unless the altitude of use is specified. For instance, if an altitude of 2,400 m (8,000 feet) is considered safe when breathing air, the equivalent partial pressure of O_2% would be provided at sea level from a gas containing 15.3% O_2.
Objective. To highlight the different levels of O_2% or altitude that are considered safe in various situations and provide means to determine how the necessary O_2% level changes with altitude.
Methods. The alveolar gas equation was used to determine the equivalence between O_2% and altitude for a given partial pressure of O_2.
Results. The equivalences between O_2% and altitude are shown in graphs for easy interpretation. For instance, if it is deemed acceptable to breathe air at 2,400 m, then the equivalent O_2% is 19.3% at 1,800 m or 17.3% at 1,000 m. Breathing gas containing 23.5% O_2 at an altitude of 3,300 m is equivalent to breathing air at 2,400 m.
Conclusion. The step-by-step approach described will allow a Safety Officer or user of respiratory protective devices to determine equivalent O_2% based upon a generally accepted safe condition from a known altitude.

Keywords: partial pressure of oxygen, partial pressure of carbon dioxide, O_2, CO_2, hypoxia, hyperoxia, alveolar gases.

INTRODUCTION

Providing safe levels of oxygen in breathing gas is essential. However, there are no universally agreed-upon absolute limits. With low O_2 concentrations (O_2%) there is the risk of hypoxia and with high concentrations there is an increased risk of fire.

Low oxygen environments are used in industrial and commercial applications because they can mitigate a process hazard. For example, using a low O_2% in entire buildings can reduce the risk of fire. It can also increase the ability to store fruits and vegetables for extended times. Inert gas is used in fuel handling and transportation industries to reduce fire potential. Low levels of O_2 can also be found in confined spaces, where oxidation processes may have used up much of this gas. Environments with low O_2% can be experienced by workers and a universal approach for determining safe levels of O_2 should be found.

It is not the O_2%, but the partial pressure of oxygen that determines how much oxygen might bind to the hemoglobin. The partial pressure of O_2 is proportional to the number of molecules of O_2 in the air. Since the barometric pressure decreases with altitude, the number of O_2 molecules in a breath of air also decreases while the O_2% remains unchanged. Since the partial pressure is the product of concentration and ambient pressure, an equivalent reduction in partial pressure can be achieved by a reduced ambient pressure (i.e., increased altitude), a reduced O_2% or both.

When deciding which type of respiratory protective device (RPD) should be used in a specific environment, the first consideration is the level of oxygen in the atmosphere. In an occupational environment it is for the Safety Officer, or equivalent, to determine if the oxygen level is sufficient. If it is, then an air purifying device will suffice (provided that all other parameters such as contaminant nature and concentration allow), otherwise an isolating RPD has to be used. Actually, it is not obvious what a safe, low limit of oxygen level is, expressed as a percentage. However, an equivalent measure that people can more easily relate to is altitude.

Many daily events involve exposures to altitudes. The following examples serve to show how widely they vary. Some people experience long-term exposures at very high altitudes, e.g., La Paz, Bolivia, a city with 800,000 inhabitants, is situated at over 3,600 m (12,000 ft[‡]). Some people experience short-lasting exposures such as in downhill skiing and crossing mountain passes. In Europe, the roads over the Stelvio Pass (Italy), the Ötztal Glacier (Austria) and Col de L'Iserau (France) are at about 2,800 m (9,300 ft) with bicyclists using the roads, for leisure or races (e.g. Giro d'Italia, Tour de France). When driving on the U.S. Interstate 70 westbound from Denver, Colorado the 2-hour drive between Mount Vernon and Gypsum (each at about 6,400 ft, 1,900 m[‡]) reaches the Eisenhower tunnel at 11,100 ft (3,400 m). Many areas of downhill skiing reach similar or higher altitudes. In the Alps, such areas are as high as 3,200 to 3,900 m (10,500 to 12,800 ft) and in the Rocky Mountains they can be at over 13,000 ft (over 4,000 m). Many people climb Mount Everest (8,800 m, 29,000 ft), some even without supplemental oxygen.

In civilian aviation, the cabin altitude (i.e., the pressure equivalent altitude) of commercial airliners must not exceed 8,000 ft (2,400 m) (U.S. CFR 14, paragraph 25.841(a)). In the U.S., the Federal Aviation Regulations (paragraph 91.211) allow a pilot to operate a U.S. registered aircraft with a cabin altitude up to 12,500 ft (3,800m) without supplemental oxygen. Per 14 CFR 135.89, aircraft for commercial aviation must provide supplemental oxygen after 30 minutes for flights with cabin altitudes between 10,000 ft and 12,000 ft (3,000 m to 3,600 m) and always for cabin altitudes above 12,000 ft (3,600 m). The U.S. Navy Flight Manual (1991) states (Table 1-10) that during daytime flights supplemental oxygen is required for flights over 10,000 ft (3,000 m). It further states that at this altitude the hemoglobin is still 90% saturated, but that the hemoglobin saturation curve drops steeply with increasing altitudes. Oxygen equipment and barometric controls are designed to maintain the user at this physiological equivalent altitude or below. However, to avoid a reduction of night vision during nighttime flights, supplemental oxygen is recommended for flights over 5,000 ft (1,500 m).

The German government agency DGUV in its document 112-190 states (Table 3) that most air purifying respirators can be used with O_2% down to 17%. The Medical Commission of Union Internationale des Associations d'Alpinisme has a consensus statement (Küpper, 2011) that "for healthy unacclimatized persons, an acute but limited exposure down to 13% O_2 does not cause a health risk" (equivalent to 3,600 m, 12,000 ft). Gustavsson et al. (1997) concluded that oxygen levels down to 14 kPa (14% at sea level) appeared not to impair visual and motor control during rest.

In contrast, the U.S. Occupational Safety and Health Agency (OSHA) states (U.S. 29 CFR 1910.134(c), Respiratory Protection) that an atmosphere containing less than 19.5% oxygen is oxygen deficient. The U.S. respirator certifying institution NIOSH defines in 42 CFR 84 (Approval of Respiratory Protective Devices) "oxygen-deficient atmosphere" more physiologically correctly as "an atmosphere which contains an oxygen partial pressure of less than 148 millimeters of mercury (19.5 percent by volume at sea level)". However, in paragraphs 84.79 and 84.141 this is simplified to "contain no less than 19.5 volume-percent of

[‡] The conversions between feet and meters in the Introduction are deliberately rounded to provide a general overview and to avoid being distracting.

oxygen". Interestingly, by NIOSH's partial pressure definition, any altitude higher than 570 m (1900 ft) would be considered oxygen deficient. Table II in OHSA's document states that oxygen concentrations can be less than 19.5% without being oxygen deficient. The minimum concentration can be allowed to vary with altitude. For instance, at 3,000 ft (900 m) the concentration can be as low as 16.4%, but at 7,000 ft (2,100 m) it can only be 19.3%.

From the descriptions above there are obviously many interpretations and opinions on which values of O_2% are acceptable.

By definition, breathing low concentrations of oxygen can induce hypoxia (low oxygen availability in the body). Detailed descriptions of hypoxia can be found in textbooks on altitude physiology and mountaineering, but might include headaches, lethargy, nausea, night vision changes, anger, euphoria, reduced work capacity and loss of judgement. Hyperventilation can be part of the body's normal response to hypoxia. Different people react differently to altitude exposure.

Elevated oxygen partial pressures can lead to pulmonary oxygen toxicity; a partial pressure of 0.55 atm is safe for several days, but 0.75 atm can cause damage in less than 24 hours (Shykoff and Lee, 2018).

As stated above, from a physiological point of view, it is the partial pressure of oxygen that is of importance, not the concentration of oxygen. It follows, that, to maintain a certain partial pressure of oxygen, the O_2% has to change with altitude. The alveolar gas equation (Fenn *et al.*, 1946) can be used for calculations that express what O_2% gives an equivalent oxygen partial pressure at a desired altitude.

The purpose of this text is not to specify what an acceptable altitude or O_2% is, but to show what the equivalent O_2% are once a maximum altitude has been decided upon for a particular purpose. A risk-benefit analysis can be used to determine such a maximum altitude using several factors: previous experiences in daily life, the expected activity or workload, the intended altitude, the duration of the exposure and the current level of altitude acclimatization.

An equivalent O_2% can then be calculated for different altitudes and be used by a Safety Officer to determine if the O_2% is acceptable, for instance using properly calibrated hand-held oxygen meters. Also, oxygen enriched air (air with an increased O_2%) can be used to raise the partial pressure of O_2 and, physiologically, put a person at a lower altitude.

METHODS

Useful equations

What matters is the oxygen partial pressure <u>in the lungs</u> where the gas exchange takes place. By the time inhaled gas has reached the alveoli, it has been diluted by water vapor and carbon dioxide. The influence of water vapor and carbon dioxide increases with increasing altitude, therefore, this has to be accounted for. Alveolar gas pressures can be calculated by the alveolar gas equation (Fenn, Rahn and Otis, 1946):

$$P_AO_2 = (P_B - P_{H_2O}) \cdot F_IO_2 - P_ACO_2 \cdot (F_IO_2 + \frac{1-F_IO_2}{R}) \quad (1)$$

where the values in parentheses are used in the calculations that follow:

- P_AO_2 = alveolar oxygen partial pressure (normoxia, 100 mm Hg, 13.3 kPa),
- P_B = ambient barometric pressure,
- F_IO_2= inspired oxygen fraction (0.2095),
- P_ACO_2= alveolar carbon dioxide partial pressure (normocapnia, 40 mm Hg, 5.3 kPa,
- R = respiratory exchange ratio (ratio of flow of carbon dioxide and flow of oxygen, 0.83 as used in ISO 17420-4) and
- P_{H_2O} = water vapor pressure at body temperature (47 mm Hg, 6.3 kPa).

To determine the inspired O_2%, equation (1) can also be rewritten as:

$$F_I O_2 = \frac{P_A\, O_2 \times R + P_A CO_2}{R \times \left(P_B - P_{H_2O} - P_A CO_2\right) + P_A CO_2} \tag{2}$$

The barometric pressure needed for a certain combination of these parameters can be calculated from:

$$P_B = \frac{P_A O_2 + P_A CO_2 \cdot (F_I O_2 + \frac{1 - F_I O_2}{R})}{F_I O_2} + P_{H_2O} \tag{3}$$

The atmospheric pressure varies with altitude (U.S Standard Atmosphere, 1976) and can be calculated as:

$$P_B = (1 - A \cdot 2.2558 \cdot 10^{-5})^{5.255963} \tag{4}$$

where A is the altitude in meters and P_B is in atmospheres. Conversely, the altitude can be calculated from the barometric pressure as:

$$A = 44330.77 \cdot (1 - P_B^{0.19026}), \tag{5}$$

Using the equations

The partial pressure equivalent O_2% can be calculated in steps:

1) Determine an altitude of interest.
2) Use equation 4 to calculate the standard barometric pressure.
3) Use equation 1 to calculate the resulting P_AO_2.
4) Use equation 2 to calculate the equivalent O_2% in ambient gas.

By keeping the P_AO_2 constant, but varying the desired altitude, the equivalent altitudes can be determined (equations (4) and (1)). The equivalent altitude for a fixed P_AO_2 and a fixed O_2% can be calculated using equations (3) and (5).

RESULTS

The P_AO_2 equivalent altitude when breathing air is shown in Figure 1. It also includes altitudes of some cities and approximate altitudes of areas of downhill skiing in the Alps and in the Rocky Mountains. For instance, it shows that breathing air in Denver is equivalent to breathing about 17% O_2 at sea level. Being in La Paz or skiing in the upper available areas is equivalent to breathing 13% O_2 or less at sea level. Conversely, breathing 19.5% O_2 at sea level is equivalent to breathing air at an altitude of 570 m (1900 ft).

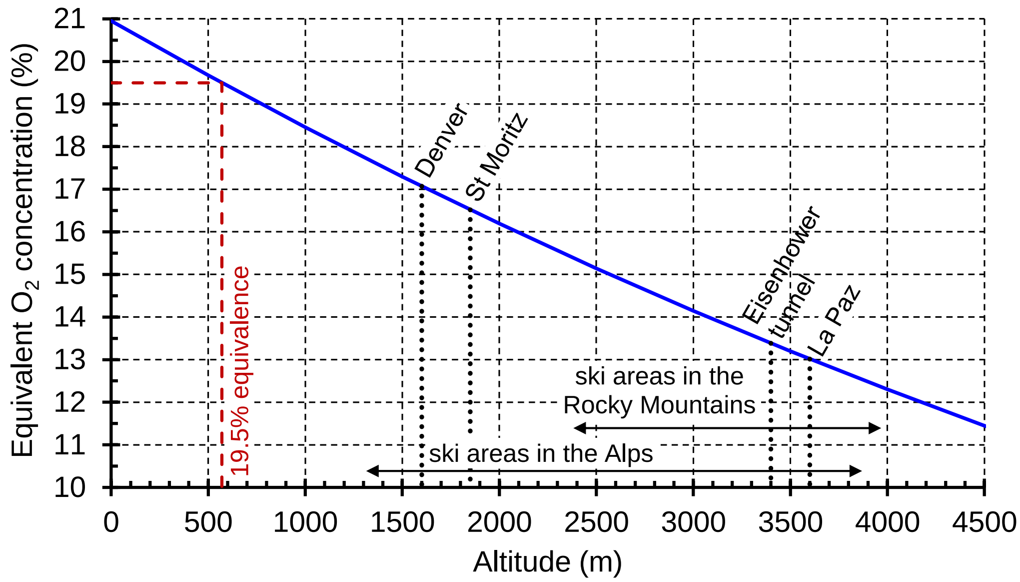

Figure 1. P_AO_2 equivalences between O_2 concentrations and altitudes. Included are locations of some cities and approximate altitudes of areas of downhill skiing in the Alps and in the Rocky Mountains. Also shown is the altitude equivalent to breathing 19.5% O_2 at sea level.

Equivalent O_2%

The partial pressure equivalent O_2% was calculated following the steps above and was used to generate the lines in Figure 2 (meters) and Figure 3 (feet). As an example, at an altitude of 2,000 m the P_B is 0.785 atm abs. (equation (4)). At this , and with the values listed above, the P_AO_2 would be 9.1 kPa (69 mm Hg), per equation (1). The line labelled 2000 m was then determined.

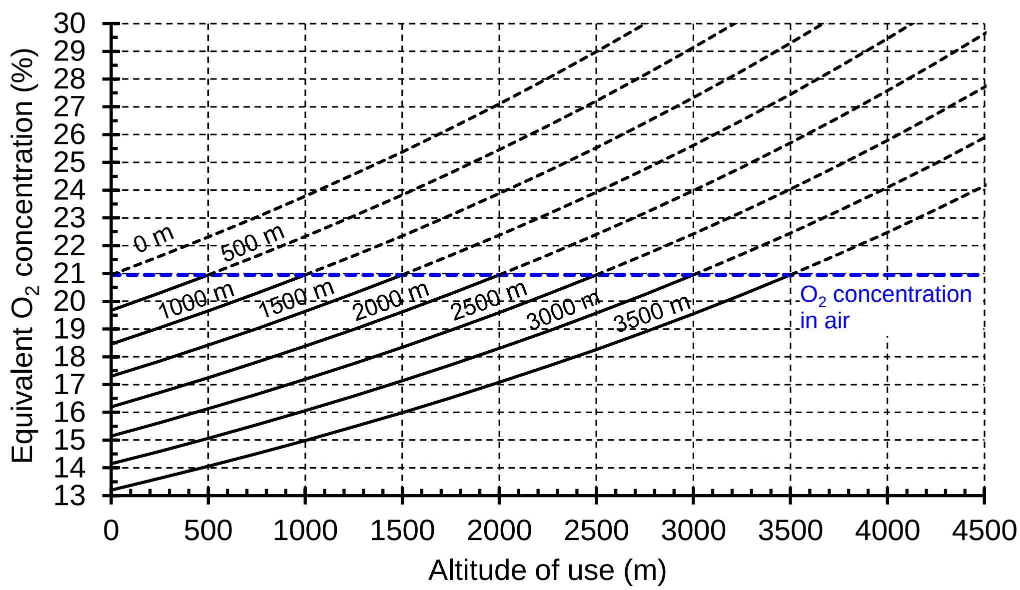

Figure 2. P_AO_2 equivalences between O_2% and different altitudes (expressed in meters). For instance, breathing 15% O_2 while being at 500 m is equivalent to breathing air at 3000 m; breathing 29% O_2 at 2500 m is equivalent to breathing air at sea level. Interrupted lines are drawn in areas where the O_2% exceeds that in air.

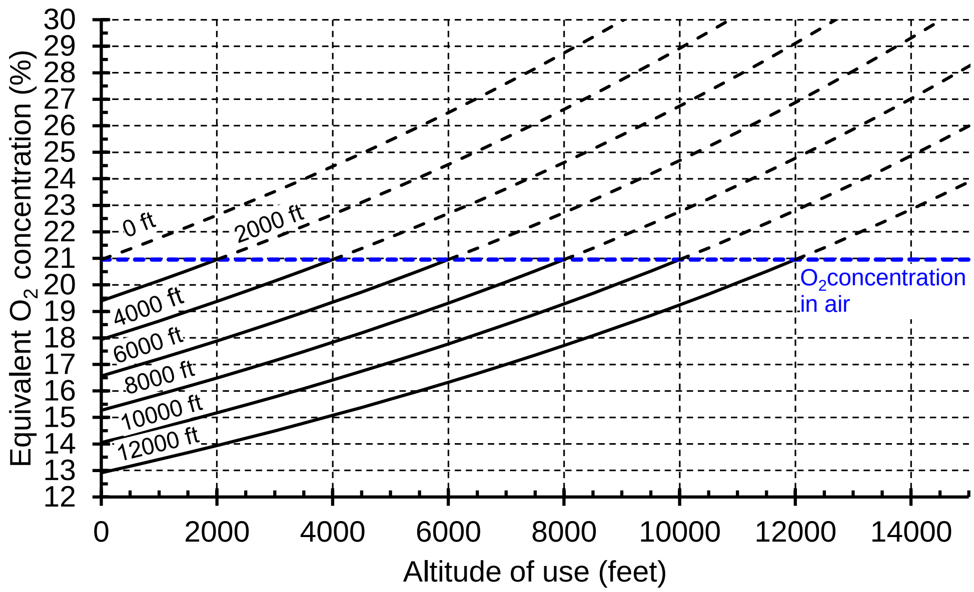

Figure 3. P_AO_2 equivalences between O_2% at different altitudes (expressed in feet). For instance, breathing 15% O_2 while being at 4000 ft is equivalent to breathing air at 12000 ft and breathing 29% O_2 at 10000 ft is equivalent to breathing air at 2000 ft. Interrupted lines are drawn in areas where the O_2% exceeds that in air.

DISCUSSION

To decide on what an acceptable altitude or O_2% might be for a certain group of people planning on a certain activity or workload, there are several factors to consider. Some include the intended altitude, the duration of the exposure and the current level of altitude acclimatization (Küpper et al., 2011) and, possibly, their physical fitness or motivation. The process could be thought of as a risk-benefit analysis.

Equivalent O_2 concentrations

As stated, a partial pressure of O_2 can be reached with a combination of O_2% and altitude. The information shown in Figure 2 can be interpreted with an example. Assume that an altitude of 2,000 m is to be used. The line for this altitude crosses the line for O_2% in air at 2,000 m. The line shows that at 1,000 m the equivalent O_2% is 18.4% and at sea level it is 16.2%. These partial pressure equivalent O_2 concentrations would be the minimum concentrations at these altitudes. A similar example can be given for an altitude of 8,000 ft. The corresponding line in Figure 3 shows that at 4,000 ft the equivalent O_2% is 17.8% and at sea level it is 15.3%.

A further example involves the values in OSHA's U.S. 29 CFR Part 1910 subpart I, Table II discussed in the Introduction. Figure 3 shows that if air breathing is considered acceptable at 9,000 ft, then it is actually acceptable to breathe 14.7% oxygen at sea level. This altitude seems to be the basis for the values presented in OSHA's U.S. 29 CFR Part 1910 subpart I, Table II. Figure 1 shows that 19.5% O_2 at sea level is equivalent to air breathing at 570 m. Obviously, being at altitudes above 570 m is not limiting. The values in OSHA's Table II represent more realistic ranges and should be emphasized.

In addition, if air breathing at 12,000 ft (3,600 m) is acceptable while downhill skiing or living in La Paz, then that would mean that the same people could breathe 12.9% at sea level.

Mixing altitudes and O_2 concentrations

The calculations for equivalent altitudes show that, at sea level, an O_2% of 17% is equivalent to air breathing at about 1,600 m (Figure 2). Figure 2 can also show that if this gas is instead breathed at 1000 m, then this combination would be equivalent to breathing air at about 2600 m and the use of it at 2,000 m would be equivalent to about 3,500 m. Similarly, Figure 3 shows that an O_2% of 17% at sea level is equivalent to about 5,400 ft and that use of it at 6,000 ft is equivalent to air breathing at 11,000 ft.

Use of oxygen enriched air

It is not uncommon to use oxygen enriched air. However, the enriched O_2% values that are considered safe vary by organizations. Some limit "air" to have less than 21% (DGUV, 2021) while others allow 23.5% oxygen (OSHA 29 CFR 1910.134, EIGA 2018). To reduce decompression times in diving, gas mixtures (sometimes called nitrox) can have up to 40% oxygen (NOAA, 2016). In military aviation, normoxia is maintained by having the aircrew breathe altitude-adjusted O_2% up to 100% (MIL STD 3050A). OSHA states in a footnote to U.S. 29 CFR Part 1910 subpart I, Table II that "Oxygen-enriched breathing air must be supplied above 14,000 feet" (4,300 m).

Calculations can show the benefit of oxygen enriched air – the increased O_2% lowers the equivalent altitude from a physiological point of view. To illustrate this effect, Figure 2 shows that use of 23.5% oxygen at 3,300 m is equivalent to breathing air at 2,500 m. This means that, physiologically speaking, it is possible to gain 800 m in altitude by breathing oxygen enriched air. Breathing 30% O_2 at 2800 m is equivalent to air at sea level. If an altitude of 3000 m must be reached by people who shouldn't go higher than 2000 m, then they could achieve that if they breathed 24% O_2.

Whether the O_2 enrichment is accomplished by breathing a pre-mixed gas, through a flow of 100% O_2 delivered through a nasal cannula, or some other means, will depend on the situation.

Limitations of the calculations

The effect of any hypoxia-induced hyperventilation means that the alveolar carbon dioxide will decrease and the value for R will increase. This results in increased P_AO_2. The exact change will depend on the person. Instead of trying to estimate the changes, the values for alveolar carbon dioxide and R were kept constant and the calculations can be considered as conservative estimates.

CONCLUSIONS

There isn't just one O_2% that is acceptable. The acceptable O_2% will depend on the intended use (taking into account workload, duration, fitness, level of acclimatization). Once a maximum altitude for a given activity for a given group of people and activity has been decided upon, equivalent O_2% and altitudes can be calculated. The method and equations provided will allow the calculations of equivalent altitude and equivalent O_2% for any desired combination of O_2% and altitude. The outcome of such calculations is that more realistic minimum O_2% in breathing gas can be used.

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