

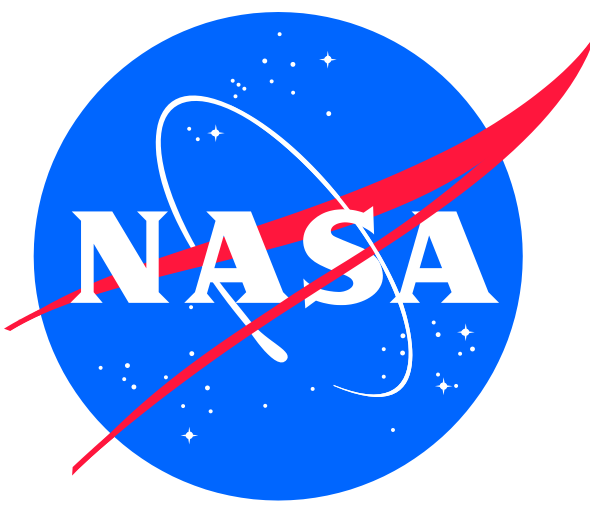
APPROXIMATE SIMULATION OF ACUTE HYPOBARIC HYPOXIA WITH NORMOBARIC HYPOXIA

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INTRODUCTION. Some manufacturers of reduced oxygen (O_2) breathing devices claim a comparable hypobaric hypoxia (HH) training experience by providing $F_{IO_2} < 0.209$ at or near sea level pressure to match the ambient O_2 partial pressure (iso- pO_2) of the target altitude. **METHODS.** Literature from investigators and manufacturers indicate that these devices may not properly account for the 47 mmHg of water vapor partial pressure that reduces the inspired partial pressure of O_2 (P_{IO_2}). Nor do they account for the complex reality of alveolar gas composition as defined by the Alveolar Gas Equation. In essence, by providing iso- pO_2 conditions for normobaric hypoxia (NH) as for HH exposures the devices ignore P_{AO_2} and P_{ACO_2} as more direct agents to induce signs and symptoms of hypoxia during acute training exposures. **RESULTS.** There is not a sufficient integrated physiological understanding of the determinants of P_{AO_2} and P_{ACO_2} under acute NH and HH given the same hypoxic pO_2 to claim a device that provides isohypoxia. Isohypoxia is defined as the same distribution of hypoxia signs and symptoms under any circumstances of equivalent hypoxic dose, and hypoxic pO_2 is an incomplete hypoxic dose. Some devices that claim an equivalent HH experience under NH conditions significantly overestimate the HH condition, especially when simulating altitudes above 10,000 feet (3,048 m). **CONCLUSIONS.** At best, the claim should be that the devices provide an *approximate* HH experience since they only duplicate the ambient pO_2 at sea level as at altitude (iso- pO_2 machines). An approach to reduce the overestimation is to at least provide machines that create the same P_{IO_2} (iso- P_{IO_2} machines) conditions at sea level as at the target altitude, a simple software upgrade.

Learning Objectives:

1. Applying basic principles of respiratory physiology to the design of reduced oxygen breathing devices.
2. Working toward a better understanding of hypoxia.



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ABSTRACT

INTRODUCTION. Some manufacturers of reduced oxygen (O₂) breathing devices claim a comparable hypobaric hypoxia (HH) training experience by providing F_IO₂ < 0.209 at or near sea level pressure to match the ambient O₂ partial pressure (iso-pO₂) of the target altitude. METHODS. Literature from investigators and manufacturers indicate that these devices may not properly account for the 47 mmHg of water vapor partial pressure that reduces the inspired partial pressure of O₂ (P_IO₂). Nor do they account for the complex reality of alveolar gas composition as defined by the Alveolar Gas Equation. In essence, by providing iso-pO₂ conditions for normobaric hypoxia (NH) as for HH exposures the devices ignore P_AO₂ and P_ACO₂ as more direct agents to induce signs and symptoms of hypoxia during acute training exposures. RESULTS. There is not a sufficient integrated physiological understanding of the determinants of P_AO₂ and P_ACO₂ under acute NH and HH given the same hypoxic pO₂ to claim a device that provides isohypoxia. Isohypoxia is defined as the same distribution of hypoxia signs and symptoms under any circumstances of equivalent hypoxic dose, and hypoxic pO₂ is an incomplete hypoxic dose. Some devices that claim an equivalent HH experience under NH conditions significantly overestimate the HH condition, especially when simulating altitudes above 10,000 feet (3,048 m). CONCLUSIONS. At best, the claim should be that the devices provide an *approximate* HH experience since they only duplicate the ambient pO₂ at sea level as at altitude (iso-pO₂ machines). An approach to reduce the overestimation is to at least provide machines that create the same P_IO₂ (iso-P_IO₂ machines) conditions at sea level as at the target altitude, a simple software upgrade.

INTRODUCTION

Reduced O₂ breathing devices create a normobaric hypoxic (NH) exposure by providing an F_IO₂ < 0.209, breathed either through a mask or within a "hypoxia tent".

The **Some** manufacturers claim an equivalent acute hypobaric hypoxic (HH) experience but under NH conditions. This eliminates the need for an expensive hypobaric chamber and the risk of decompression sickness associated with hypobaric exposure, **creating** ~~–~~So a cost-effective hypoxia training niche-is ~~created with these devices, if they~~ **these devices** deliver ~~what they~~ **as promised**.

METHODS

We ~~reviewed~~ Literature **was reviewed** to understand the operations of three reduced O₂ breathing devices: ROBD® (1), PROTE® (8), and GO₂Altitude® (http://www.hypoxic-training.com).

The devices seem to duplicate the ambient partial pressure of O₂ (iso-pO₂) at sea level as exists at the target altitude, ~~or something else besides P_IO₂ (7).~~

The method to convert feet altitude to ambient pressure was never specified, a necessary detail to understand the operation of these devices. ~~But~~ **Th**rough analysis, it appears that Eq. 1 is used.

Eq. 1 defines a "Standard Atmosphere - 1976" where distance in kilometers is converted to the equivalent ambient pressure as mmHg.

$$PB_{\text{hypo}} \text{ (mmHg)} = 760 * [288.15 / (288.15 - 6.5 * \text{altitude (km)})]^{5.25588} \quad \text{Eq. 1}$$

Eq. 2 is an alternative to Eq. 1 (10).

$$PB_{\text{hypo}} \text{ (mmHg)} = \exp[6.63268 - 0.1112 * \text{altitude (km)} - 0.00149 * \text{altitude}^2 \text{ (km)}] \quad \text{Eq. 2}$$

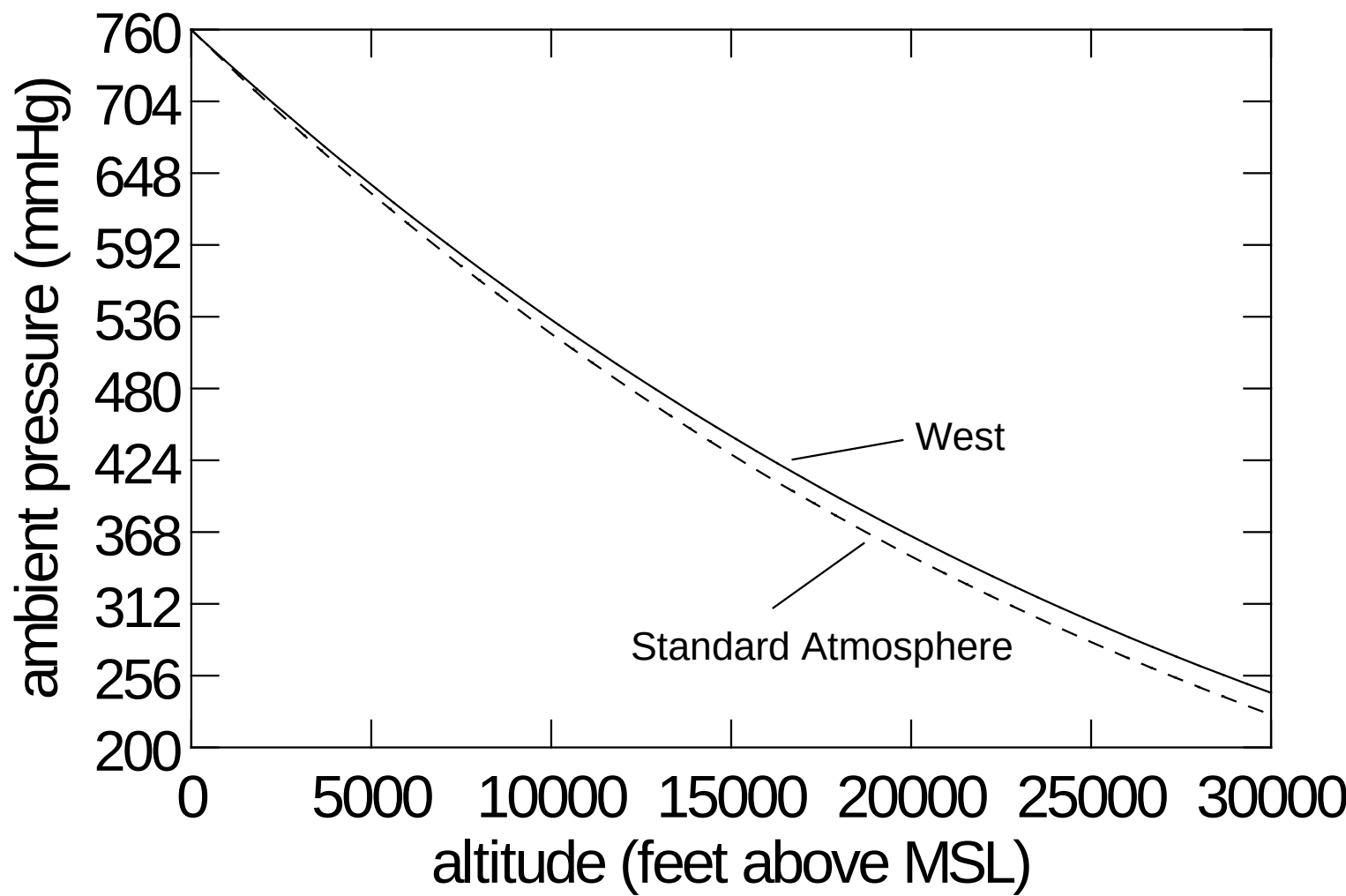


Fig. 1: The relationship between pressure and altitude as feet above mean sea level (MSL) diverges given two equations.

Eq. 3 converts the y-axis in Fig. 1 to F_IO₂ under normobaric pressure (F_IO_{2normo}) that represents the pO₂ while breathing air at these pressures for the iso-pO₂ machines (Fig. 2).

$$F_{I\text{O}_{2\text{normo}}} = PB_{\text{hypo}} * F_{I\text{O}_{2\text{hypo}}} / PB_{\text{normo}} \quad \text{Eq. 3}$$

where PB_{normo} is most often 760 mmHg, but could be different if the training is done at a location other than sea level, F_IO_{2hypo} is most often 0.209 but could be different if you are breathing an O₂ mixture that is not "air", and PB_{hypo} comes from either Eq. 1 or 2 that computes the ambient pressure for a particular altitude.

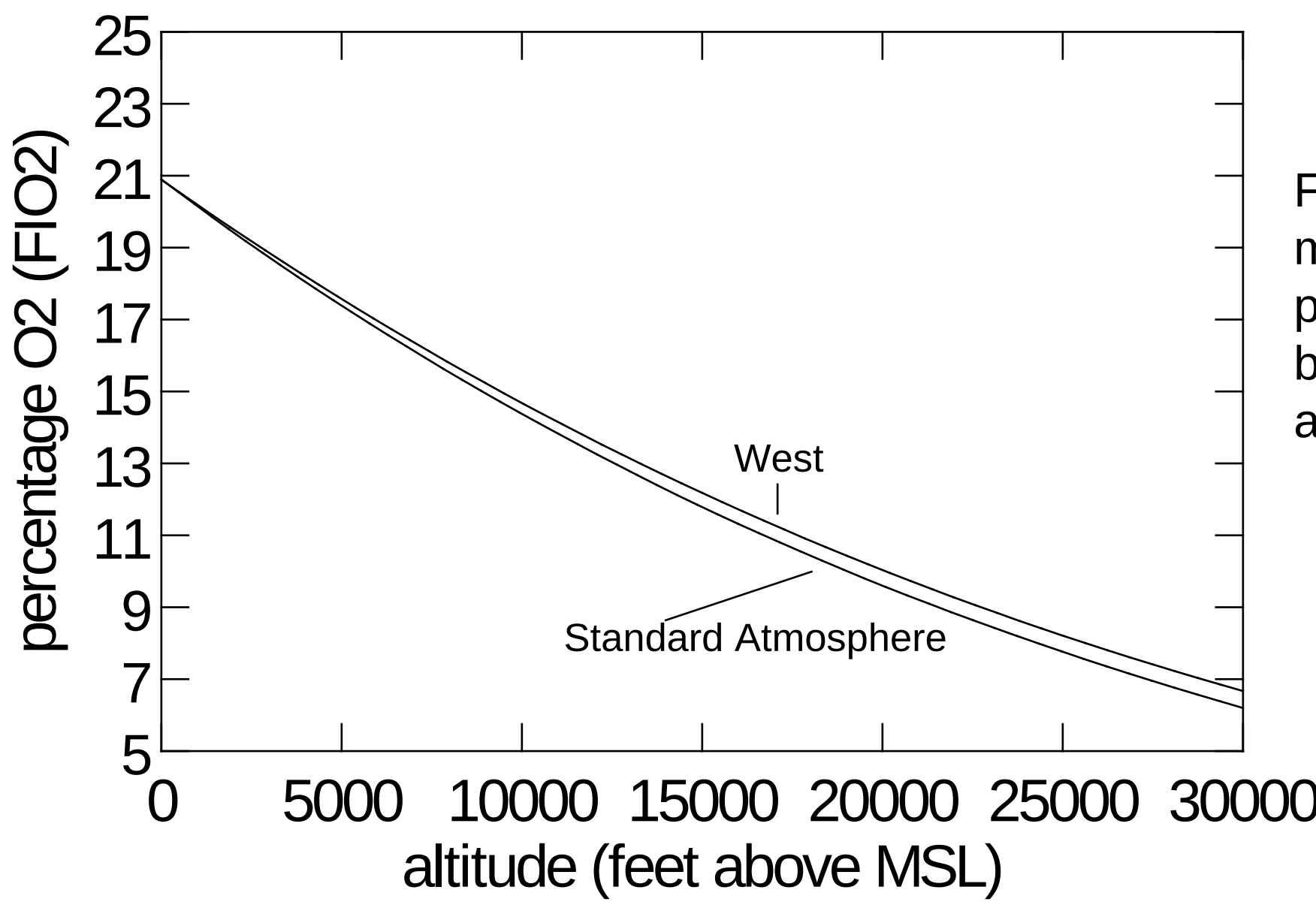


Fig. 2: F_IO₂ needed at 760 mmHg to provide the equivalent pO₂ you would breathe while breathing air at the given altitude.

Eq. 4 computes the F_IO₂ under normobaric conditions (F_IO_{2normo}) to provide for iso-P_IO₂.

$$F_{I\text{O}_{2\text{normo}}} = (PB_{\text{hypo}} - 47) * F_{I\text{O}_{2\text{hypo}}} / (PB_{\text{normo}} - 47) \quad \text{Eq. 4}$$

This simple improvement would provide a device that delivers a simulation of HH while under NH conditions accounting for 47 mmHg of water vapor pressure, as seen in Fig. 3.

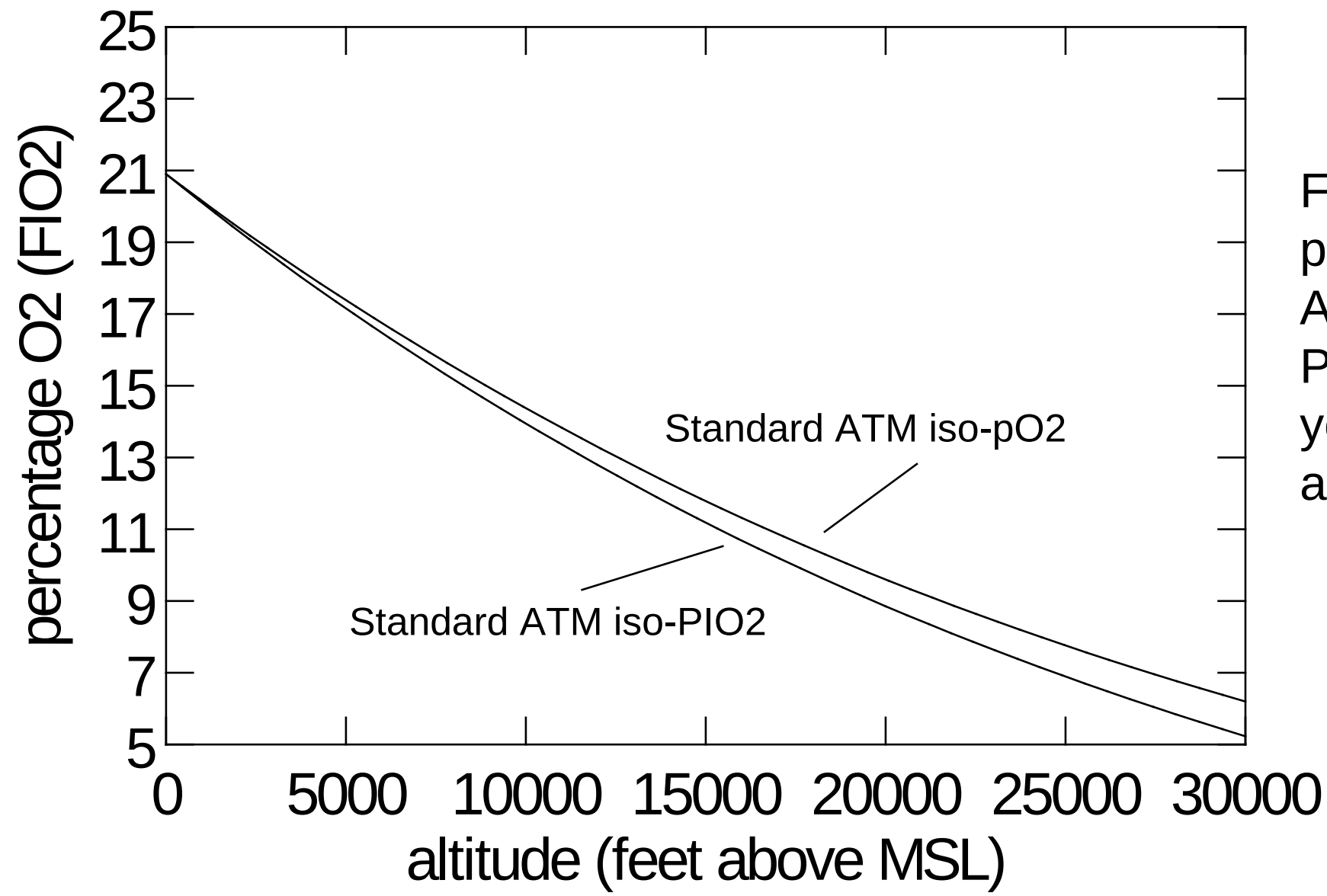


Fig. 3: F_IO₂ needed at 760 mmHg to provide the equivalent pO₂ (Standard ATM iso-pO₂ curve) or the equivalent P_IO₂ (Standard ATM iso-P_IO₂ curve) you would breathe while breathing air at the given altitude.

The difficulty in using the upper curve in Fig. 3 is that when you provide a F_IO₂ at sea level to match the pO₂ at the target altitude you create a P_IO₂ that is greater than the P_IO₂ at the target altitude, a consequence of ignoring pH₂O.

It is best to provide a F_IO₂ at sea level as defined by the lower curve in Fig. 3 that at least produces the equivalent P_IO₂ at sea level as at the target altitude, ~~a consequence of not ignoring~~ **which would account for** pH₂O.

Example: 9.0% F_IO₂ at 1 ATA on the display of an iso-pO₂ machine would indicate that you are at about 21,500 feet altitude with a pO₂ of 68.5 mmHg (Eq. 3). But P_IO₂ at 1 ATA is 64.1 mmHg, equivalent to breathing air at 19,700 feet, so an iso-pO₂ machine overestimates the simulated altitude by 1,800 feet. This is a consequence of ignoring the contribution of pH₂O.

RESULTS

Even accounting for pH₂O is not sufficient to account for P_AO₂ and P_ACO₂ as more direct agents to induce signs and symptoms of hypoxia during acute training exposures (2).

Fenn et al., as early as 1946, provided the theoretical foundation on why alveolar gas composition would *never be identical* under NH and HH conditions given the same hypoxic P_IO₂, a consequence captured in the derivation of the Alveolar Gas Equation.

Fig. 4 is an example of how NH and HH given the same P_IO₂ of 57.3 mmHg (22,000 ft) would not produce identical P_AO₂ and P_ACO₂.

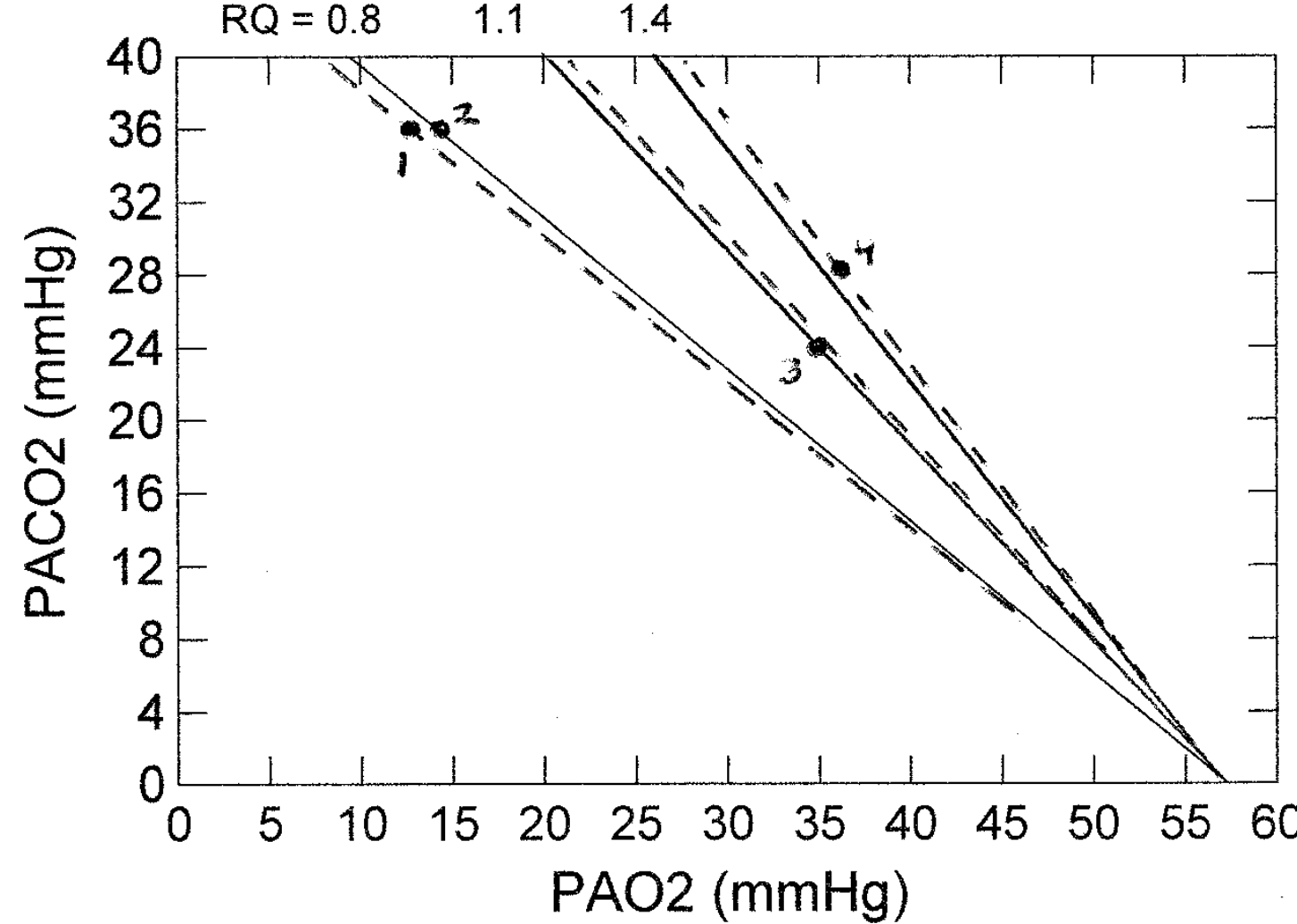


Fig. 4. Application of the Alveolar Gas Equation to demonstrate the inability to accurately reproduce HH under NH conditions given an example of an acute hypobaric training exposure to 22,000 ft. P_IO₂ is 57.3 mmHg in both conditions, the intercept for all respiratory quotient (RQ) diagonals when P_ACO₂ is zero. Diagonals for HH are solid lines and those for NH (8% F_IO₂) are dashed lines, all from the Alveolar Gas Equation (Eq. 5).

$$P_{A\text{O}_2} = P_{I\text{O}_2} - P_{A\text{CO}_2} * [F_{I\text{O}_2} + ((1 - F_{I\text{O}_2}) / RQ)]. \quad \text{Eq. 5}$$

Point 1: NH trainee dons mask at 760 mmHg with F_IO₂ of 8% and RQ of 0.8, and P_AO₂ quickly drops to 13 mmHg – a stimulus to hyperventilate.

Point 2: HH trainee rapidly ascends on air to 22,000 feet with same RQ of 0.8, and P_AO₂ quickly drops to about 14 mmHg – a slightly less stimulus to hyperventilate than NH.

Point 3: Hyperventilation of *rarified air* in this example acutely places HH trainee on the 1.1 RQ diagonal given the conditions in Table 1, column 2.

TABLE 1. Reasonable Response to Acute HH and NH Exposures

parameter	HH Example P _I O ₂ 57 mmHg	NH Example P _I O ₂ 57 mmHg
PB (mmHg)	321	760
F _I O ₂	0.21	0.08
V _E (l _{BTPS} /min)	14.3	16.5 ↑
V _A (l _{BTPS} /min)	10.4	12.0 ↑
VCO ₂ (ml _{STPD} /min)	289	389 ↑
VO ₂ (ml _{STPD} /min)	262	278 ↑
RQ	1.1	1.4 ↑
V _A /VCO ₂	0.036	0.031 ↓
P _A O ₂ mmHg	35	37 ↑
P _A CO ₂ mmHg	24	28 ↑
P _A N ₂ (mmHg)	215	648 ↑

Point 4: Hyperventilation of *dense air* in this example acutely places NH trainee on the 1.4 RQ diagonal given the conditions in Table 1, column 3.

Loepky et al. 1997 (and others) shows a greater increase in the rate and depth of breathing in NH relative to HH. In the above example the increase in minute ventilation (V_E) and alveolar ventilation (V_A) in NH relative to HH results is a greater P_AO₂ and P_ACO₂ as a result of increased VCO₂ from breathing the relatively dense gas during NH.

It follows from Loepky and our example in Fig. 4 that physiological responses would be different after peripheral and central chemoreceptor responses are integrated within the central nervous system.

Even if the Alveolar Gas Equation was used in reduced O₂ breathing devices one must account for the complex time-dependent role that P_AN₂ has in modifying P_AO₂ and P_ACO₂ under a particular hypoxic P_IO₂.

An accurate application of the Alveolar Gas Equation requires that the inspired N₂ volume be equal to the expired N₂ volume:

$$VN_2 = V_I * F_{I\text{N}_2} - V_E * F_{E\text{N}_2} = 0. \quad \text{Eq. 6}$$

Eq. 6 is applicable in maneuvers such as breath holding, voluntary hyperventilation, or exercise. But Eq. 6 is invalid to greater or lesser degree when ambient pressure changes or F_IO₂ ≠ 0.209, or some combination of both *until* a new P_AN₂ equilibrium is established.

NH necessarily requires N₂ molecules to move from the lungs into the tissues while HH requires N₂ molecules to move from the tissues into the lungs, each moving under different concentration gradients and possibly different time constants until a new dynamic equilibrium is achieved during a chronic NH or HH exposure.

The transient movement of N₂ changes P_AN₂ at constant PB, so changes the O₂-CO₂ point between NH and HH until the differences eventually become small and constant as each O₂-CO₂ point migrates onto its appropriate RQ diagonal near 0.8.

CONCLUSIONS

TABLE 2. Unresolved Issues Given Same Hypoxic P_IO₂

parameter	HH	NH	acute→time→chronic
f _v	↓	↑	?
V _T	↓	↑	?
V _E	↓	↑	?
V _A	↓	↑	?
VCO ₂	↓	↑	?
VO ₂	↓	↑	?
RQ	↓	↑	?
V _A /VCO ₂	↑	↓	?
P _A O ₂	↓	↑	?
P _A CO ₂	↓	↑	?
F _E N ₂ /F _I N ₂	↑	↓	?
V _E /V _T	?	?	?
Q	?	?	?
V _A /Q	↑ (5)	?	?
pH _{CSF}	?	?	?
% AMS	↑	↓	?

There is not an adequate integrated physiological understanding of the determinants of P_AO₂ and P_ACO₂ under NH and HH given the same hypoxic pO₂ to claim a device that provides TRUE isohypoxia.

Isohypoxia is defined as the same distribution of hypoxia signs and symptoms under any circumstances of equivalent hypoxic dose, and hypoxic pO₂ or even P_IO₂ are incomplete doses (3).

Both time-dependent P_AO₂ and P_ACO₂ should be considered in a calculation of hypoxic dose.

We *hypothesize* that the integrated hypoxic dose over the same exposure time is less in NH than HH for the same hypoxic P_IO₂.

Some devices that claim an equivalent HH experience under NH conditions significantly overestimate the HH condition, especially when simulating altitudes above 10,000 feet (3,048 m).

At best, the claim should be that the devices provide an *approximate* HH experience since they only duplicate the ambient pO₂ at sea level as at altitude (iso-pO₂ machines).

A **first step** n approach to reduce the overestimation is to at least provide machines that create the same P_IO₂ (iso-P_IO₂ machines) conditions at sea level as at the target altitude, a simple software upgrade from Eq. 3 to Eq. 4.

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