Variations on Ernsting's Post-Decompression Hypoxia Prevention Model

Todd S. Dart; Bria G. Morse

INTRODUCTION: In the event of decompression using an isobaric differential cockpit pressurization system, oxygen concentration breathed pre-decompression must be greater than required for the given cockpit altitude in order to prevent hypoxia. The model for determining oxygen concentration requirements advanced by Dr. John Ernsting, when graphed against cockpit altitude, creates a hypoxia safety "notch" which has become a standard requirement for aircraft oxygen systems. Although variables in the Ernsting notch model are not fixed, they are often presented as such.

METHODS: Model equations are presented to evaluate the effects of different cockpit pressurization, oxygen regulator PBA schedules, and changes to the physiological state of the aircrew.

RESULTS: Increased cockpit differential pressure, regulator breathing pressure, and aircrew respiratory quotient decreased pre-decompression oxygen concentration requirements by up to 6%, eliminating the hypoxia safety "notch." Although effects were small, reducing alveolar carbon dioxide pressure decreased oxygen concentration requirements while reducing respiratory quotient increased oxygen concentration requirements. A 10-mmHg increase in the minimal oxygen hypoxia threshold increased the pre-decompression oxygen concentration requirement 8 to 12% depending on cockpit altitude.

CONCLUSION: Variation in cockpit and regulator pressure schedules which stray outside the parameters used by Ernsting need to be independently calculated. During flight, an individual's physiological "notch" will be dynamic, wavering in response to changes in metabolic load, respiratory dynamics, and environmental conditions. Consideration of aircrew activity should be factored in when considering minimal oxygen concentration for pre-decompression hypoxia protection in the design of aircrew life support systems.

KEYWORDS: decompression, model, oxygen concentration, prevention, hypoxia.

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Aircraft cockpit pressurization creates a safe barometric environment for aircrew, protecting them from hypoxia, barotrauma, and decompression sickness.[11] In fighter and attack aircraft, structure and weight constraints require the use of isobaric-differential pressurization systems which allow cockpit pressure to decrease with altitude until reaching 2438 m (8000 ft). Cockpit pressure will remain at 2438 m until a set pressure differential between atmospheric and cockpit pressure is reached.[7,11] A 5 lb/in^2 (34.47 KPa) differential is the most common for fighter and attack aircraft, although lower or higher differentials may be used.[1] Regardless of the design pressure, once the differential is reached, cockpit pressure will start to decrease.

Although pressure differential systems maintain a constant cockpit-to-ambient pressure, the differential between cockpit altitude and ambient altitude does increase. For example, an aircraft with a 5-psid system flying at 7010 m (23,000 ft) will have a cockpit altitude of 2438 m, a cockpit-to-ambient altitude difference of 4572 m (15,000 ft). The same aircraft at 15,240 m (50,000 ft) will have a 6096 m (20,000 ft) cockpit altitude, an altitude difference of 9114 m (29,900 ft). Thus, while absolute pressure change for a decompression from 7010 m to 15,240 m is the same, the change in altitude is nearly doubled. As oxygen

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requirements for the prevention of hypoxia are determined by the ambient pressure, the greater the altitude differential, the greater the importance the pre-decompression alveolar oxygen pressure (P_AO_2) plays in preventing post-decompression hypoxia.[5–7]

Because cockpit altitudes in isobaric-differential systems can exceed 3048 m (10,000 ft), supplemental oxygen is needed to maintain P_AO_2 at physiologically safe levels.[10,11] In aircraft with diluter-demand regulators or with oxygen concentrators with variable oxygen output, the oxygen percentage provided to the aircrew is determined by the cockpit pressure.[11,14] Thus, in the event of cockpit decompression, supplemental oxygen being provided to the aircrew pre-decompression is based on cockpit altitude, not aircraft altitude.

For normal flight operations the objective is to keep the P_AO_2 at a sea level equivalent of 103 mmHg (13.73 KPa),[5–7] although it is generally considered physiologically safe to allow P_AO_2 to fall as low as 60 mmHg (8 KPa) for sustained periods.[11] To maintain sea level lung oxygen pressure, the inspired oxygen concentration must increase as cockpit pressure decreases. However, in the event of cockpit decompression, aircrew would suddenly find themselves exposed to the ambient pressure altitude while breathing an oxygen mixture intended for the lower cockpit altitude. Furthermore, due to Boyle's law, gas expansion causes expulsion of much of the gas in the lung, leading to a sudden drop in P_AO_2.[12] This is especially critical if the decompression is at or above 10,058 m (33,000 ft) where ambient Po_2 falls below that of the mixed venous oxygen pressure, average range 30 to 40 mmHg,[4,12] leading to a reversal of oxygen diffusion from the blood into the alveoli.[12] Following decompression, a P_AO_2 as low as 30 mmHg (4 Kpa) is tolerable for short periods without causing impairment.[6–8] Validation of this 30-mmHg threshold was accomplished by Ernsting et al.[8] through an analysis of the effects of hypoxia on an electroencephalogram (EEG) variance index in three individuals subjected to variable-rate decompressions from 2438 m (8000 ft) to 12,192 m (40,000 ft) while breathing air and 100% oxygen. Comparison of the frontal EEG variance index to various minimal P_AO_2 levels showed a linear correlation "… between the intensity of the hypoxia as measured by the area on a P_AO_2 time plot below a P_AO_2 = 30 mmHg and the associated increase in activity (variance index) of the 8–16 Hz band of the EEG recorded from the frontal and middle regions of the head." Ernsting et al. also evaluated 25 and 35 mmHg (3.3 and 4.6 KPa) P_AO_2 values against the same criteria, but these pressures did not provide the linear fit obtained when using 30 mmHg. Their conclusion was that to maintain cognitive function following a decompression, P_AO_2 should remain above a 30-mmHg threshold. Under certain conditions this meant the oxygen concentration breathed before a decompression must be greater than the oxygen concentration needed for given cockpit altitude.[8] This requirement, when combined with the ground level oxygen concentration requirement by cockpit altitude, was used to produce the graph shown in **Fig. 1**. The change in the 103-mmHg oxygen equivalency slope within the graph which occurs at about 4877 m (16,000 ft) cockpit altitude corresponds to the ambient altitude which would trigger the oxygen regulator to initiate pressure breathing for altitude (PBA) in the event of a decompression. The graph slope continues to increase up to the maximal cockpit pressure corresponding to the oxygen regulator's maximum output pressure were it to be exposed to ambient pressure. Upon

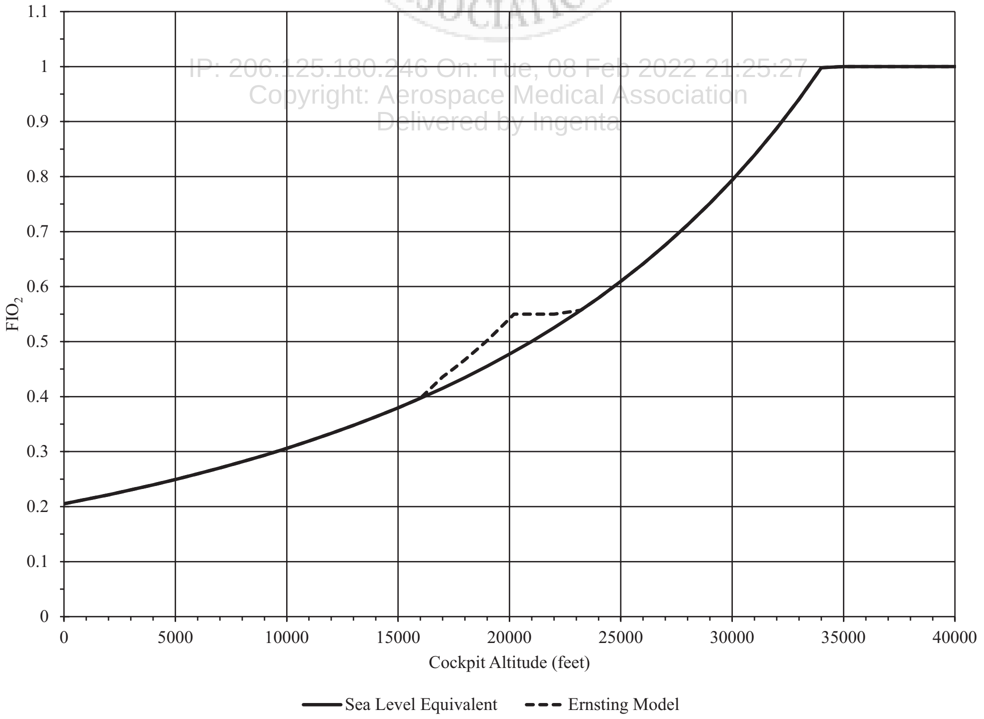

Fig. 1. Minimum inspired oxygen fraction (F_IO_2) needed for prevention of hypoxia following decompression with respect to cockpit altitude (feet). Cockpit pressurization schedule 5 psid; aircraft/regulator ceiling 15,240 m (50,000 ft); maximum regulator pressure 30 mmHg.

reaching this point the concentration plateaus produce what has been referred to as a "hook,"[10] "step,"[14] "notch,"[9] or "Ernsting notch,"[15] as shown by the dashed line in Fig. 1. The plateau of the notch is not calculated but manually added to connect the peak pre-decompression oxygen concentration requirement at maximum aircraft altitude to the ground level oxygen requirement line. Fig. 1 is a common reference used in the development of oxygen systems and in determining the pre-decompression oxygen concentration needed when operating at high altitude.[13–15]

In general, the calculations for determining the appropriate pre-decompression breathing oxygen concentration receive only cursory description in the literature[6,7,10] and military standards.[13,14] The most thorough mathematical description of what herein is referred to as the post-decompression hypoxia prevention (PDHP) model comes from an unpublished 1980 paper written by Dr. John Ernsting while a Royal Air Force exchange officer with the Crew Technology Division at the U.S. Air Force School of Aerospace Medicine, Brooks AFB, TX, USA. This paper serves as the basis for the equations presented below.

To derive the notch graph, Ernsting used two calculations; the first being the oxygen concentration required to maintain sea level (SL) P_AO_2 for a given cockpit pressure (Pc), and the second the oxygen concentration required to prevent hypoxia following cockpit decompression. To calculate SL P_AO_2 Ernsting started with the alveolar gas equation.

$$P_AO_2 = \left(Pc - P_{H_2O}\right)F_IO_2 - P_ACO_2\left(F_IO_2 + \frac{(1 - F_IO_2)}{R}\right) \qquad \text{Eq. 1}$$

Setting P_{H2O} to 47 mmHg (6.2 KPa), the water vapor pressure at a body temperature of 37°C, P_ACO_2 to 38 mmHg (5 KPa), respiratory quotient (R) to 0.85, and P_AO_2 to 103 mmHg as representative of a normal healthy individual at sea level, Eq. 1 becomes:

$$F_IO_2\left(Pc - 47\right) = 103 + 38\left(F_IO_2 + \frac{(1 - F_IO_2)}{0.85}\right) \qquad \text{Eq. 2}$$

Solving for the inhaled oxygen fraction (F_IO_2) for SL equivalency:

$$F_IO_2 = \frac{147.7}{Pc - 40.3} \qquad \text{Eq. 3}$$

Having established in Eq. 3 the F_IO_2 at sea level relative to Pc, the next step is to calculate the oxygen concentration notch. To do so, Ernsting made several assumptions. First, the minimum allowable P_AO_2 needed to prevent hypoxia post-decompression is 30 mmHg. Second, cockpit altitude prior to decompression maintains a 5-psi isobaric-differential pressurization schedule. Third, the oxygen regulator provides a 2-mmHg (0.3-KPa) constant safety pressure from ground level until cockpit pressure reaches 11,887 m (39,000 ft), at which time PBA initiates. Fourth, PBA increases linearly, starting from the 2-mmHg safety pressure at 11,887 m up to a maximum of 31.8 mmHg (4.2 KPa) at 15,240 m (50,000 ft), the maximum ceiling for a hypothetical combat aircraft. Fifth, respiratory quotient and P_ACO_2 remain at 0.85 and 38 mmHg, respectively.

Once regulator and cockpit pressure performance limits have been established, the first step in calculating the minimum necessary F_IO_2 by cabin altitude is to determine the pre-decompression lung pressure (Pl), which is the sum of the cockpit pressure and regulator output pressure (Pr).

$$Pl = Pc + Pr \qquad \text{Eq. 4}$$

Prior to decompression, Pr will be safety pressure (if any) in mmHg.

Post-decompression (final) cockpit pressure (Pcf) is the difference between initial and differential pressure.

$$Pcf = Pci - Pd \qquad \text{Eq. 5}$$

where Pci is the initial cockpit pressure and Pd is the cockpit pressure differential in mmHg. For a 5-psid aircraft this value is 259 mmHg (34.5 KPa); when the aircraft altitude exceeds 7010 m (23,000 ft), Eq. 5 becomes:

$$Pcf = Pci - 259 \qquad \text{Eq. 6}$$

Postdecompression (final) lung pressure (Plf) is the sum of the final cockpit pressure and regulator output pressure.

$$Plf = Pcf + Pr \qquad \text{Eq. 7}$$

Substituting the Pcf formula from Eq. 6 into Eq. 7, Plf becomes:

$$Plf = Pci - 259 + Pr \qquad \text{Eq. 8}$$

At the assumed 30-mmHg hypoxia limit, the final alveolar oxygen concentration fraction (FAO_2f) immediately following decompression is the ratio of the minimal O_2 requirements to Plf, taking into consideration the presence of P_{H2O} (47 mmHg) in the alveoli.

$$FAO_2f = \frac{30}{Plf - 47} \qquad \text{Eq. 9}$$

Assuming alveolar oxygen concentration immediately before a decompression is identical to the initial post-decompression oxygen concentration, then the initial P_AO_2 (P_AO_2i) is:

$$P_AO_2i = 30\left(\frac{Pli - 47}{Plf - 47}\right) \qquad \text{Eq. 10}$$

The initial inspired oxygen fraction (F_IO_2i) needed to maintain P_AO_2i is calculated by incorporating Eq. 10 into Eq. 3, keeping R = 0.85 and Pco_2 = 38 mmHg.

$$F_IO_2i = \frac{P_AO_2i + 44.7}{Pci - 40.3} \qquad \text{Eq. 11}$$

When P_AO_2 is at ground level equivalent pressure (103 mmHg) the numerator is 147.7 mmHg per Eq. 3. For aircraft altitudes in which calculated F_IO_2i is less than the F_IO_2 needed to maintain ground level P_AO_2, then F_IO_2 from Eq. 3 takes precedence when graphed. Only when the F_IO_2i from Eq. 11 exceeds F_IO_2 is the F_IO_2i value graphed.

METHODS

In aircraft with different pressurization gradients[1] and regulator PBA schedules,[3] the assumptions used by Ernsting to generate Fig. 1 no longer apply and the importance these changes have on the minimal oxygen concentration needed to prevent post-decompression hypoxia need to be reassessed. Further, in light of the increased attention given to physiological events in military aircraft, it is important to also understand the effects of changes to the physiological parameters used in the PDHP model and their impact on post-decompression hypoxia risk.

The effect of cockpit pressurization schedule on the PDHP model was evaluated against the 3.6-psid cockpit pressurization used in the T-6A primary military trainer aircraft[1] and two hypothetical pressurization schedules of 4.5 psi and 5.5 psi. The T-6A was assessed with 2 mmHg (0.27 KPa) safety pressure only as the regulator is a non-PBA system,[1] while the Ernsting PBA schedule was used for the other pressure schedules. Oxygen regulator PBA schedule effect on pre-decompression oxygen concentration requirements was evaluated using PBA schedules from the CRU-103[2] and CRU-122[3] regulator. The CRU-103 is designed for use with only high oxygen concentration supply sources, but was modeled as a dilution regulator to allow comparison of its slightly greater PBA schedule on pre-decompression oxygen concentration requirements.

Effects of changes to aircrew physiological state were modeled by adjusting the respiratory quotient (R), alveolar carbon dioxide pressure ($P_{A}CO_2$), and the $P_{A}O_2$ hypoxia threshold. For physiological state models a cockpit pressure differential of 5 psid and the Ernsting PBA schedule were used. Three values of R were evaluated; 0.7, 0.85 (Ernsting), and 1.0 to evaluate the impact of diet and increased physical activity on model behavior.[4,6,7] The effect of $P_{A}CO_2$ change on required oxygen concentration requirements was evaluated at 30 mmHg (moderate hypocapnia condition), 38 mmHg (Ernsting value), and 45 mmHg (moderate exercise). For every change to R or $P_{A}CO_2$, $F_{I}O_2$ from Eq. 3 and $F_{I}O_2i$ from Eq. 11 must be recalculated with the new physiological constant.

Although the 30-mmHg hypoxia prevention threshold is a reliable lower $P_{A}O_2$ limit for hypoxia protection, the data upon which the threshold was determined came from individuals at physical rest and engaged in only mild cognitive activity.[8] In the event aircrew are more physically or mentally active at the moment of decompression, a greater metabolic oxygen usage rate (metabolic load) may be placed on available physiological oxygen stores. In this situation, a $P_{A}O_2$ threshold of 30 mmHg may not be sufficient to prevent hypoxia impairment. The impact of increased metabolic load on pre-decompression oxygen needs may be simulated by increasing the hypoxia threshold. For the PDHP model analysis the threshold was increased from 30 to 40 mmHg (5.3 KPa). Except for a few examples where R and $P_{A}CO_2$ were adjusted simultaneously, only one input variable was changed per model run.

RESULTS

An increase in the pressure differential results in the "notch" starting at a lower cockpit altitude, corresponding to the greater change in pressure experienced by the aircrew following a decompression, while a decrease in the pressure differential slides the notch starting point upwards on the minimal oxygen concentration curve, producing a smaller notch (**Fig. 2**). Included within Fig. 2 is a marker to indicate the maximum cockpit altitude of 5059 m (16,600 ft) for the T-6A at its maximum operational altitude of 9488 m (31,000 ft). Oxygen concentration requirements for the T-6A for cockpit altitudes less than 4876 m (15,997 ft) fall along or below the sea level oxygen equivalent curve. Thus, the T-6A has no pre-decompression hypoxia prevention notch.

Though cockpit pressure is assumed to be a fixed value within the model, worn or faulty cockpit pressurization systems can lead to increased, decreased, or even fluctuating cockpit pressure differentials.[16] For example, in situations where a 5-psid system cockpit is greater than 5 psi, the PDHP model will underestimate the needed pre-decompression oxygen concentration.

Pre-decompression oxygen concentration notch height is inversely related to post-decompression breathing pressure (**Fig. 3**). The assumed PBA schedule used by Ernsting, which provides less breathing pressure for an equivalent altitude than the CRU-103 and CRU-122 regulators, results in a greater pre-decompression oxygen requirement. The CRU-103 initiates PBA earlier than the Ernsting pressure schedule and achieves an approximately 5 mmHg (0.7 KPa) greater maximum pressure at a peak operating altitude of 15,240 m (50,000 ft).[2] The result is a lower pre-decompression concentration requirement (Fig. 3). Alternatively, the CRU-122 uses a much more robust output pressure-to-altitude schedule, initiating PBA at 11,887 m (39,000 ft) and producing 58 mmHg (7.7 KPa) pressure at 15,240 m (50,000 ft) and 70 mmHg (9.3 KPa) at 16,459 m (54,000 ft).[3] The absence of a notch, corresponding to a 6% reduction in the oxygen concentration requirement at maximum cabin altitude, for the CRU-122 PBA schedule simply means the calculated $F_{I}O_2i$ never rises above the oxygen concentration needed to maintain sea level equivalent lung oxygen pressure.

The impact of cockpit pressure and PBA schedule are recognized factors affecting post-decompression hypoxia risk.[7,10,14] However, changes to R, $P_{A}CO_2$, or the hypoxia threshold are often not considered but will also affect the magnitude of the notch. Changes to these physiological parameters are such that as R increases, or $P_{A}CO_2$ decreases, the pre-decompression oxygen requirement is reduced, and vice versa (**Fig. 4**).

DISCUSSION

The post-decompression hypoxia prevention model provides quantitative estimates on the minimal oxygen concentration needed to prevent hypoxia immediately after loss of cockpit pressure. The original estimate by Ernsting has proven to be

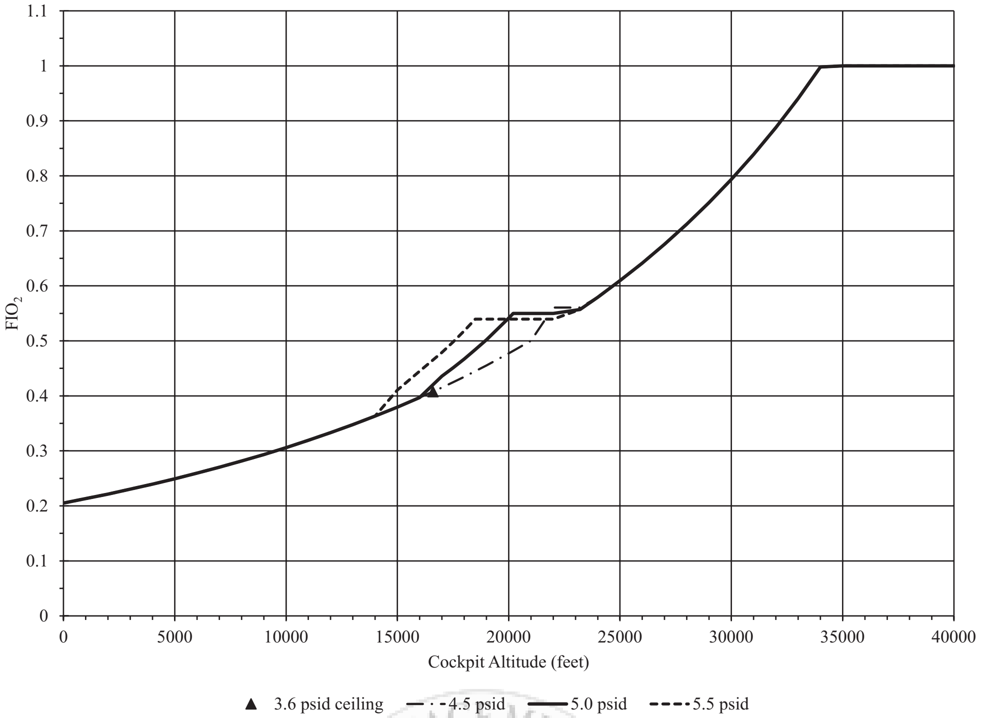

Fig. 2. Cockpit pressurization schedule impact on minimum inspired oxygen fraction (F_{IO_2}) for prevention of hypoxia following decompression with respect to cockpit altitude (feet). Solid triangle is maximum cockpit altitude of the T-6A using a 3.6-psid cockpit pressurization schedule. Aircraft/regulator ceiling 15,240 m (50,000 ft); maximum regulator pressure 30 mmHg. Psid = pounds per square inch, differential.

a useful tool in aircraft life support systems development for determining minimal oxygen requirements. Since its development, the Ernsting notch graph's utility for improving aircrew safety has grown to the point where it can now be found within most military standards[13–15] and aeromedical reference sources,[7,9,10] where it is often presented with limited to no consideration of its inherent assumptions. Variation in cockpit pressurization and regulator PBA schedules

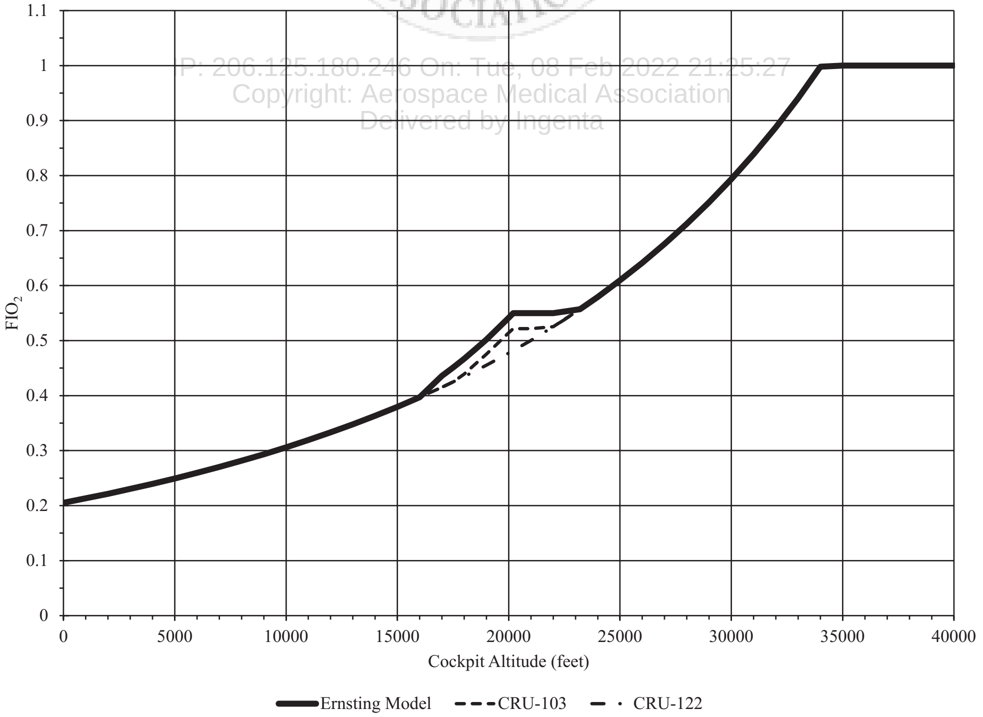

Fig. 3. Pressure breathing for altitude schedule impact on minimum inspired oxygen fraction (F_{IO_2}) for prevention of hypoxia following decompression with respect to cockpit altitude (feet).

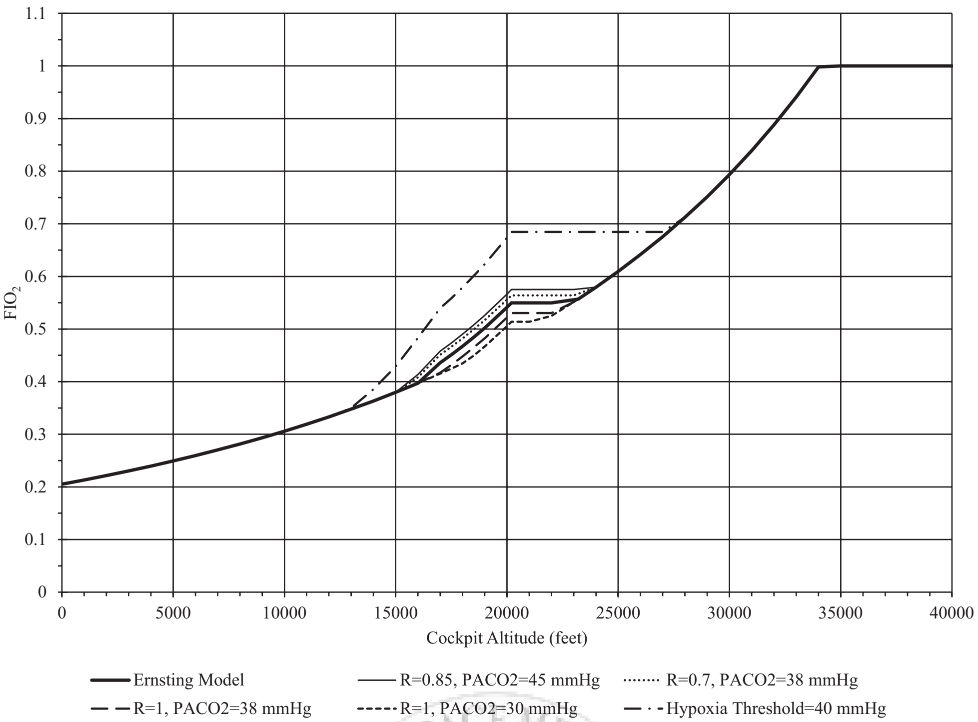

Fig. 4. Response to changes in respiratory values R, P_{CO_2}, and hypoxia threshold on minimum inspired oxygen fraction (F_IO_2) for prevention of hypoxia following decompression with respect to cockpit altitude (feet). Maximum altitude 15,240 m (50,000 ft); maximum regulator pressure 30 mmHg. Ernsting model: R = 0.85, P_ACO_2 = 38 mmHg.

which stray outside the parameters used by Ernsting need to be independently calculated.

The impact of adjusting R or P_ACO_2 on the overall change in pre-decompression oxygen concentration requirement is small, varying by about 5%. While such a negligible change to the pre-decompression oxygen requirement might be generally disregarded during life support system development, the margin of safety for minimal oxygen concentration prior to decompression could nonetheless be improved by the use of lower R (e.g., ≤ 0.8) and higher P_ACO_2 (e.g., ≥ 40 mmHg) values when determining the pre-decompression oxygen concentration requirements for aircraft. Further, although the Ernsting notch may be calculated as a fixed value for practical use, during flight an individual's physiological "notch" will be dynamic—constantly wavering upwards and downwards in response to changes in metabolic load, respiratory dynamics, and environmental conditions.

Setting the P_AO_2 hypoxia threshold to 40 mmHg to simulate greater metabolic load produced an approximate 8–12% increase, depending on cockpit altitude, in required pre-decompression oxygen concentration. The effect of increased metabolic load on the hypoxia threshold may be somewhat ameliorated by an increase in P_ACO_2 and R values but, as discussed, the impact of these parameters on the model's pre-decompression oxygen requirement is more constrained than the impact of changes to the hypoxia threshold. While the minimal P_AO_2 threshold for active individuals would need to be experimentally determined, some consideration to physiological condition and metabolic load may be warranted to further improve the post-decompression hypoxia protection margin.

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