Gas Related Problems related to Spacesuits

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Learning Objectives

Understand how various atmospheric (Oxygen) and metabolic gas (Carbon Dioxide) compositions relate to human performance and survival in space

Understand how the relationship between gas composition and ambient pressure may affect human performance and survival in space

Earth Atmospheric Gas Composition

Earth's sensible atmosphere is essentially constant, and by mole fraction, is composed of 78% nitrogen, 21% oxygen, and 1% other gases (argon 0.93%, CO2 0.03%, and neon, helium, krypton, hydrogen, xenon, and ozone in increasingly smaller amounts

Humans have evolved to tolerate and accommodate to these levels, but under different percentages or partial pressures, they can have adverse physiologic effects

Earth's atmospheric oxygen hit 35% in Carboniferous Period (300 million years ago)

Oxygen at high concentrations (hyperoxia) can be toxic to lungs and brain

Absorption Atelectasis - Intrapulmonary shunts redirect blood flow to areas with higher O2 and causes alveolar collapse in less perfused lung

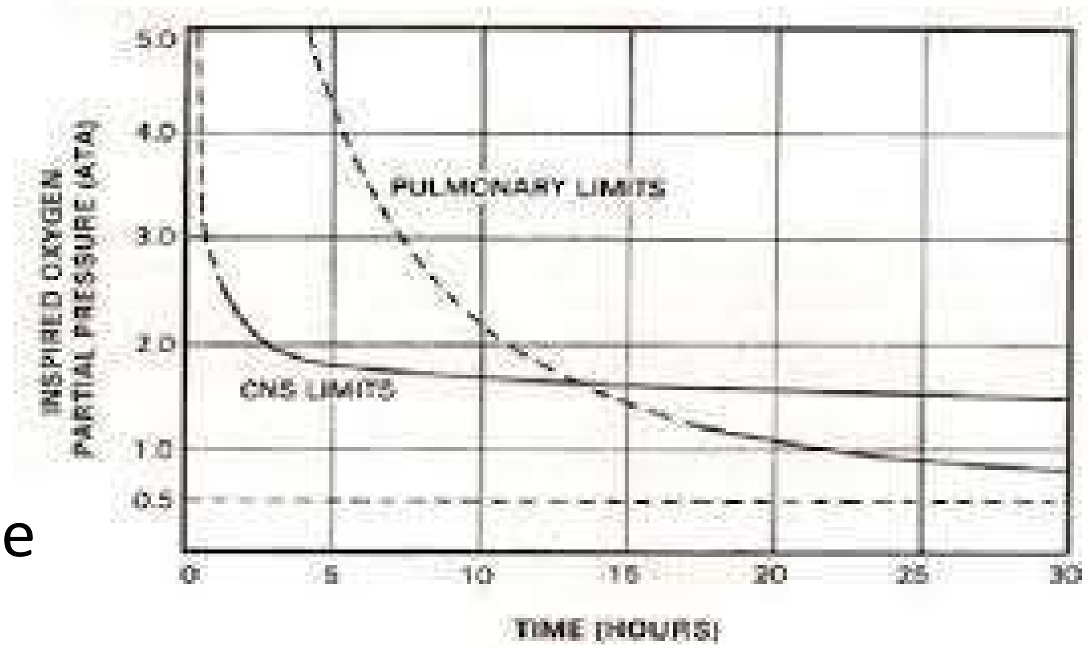
Pulmonary O2 Toxicity occurs above 60% O2 (FiO2)

Nitrogen (N2) at high pressures is anesthetic (Nitrogen Narcosis)

N2 is inert at sea level, 1 Atmosphere Absolute (ATA)

N2 is a CNS depressant at 4 ATA and anesthetic at higher pressures (> 6 ATA)

Even a good thing can be bad for you: Oxygen Toxicity



O2 can be toxic to pulmonary and/or central nervous system (CNS)

CNS O2 Toxicity

Above 1.3 Atmospheres Absolute (ATA), oxygen can cause blurred vision, nausea, vomiting, twitching, irritability, incoordination, ataxia and seizures

Is Oxygen Toxicity a concern for EVA operations?

Scenario 1

100% Oxygen used for O2 Prebreathe to wash out Nitrogen for DCS risk reduction, and 100% O2 in spacesuit for entire EVA

May result in mild pulmonary O2 toxicity (absorption atelectasis)

Scenario 2 (worst case)

Above scenario with DCS during EVA necessitating In-suit O2 protocol post-EVA in ISS at 14.7 psi (1 ATA) + 4.3 psid suit (.29 ATA) + Bends Treatment Apparatus with additional 4.5 psid (.30 ATA) = 1.59 ATA (CNS O2 toxicity at 4 hours)

Barometric Pressure Related Problems

Hypoxia (hypoxic)

reduced oxygen delivery to tissues within seconds to minutes

Barotrauma

expansion of gas filed cavities, worst situation is pulmonary over-inflation with collapsed lungs, arterial gas embolism within seconds

Decompression Illness (DCI) aka DCS

with pressure reduction, evolved gas bubble from dissolved nitrogen can cause pain, pulmonary or nervous system damage within minutes to hours

Ebullism

gas evolved from water (vapor pressure) below 47 mm Hg
severe lung damage within minutes

Relevant Gas Laws

Dalton's Law: the pressure of a mixture of gases is the sum of the partial pressures of the individual components

—> HYPOXIA: As you ascend in altitude (pressure decreases), the percentage of oxygen remains constant, but O2 partial pressure decreases

Boyle's Law: gas volume is inversely proportional to pressure

—> BAROTRAUMA (trapped gas disorder) As you ascend, pressure goes down and volume goes up, causing gas-expansion in digestive system, teeth cavities, sinuses, ears, lungs

Henry's Law: amount of dissolved gas in a liquid will decrease if the pressure around the liquid decreases.

—> DECOMPRESSION SICKNESS (evolved gas disorder) When pressure is reduced, gas comes out of solution in the form of bubbles nitrogen bubbles in blood and tissues cause pain, tingling, chokes, CNS damage

Inspired Oxygen Partial Pressure Exposure Ranges
NASA Standard 3001 Volume 2 rev B (2019)

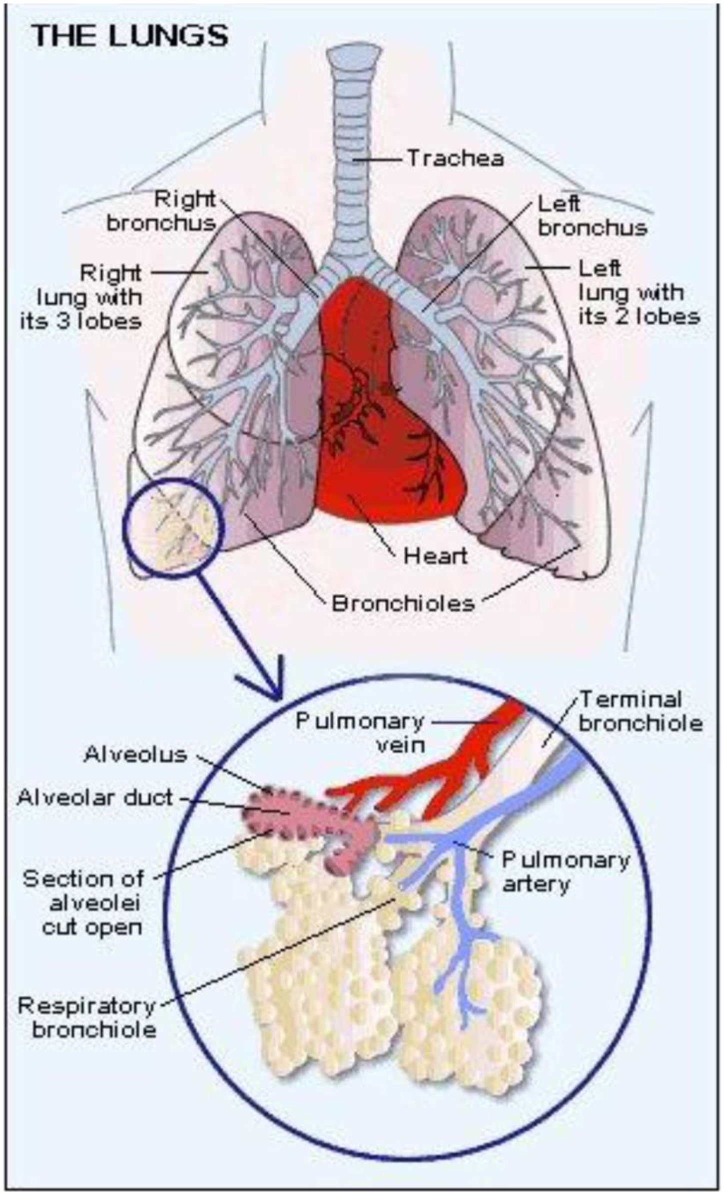
Inspired O2 partial pressure **$PIO2 = (PB-47)*FIO2$**	**Normoxia Target Range**	**Indefinite Hyperoxia Upper Limit**	**Short-Term Hyperoxia Upper Limit**	**Mild Hypoxia Lower Limit**
PIO2 (mmHg) $PIO2 = (PB-47)*FIO2$	145-155	356	791	127
PIO2 (psia)	2.8-3.0	6.9	15.3	2.5
Acceptable Duration	Indefinite	Indefinite	6-9 Hours *	1 week**
Examples	Habitat and Spacesuit Minimum	EVA and Cabin Depress In-Suit Survival	O2 Prebreathe for EVA Preparation	EVA Preparation (ISS Campout, Shuttle 10.2, Exploration Atmosphere of 8.2 psia and 34% O2)

PB- Ambient Barometric Pressure
FI - Fractional concentration of inspired O2
FIO2 – dry-gas decimal fraction of ambient O2

* From Johnson Procedural Requirements (JPR) 1880.4, Requirements and Limitations for Exposure to Reduced Atmospheric Pressure. (9 hours in 48-hour period, 6 hours in 24-hour period not to exceed 5 consecutive days)

** At time of publication, 1 week was accepted limit for this hypoxic exposure..

Components Of The Respiratory System



300 Million Alveoli in human lungs

Lung respiratory area: 750 cu. ft. (70 cu. meters)

Inspiration is active (intercostal muscles and diaphragm expand ribcage)

Expiration is passive

Tidal volume is 500 ml with 12-15 breaths/ minute

Anatomic dead space (trachea, bronchi, bronchioles is 150 ml (1 ml/ lb ideal body weight)

Alveolar Ventilation rate is breathing rate x (tidal volume – dead space) = 12 x (500-150) = 4200 ml/min

Pulmonary Gas Exchange

Gas exchange occurs between the alveolar gas and venous blood by diffusion across the respiratory membrane (0.6 micron thick), which is only 2 cell layers thick (blood vessel cell and alveolar cell)

Gas diffusion is based on gas water solubility, and CO2 is 20 times more soluble than O2

Gas diffusion is also based on gas partial pressure differential

After O2 is consumed in body tissues O2 is lower in venous blood, and O2 moves from alveoli into the blood vessel

CO2 is produced by body metabolism, is higher in venous blood and moves from blood into the alveoli

With hypobaric hypoxia the alveolar O2 will be lower and the O2 partial pressure differential is reduced, ie the O2 diffusion gradient is reduced

With heavy exercise the RBC transit time in the capillary bed is shorter and less time is available for gas diffusion exchange is lessened because O2 diffusion from alveoli to blood is slower than CO2 from blood into to the alveoli

Respiratory Control

Rhythmic subconscious ventilation is controlled by the respiratory center in the brainstem (medulla and pons) by active inspiration (excitatory) signals to chest (intercostal) muscles and diaphragm and (inhibitory) signals facilitate passive expiration

Rate and depth of breathing are in response to arterial blood CO2, O2, and H+ ions and influence central (brain) and peripheral chemoreceptors (aortic arch and carotid bodies)

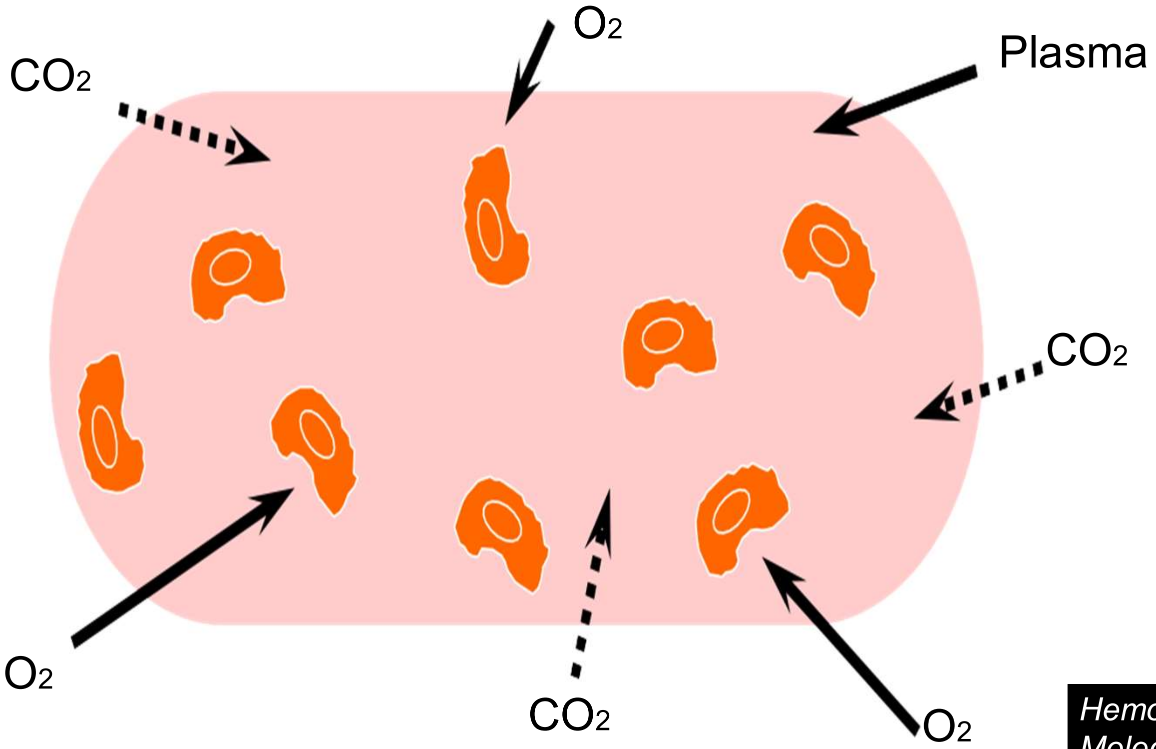
Respiratory Control

CO2 is the primary respiratory stimulus. CO2 crosses blood brain barrier but H+ does not. CO2 binds with H20 to make carbonic acid (H2CO3) which quickly breaks down to HCO3 (bicarbonate) and H+ ion. The H+ ion stimulates central chemoreceptors to increase breathing. A 5 mmHg increase in arterial CO2 doubles respiratory ventilation, and low arterial CO2 can drastically reduce breathing.

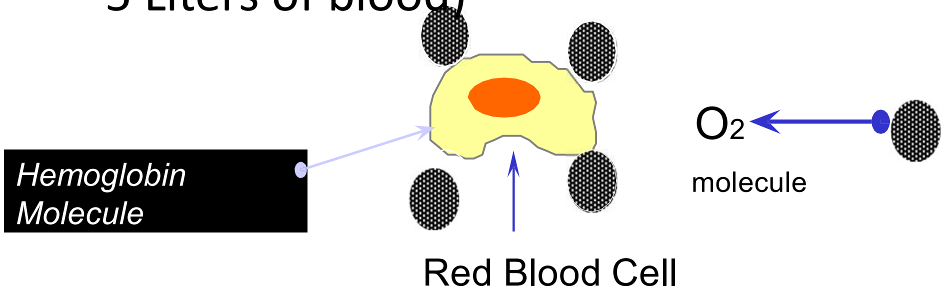
The peripheral (carotid body) chemoreceptors respond to arterial ppO2 below 60 mmHg by increasing ventilation rate via the brainstem respiratory center. This is the hypoxic ventilatory response.

Higher brain centers can increase ventilation in response to pain or emotion stress, which can drastically reduce arterial PCO2, constricting cerebral blood vessels, reducing blood flow causing ischemic hypoxia.

Blood transport of O_2 and CO_2



Plasma carries the majority of CO2
10% is dissolved in plasma
70% is bound as Bicarbonate (HCO3)
CO2 + H2O forms Carbonic Acid (H2CO3) which breaks down to HCO3 and H+ ion
97% of O2 is bound to Hemoglobin
20 mL of O2/ 100 mL of blood (1 L O2 in 5 Liters of blood)



55% Plasma: 90% H_2O with 100 solutes
45% RBCs: each RBC has 250 Million Hemoglobin (Hgb) molecules
RBC is 7.5 micron biconcave cell, each cc of blood has > 5 million RBCs
In the 5 liters of blood there are 26 Billion RBCs, RBCs live 100-120 days

Physiologic Effects of Microgravity

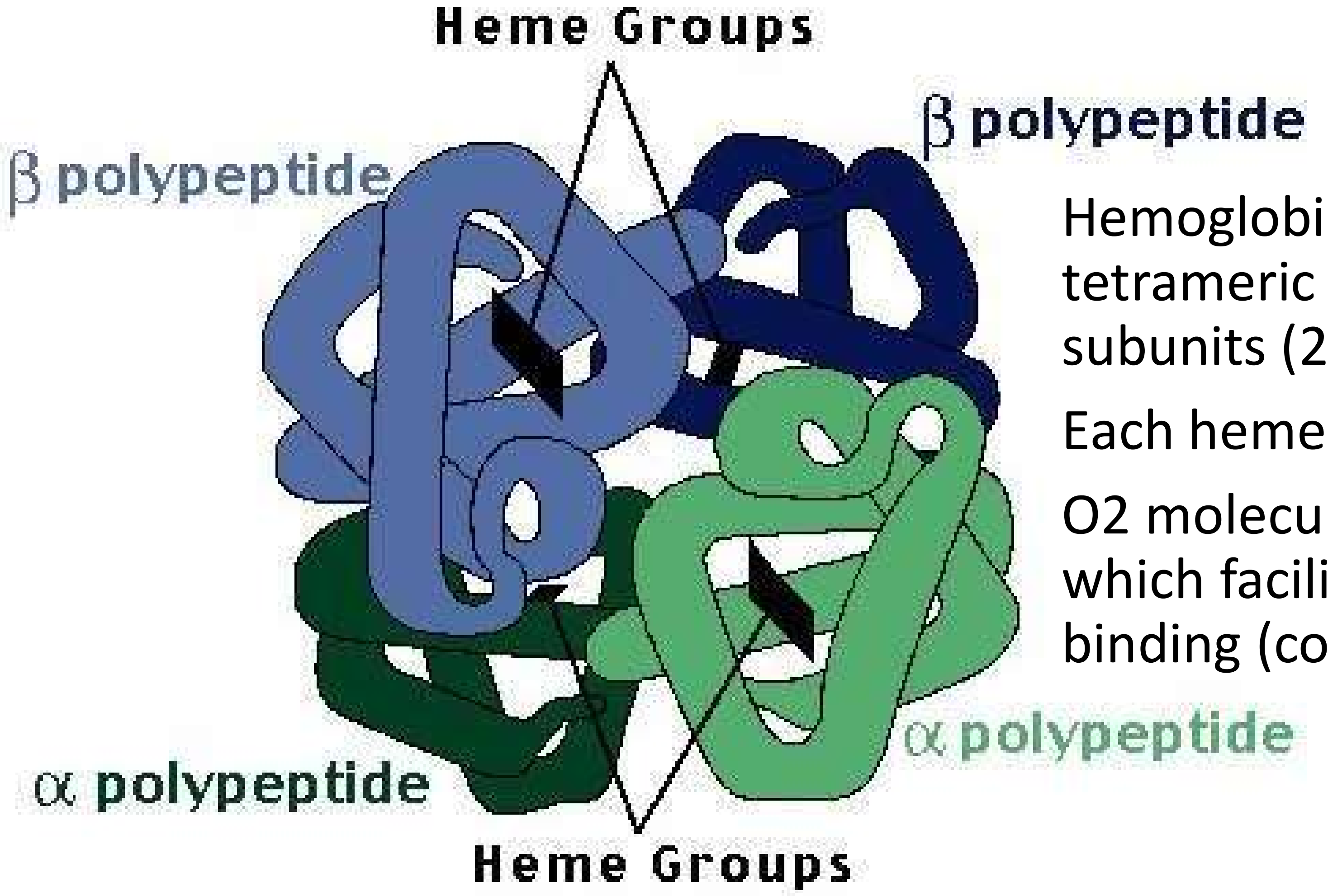
Plasma volume – decrease 17% in first 24 hours then stabilizes to 15.9 %

Red cell mass – decreased by 10-11%

Cardiac output – decreased by 17-20%

Lung ventilation perfusion more evenly distributed in microgravity

The Hemoglobin Molecule

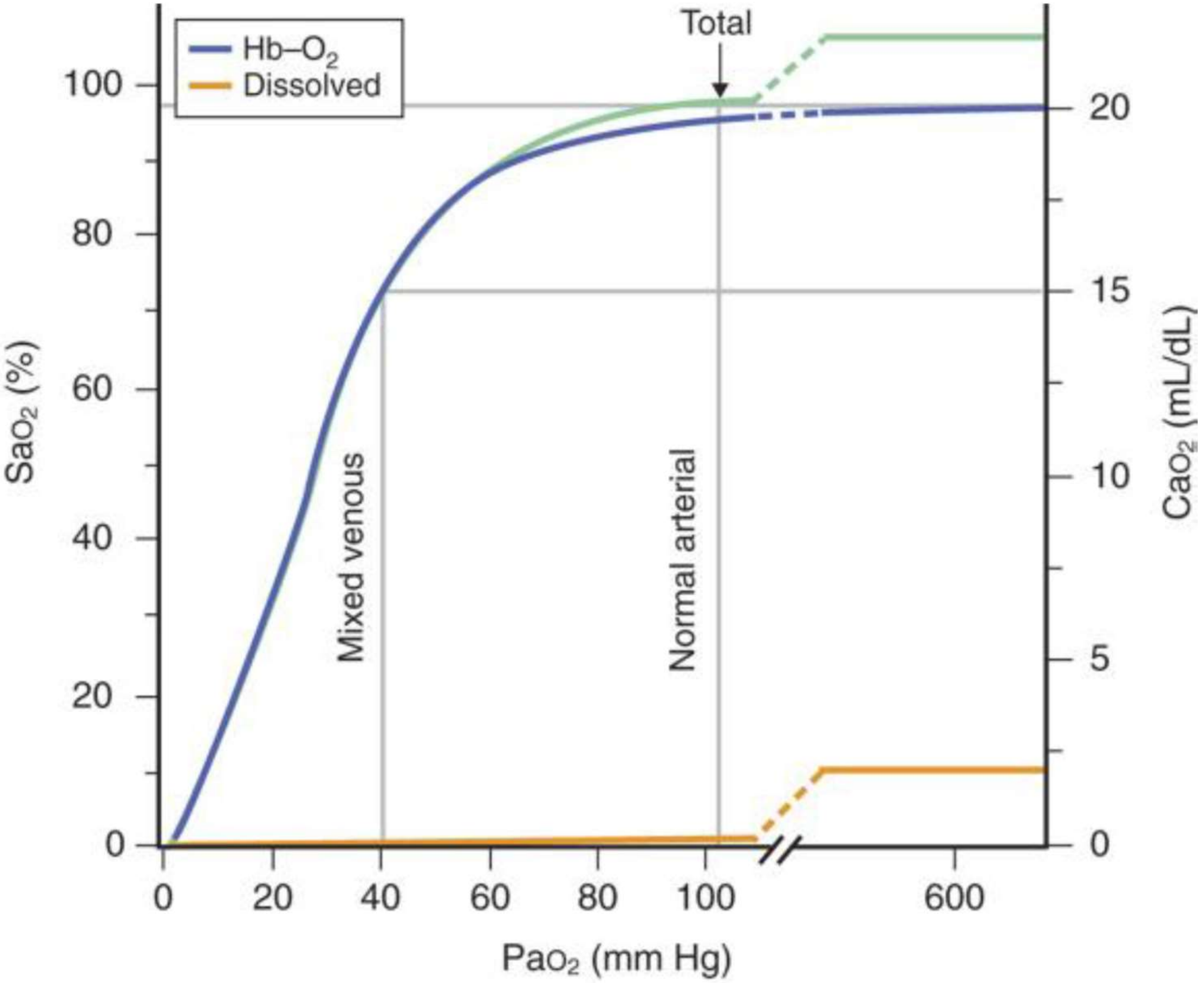


Hemoglobin (Hgb) is a tetrameric protein with 4 subunits (2 alpha, 2 beta)

Each heme binds 1 O2 molecule

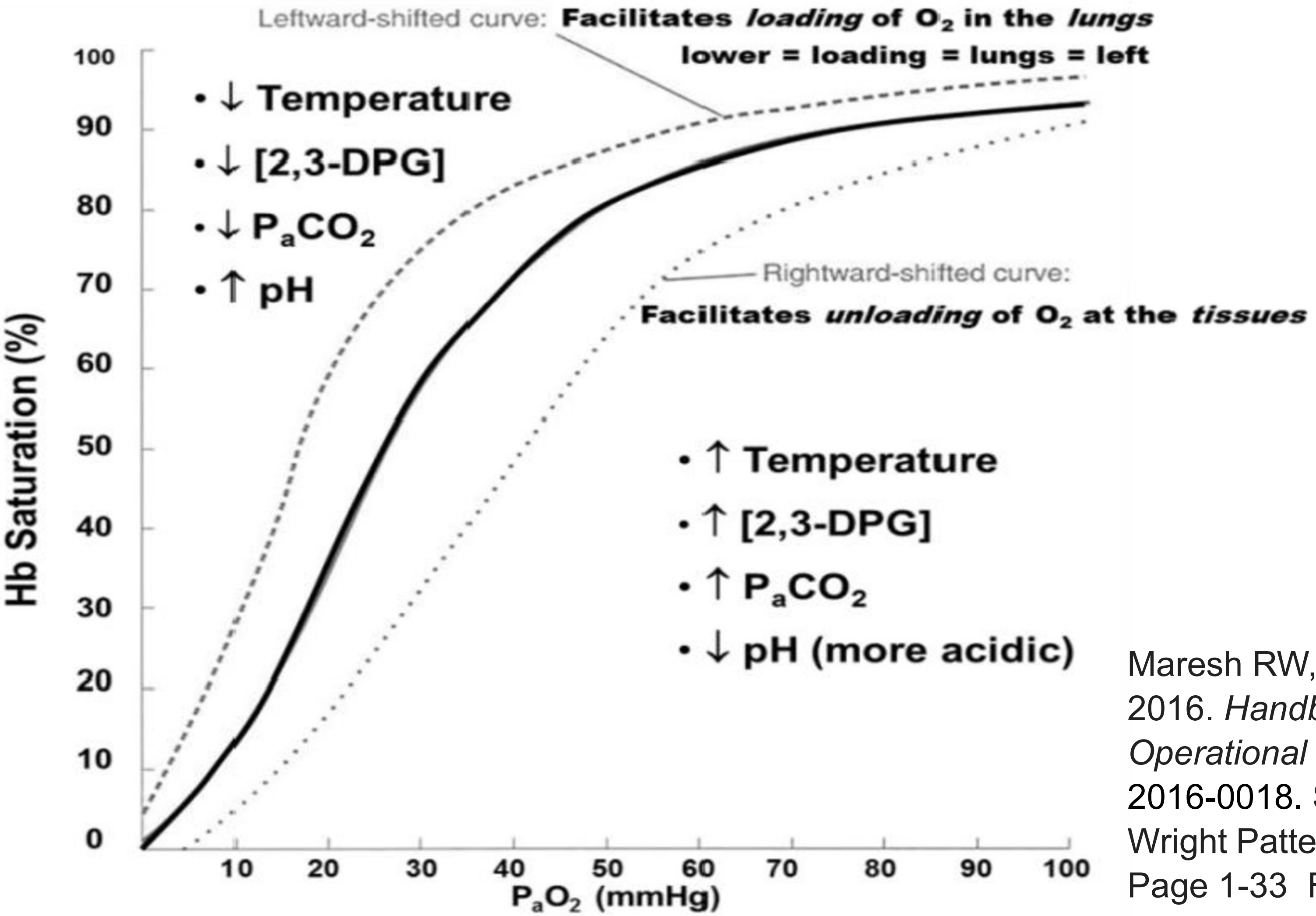
O2 molecule alters Hgb protein which facilitates subsequent O2 binding (cooperative binding)

Oxygen (O2) Hemoglobin (Hb) Dissociation Curve



Maresh RW, Woodrow AD, Webb JT., 2016. *Handbook of Aerospace and Operational Physiology*. AFRL-SA-WP-SR-2016-0018. School Of Aerospace Medicine Wright Patterson AFB OH United States. Page 1-30 Figure 1.2.6.1

Factors Affecting Oxygen-Hemoglobin Dissociation Curve



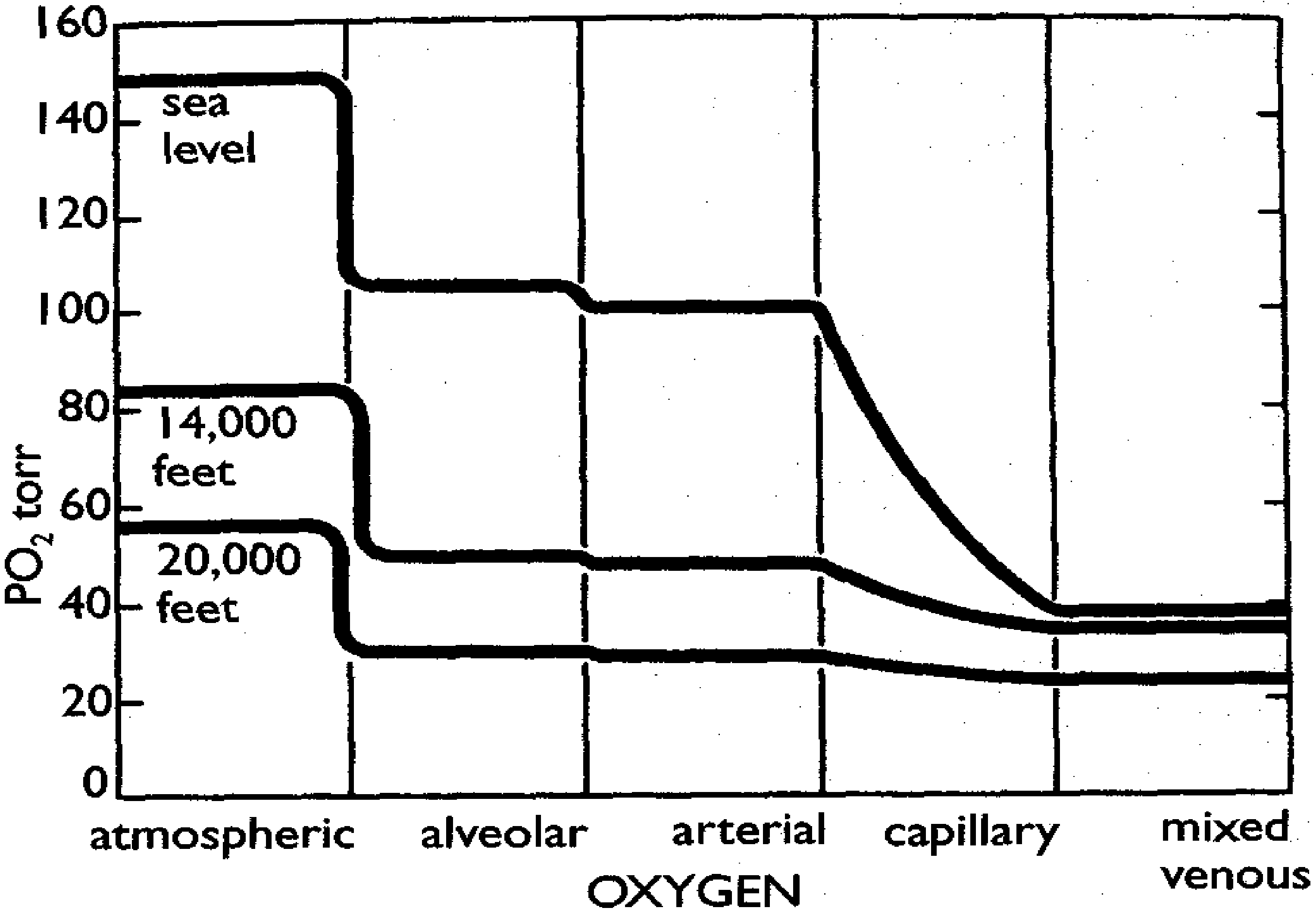
Maresh RW, Woodrow AD, Webb JT., 2016. *Handbook of Aerospace and Operational Physiology*. AFRL-SA-WP-SR-2016-0018. School Of Aerospace Medicine Wright Patterson AFB OH United States. Page 1-33 Figure 1.2.7.1

Gas Composition in Atmosphere Verses Alveolus (Lung)

Atmosphere: 2 Gases
- Nitrogen
- Oxygen

Alveolus: 4 Gases
- Nitrogen
- Oxygen
- Carbon Dioxide
- Water Vapor

The Oxygen Cascade



Types of Hypoxia

Hypoxic (Hypobaric) Hypoxia

Oxygen deficiency from ineffective gas exchange at lung or inadequate oxygen inspiration

Hypemic (Anemic) Hypoxia

Oxygen deficiency from reduced oxygen carrying capacity in the blood (anemia, dyshemoglobin medication)

Histotoxic (Cytotoxic) Hypoxia

Oxygen deficiency from inability to use oxygen at the molecular level (alcohol, carbon monoxide, cyanide)

Stagnant (Ischemic) Hypoxia

Oxygen deficiency from inadequate blood flow

Dyshemoglobin Medication cause Functional Anemia

Methemoglobin

Some medications cause heme group to oxidize from Fe_{+2} to Fe_{+3} and form methemoglobin (dyshemoglobin) which is no longer able to bind and release oxygen properly, resulting in functional, or “relative,” anemia

Sulfhemoglobin

Sulfa medications react with hemoglobin to form sulfhemoglobin causing a conformational change in the hemoglobin molecule, prevent efficient oxygen transport, and cause relative anemia

Altitude, Alveolar pO_2 & Hgb Saturation Ambient Air

Altitude (Feet)	**Barometric Pressure (mm Hg)**	**Alveolar Oxygen (PAO_2)**	**Hemoglobin Saturation % (Hgb)**
Sea level	760	**104**	97
10,000	523	**67**	90
20,000	349	40	70
30,000	226	21	20
40,000	141	6	5
50,000	87	1	1

Altitude, Alveolar pO_2 & Hgb Saturation 100% Oxygen

Altitude (Feet)	Barometric Pressure (mmHg)	Alveolar Oxygen (PAO_2)	Hemoglobin Saturation % (Hgb)
Sea level	760	673	100
10,000	523	436	100
20,000	349	262	100
30,000	226	**139**	99
40,000	141	**58**	87
50,000	87	16	15

Hypoxia Signs and Symptoms

Objective Signs (Observable)

Cyanosis (blue fingernails and lips) (a)

Decreased reaction time

Euphoria (unusually happy or belligerent) (a)

Impaired judgment

Increased respiration (increased depth/ rate of breathing) (a)

Mental confusion (a)

Muscle incoordination (a)

Unconsciousness

Subjective Symptoms (Self Observed)

Air hunger

Apprehension (worried or nervous)

Dizziness (lightheaded or dizzy sensation)

Fatigue

Headache

Hot and cold flashes

Nausea

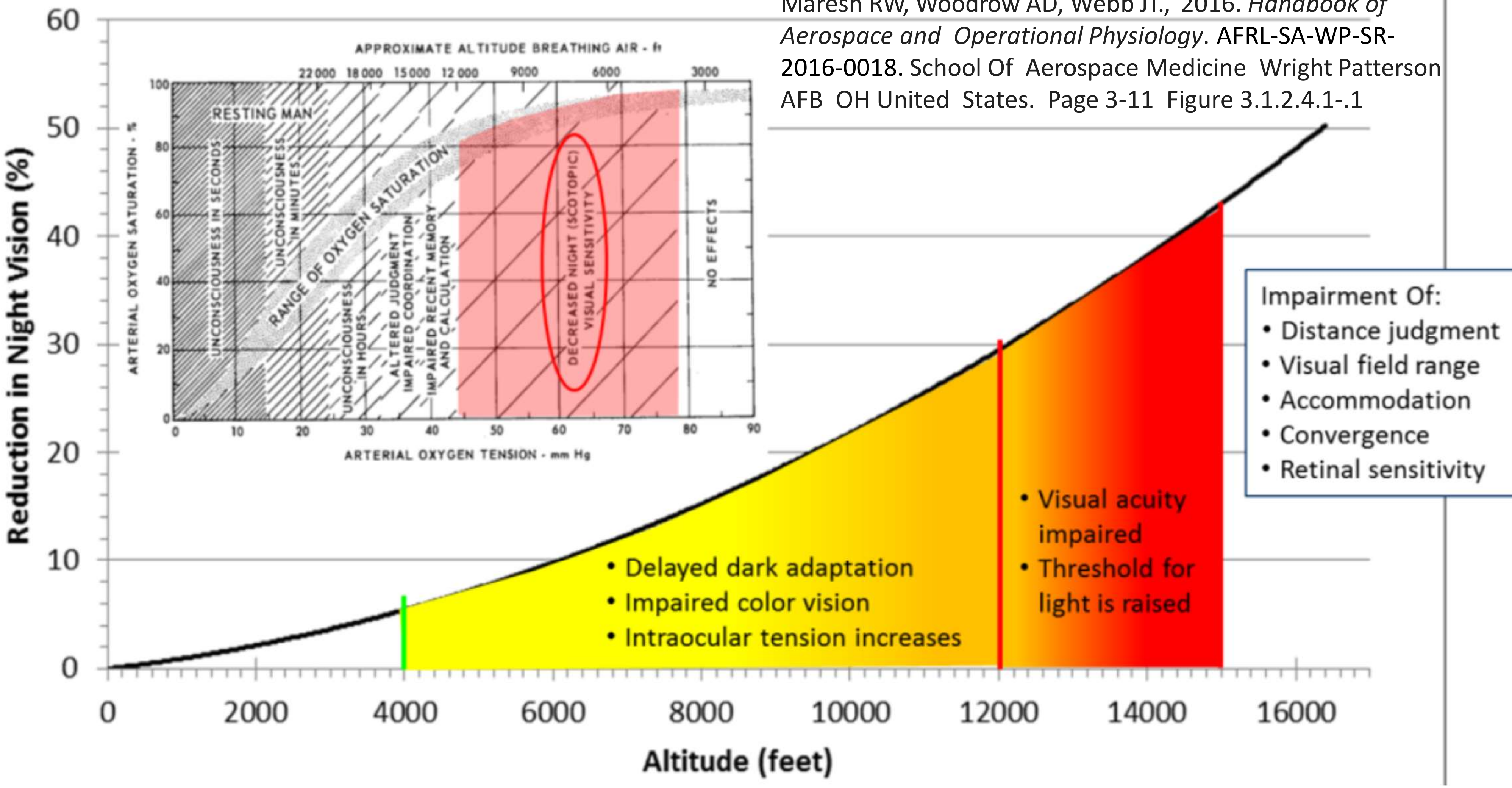
Numbness

Tingling in fingers and toes

Visual impairment (blurred/ tunnel vision, dimming of light or color

(a) Could also be self-observed

Dark Visual Capability vs. Altitude



Maresh RW, Woodrow AD, Webb JT., 2016. *Handbook of Aerospace and Operational Physiology*. AFRL-SA-WP-SR-2016-0018. School Of Aerospace Medicine Wright Patterson AFB OH United States. Page 3-11 Figure 3.1.2.4.1-.1

- Delayed dark adaptation
- Impaired color vision
- Intraocular tension increases

- Visual acuity impaired
- Threshold for light is raised

Impairment Of:
- Distance judgment
- Visual field range
- Accommodation
- Convergence
- Retinal sensitivity

Factors Affecting Hypoxia Symptoms

Pressure altitude

Rate of ascent

Time at altitude

Temperature

Physical activity (higher metabolic workload)

Individual factors (smoking, anemia, dyshemoglobin medications)

Physical fitness (less lean body mass)

Time of Useful Consciousness (TUC)

Also called Effective Performance Time (EPT)

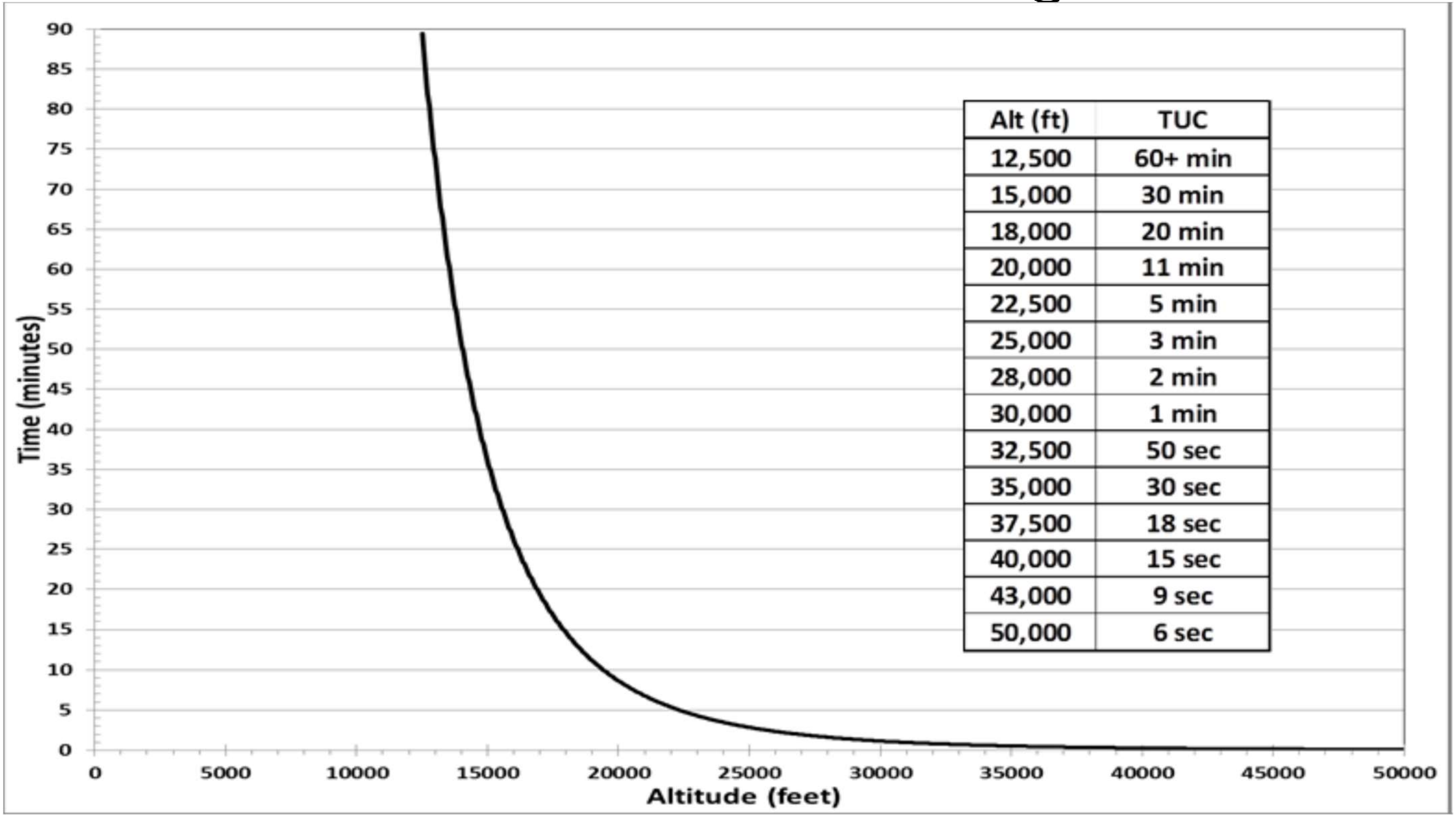
TUC is the time between reduction in inspired oxygen tension and the point where a specified degree of performance impairment ioccurs

Most importantly TUC/ EPT is the time an affected individual must recognize and respond to correct their predicament (get on oxygen and lower altitude)

Above 43,000 ft the TUC is 9 - 12 seconds

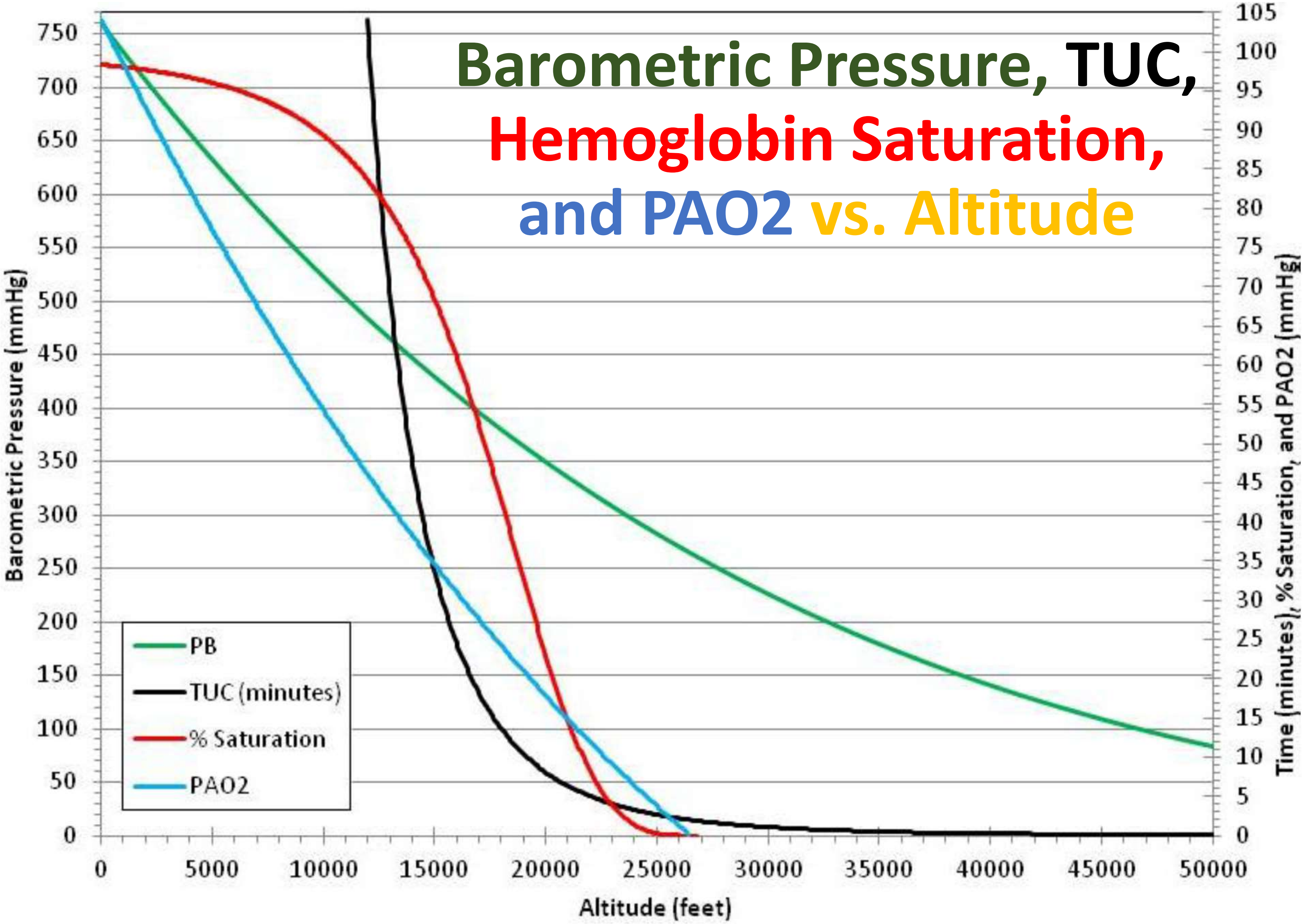
Relates to brain’s neuronal oxygen reserve and circulation time

Time of Useful Consciousness Breathing Air vs. Altitude



Alt (ft)	TUC
12,500	60+ min
15,000	30 min
18,000	20 min
20,000	11 min
22,500	5 min
25,000	3 min
28,000	2 min
30,000	1 min
32,500	50 sec
35,000	30 sec
37,500	18 sec
40,000	15 sec
43,000	9 sec
50,000	6 sec

Barometric Pressure, TUC, Hemoglobin Saturation, and PAO2 vs. Altitude



Altitude vs. Time of Useful Consciousness (TUC) also called Effective Performance Time (EPT)

TUC/ EPT decreases with

↑ altitude

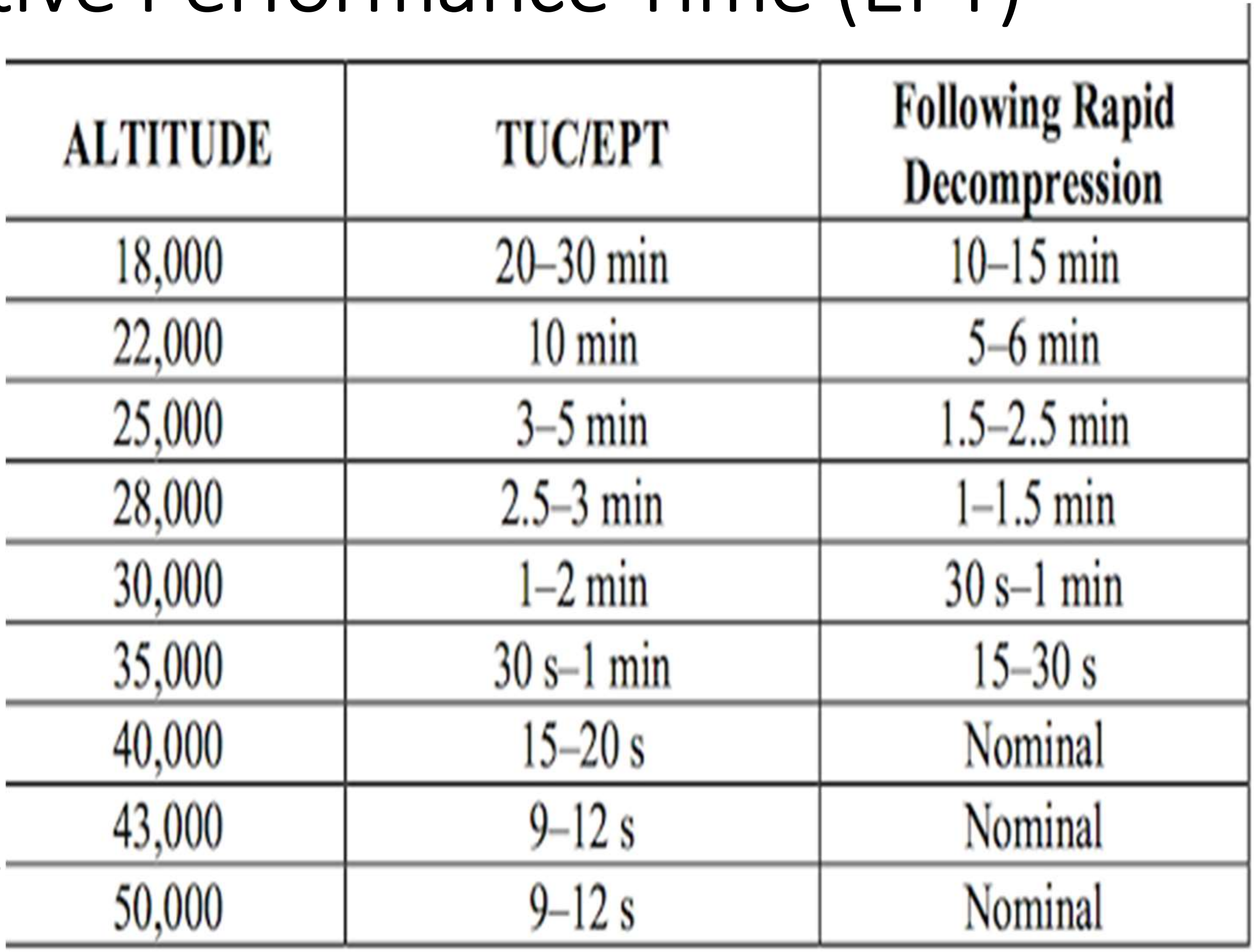
↑ metabolic workload

↓ cabin pressure (leak)

↓ O2 % (mask leak)

Rapid depressurization

Underlying medical issues



ALTITUDE	TUC/EPT	Following Rapid Decompression
18,000	20–30 min	10–15 min
22,000	10 min	5-6 min
25,000	3–5 min	1.5–2.5 min
28,000	2.5–3 min	1–1.5 min
30,000	1–2 min	30 s–1 min
35,000	30 s–1 min	15–30 s
40,000	15–20 s	Nominal
43,000	9–12 s	Nominal
50,000	9–12 s	Nominal

Rapid Decompression (RD) and Hypoxia

The sudden drop in barometric pressure accompanying RD produces rapid drop in O_2 partial pressure (O_2 tension) of alveolar gases

Oxygen tension in the blood is higher than in the lungs, so oxygen passes from the blood into the alveoli

Oxygen Gradient results in **oxygen leaving the body**

Hypoxia-induced neurological consequences occur when alveolar oxygen falls below ~30 mmHg

Absolute Respiratory Limit: 50,000 Feet

At 50,000 feet the Atmospheric Pressure is 87 mm Hg

In the lung the alveolar pressures are

PACO2 = 40 mm Hg

Vapor Pressure of Water = 47 mm Hg

No atmospheric air (nitrogen & oxygen) gets into alveolus

Returning venous blood from tissue has paO_2 about 40 mm Hg

O_2 diffuses towards lower partial pressure in lungs

Oxygen gradient results in **oxygen leaving the body**

Carbon Dioxide Issues

Hyperventilation and Hypocapnia

Hyperventilation is an increase in ventilation (rate and/or depth of respiration) beyond that necessary to maintain normal blood carbon dioxide CO_2 levels for the current metabolic activity

Arterial $PaCO_2$ level is closely maintained at 40 mmHg +/- 3 mmHg

Hyperventilation/ Hypocapnia can lead to respiratory alkalosis affecting cellular metabolism and blood acid/ base balance

Hyperventilation/ Hypocapnia can lead to severe cerebrovascular vasoconstriction leading to stagnant (ischemic) hypoxia resulting in neurologic dysfunction and even unconsciousness

Causes of Hyperventilation and Hypocapnia

Emotional or psychological stress (anxiety, fear, excitement)

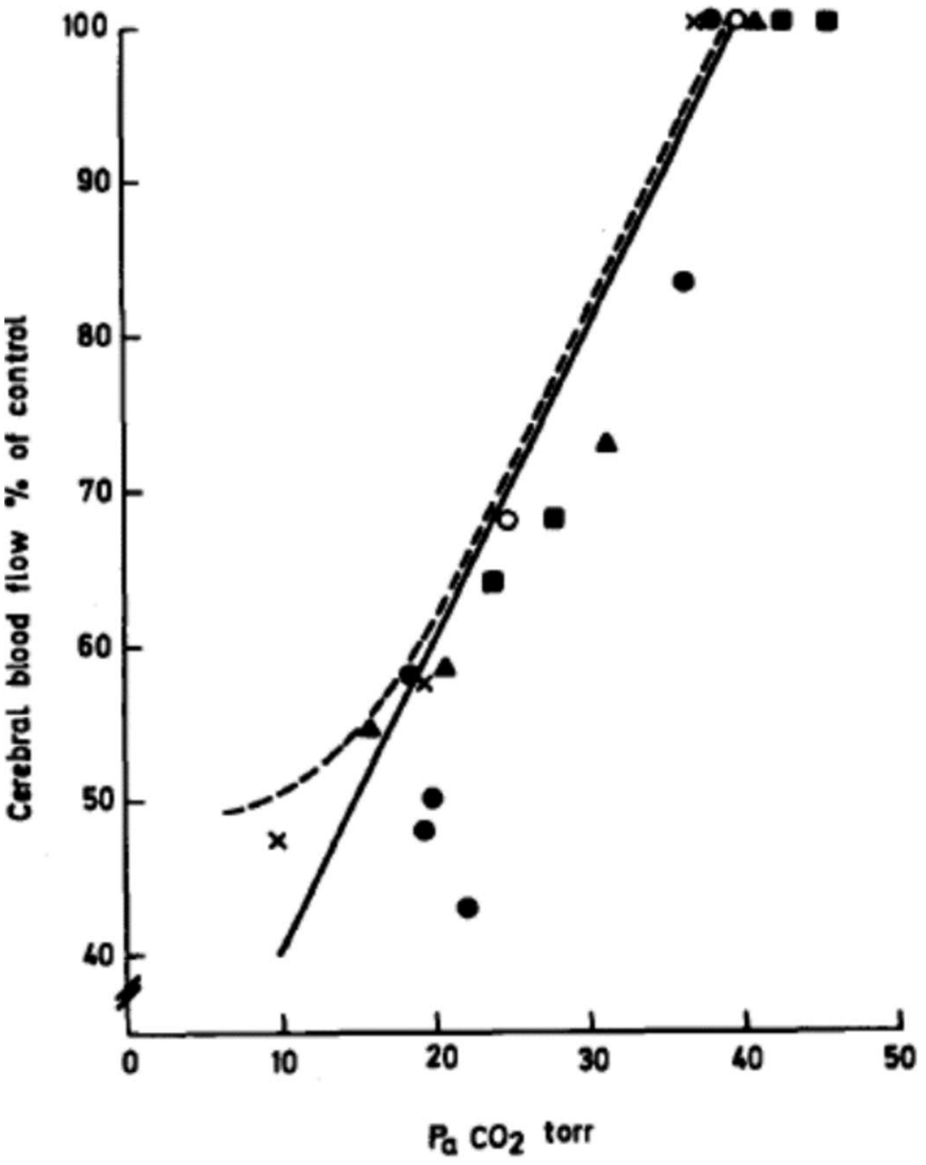
Physical or physiological stress (pain, motion sickness)

Environmental stress (altitude, heat, vibration, positive pressure breathing)

Improperly sized or fit aircrew equipment (increased breathing resistance, restricted chest expansion, shallow breathing)

Volitional hyperventilation prior to breath hold dive

Hyperventilation is a normal response to hypoxic hypoxia



Hyperventilation induced Hypocapnia leads to cerebral vasoconstriction and reduced cerebral blood flow

Gibson TM. Hyperventilation in Aircrew: A Review. Aviat Space Environ Med (1979) 50(7):725-733.

Hyperventilation/ Hypocapnia mimics Hypoxia

What distinguishes it from hypobaric hypoxia

An altitude not consistent with hypoxia, ie below 10,000 feet
Pale clammy skin, not cyanotic
Muscle spasms or tetany like carpopedal spasms

Response to slower rate and depth of breathing, talking out loud slows respiration

Aircrew taught if not sure if hyperventilation or hypoxia then give oxygen do PRICE check
(Hyperventilation/ hyponocapnia on O2 may lead to Oxygen Paradox

Differences between Hypoxic Hypoxia and Hyperventilation

Signs/ Symptoms	Hypoxic (Altitude) Hypoxia	Hyperventilation
Sign symptom Onset	Rapid (altitude dependent)	Gradual
Muscle activity	Flaccid, limp	Spasm
Appearance	Cyanosis	Pale, clammy
Tetany	Absent	Present
Recovery on O2	Rapid	Gradual

Maresh, R.W., Woodrow, A.D. and Webb, J.T., 2016. *Handbook of Aerospace and Operational Physiology*. AFRL-SA-WP-SR-2016-0018.School Of Aerospace Medicine Wright Patterson AFB OH United States. Page 3-24

Oxygen Paradox

Hypoxia like symptoms made worse by Oxygen administration

Hyperventilation related Hypocapnia leads to cerebral vasoconstriction (stagnant/ ischemic hypoxia) and reduced cerebral blood flow which would compound hypoxia hypoxia

Supplemental Oxygen overrides peripheral chemoreceptors which trigger respiration when PaO2 < 60 mmHg and the reduced PaCO2 from hyperventilation does not trigger the central chemoreceptors to trigger respiration

Supplemental O2 causes peripheral vasodilation, reducing blood pressure and cerebral perfusion pressure

Hyperventilation Related Aerospace Events

Multiple US military tactical jet and training jet pilots experienced Hypoxia Like Physiologic Events related to aircraft oxygen systems (On-board Oxygen Generating Systems) and oxygen life support equipment issues. Multiple root causes identified, including hyperventilation related episodes with recommendation for Controlled Breathing Exercises

During Red Bull Stratos Manned Balloon Flight 3 the parachutist in a full pressure suit was overbreathing and encounter transient visor fogging and anxiety. Controlled breathing eliminated symptoms

Health and Performance Consequences of Elevated CO2

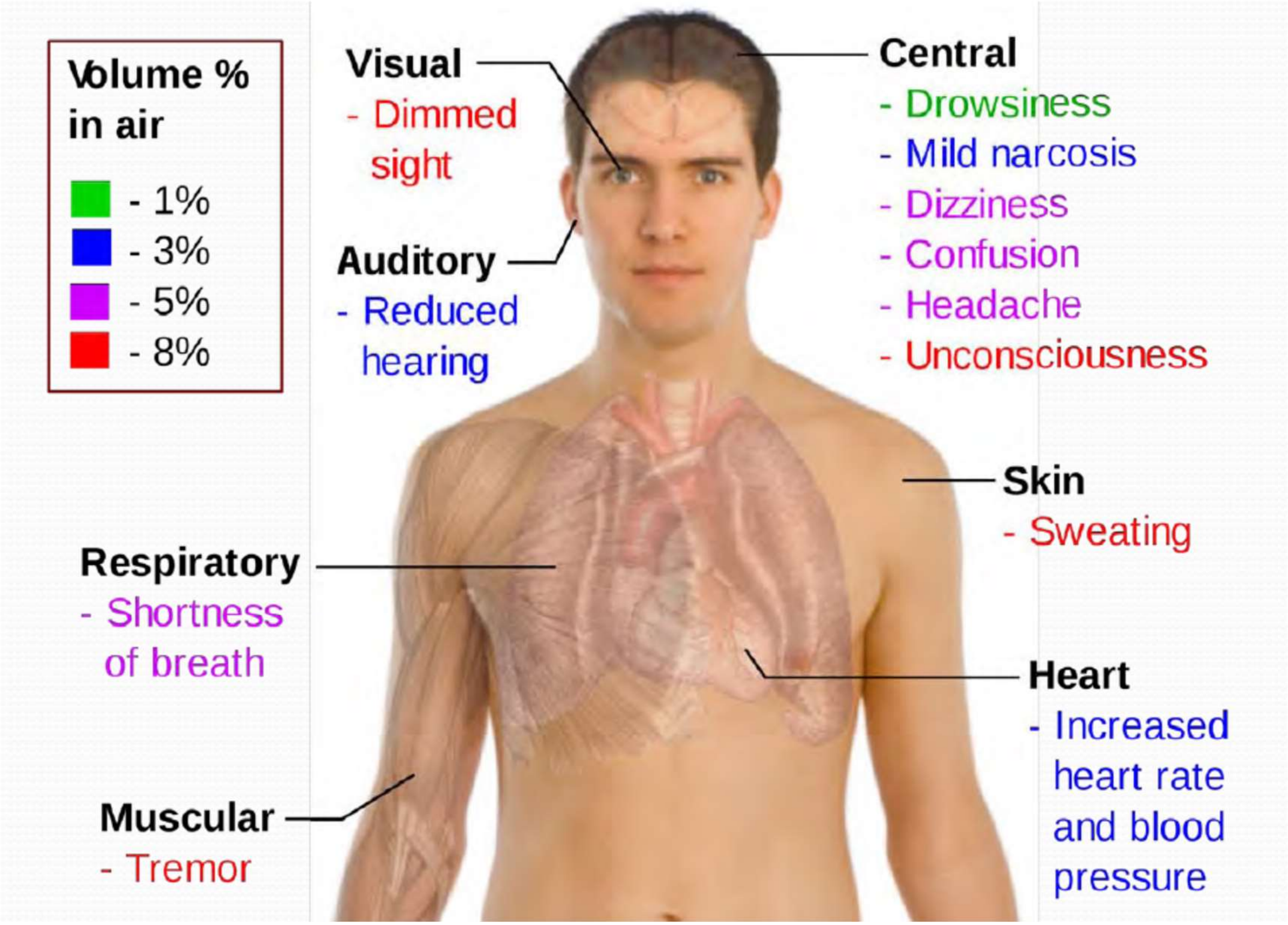
CO_2 is the most potent cerebral vasodilator

Spacecraft have elevated ambient carbon dioxide (CO_2) concentrations compared to Earth's atmosphere due to CO_2 removal life support constraints

Likelihood of headaches in astronauts increase with elevated CO_2 (1 to 4% with 24-hr average CO_2 level from 2.5 to 4 mmHg, respectively)

Astronauts anecdotally report irritability with higher CO2 levels

Carbon Dioxide Toxicity Symptoms



Risk Associated with Acute or Chronic CO_2 Elevation

NASA Spacecraft Maximum Allowable Concentration (SMAC)

Acute risks - <24 h CO_2 concentrations above baseline contingency SMACs

1 h SMAC = 2%

24 h SMAC = 1.3%

Sub-acute risks - CO_2 elevation of days up to 30 days
Sub-acute SMACs 7-d/ 30-d SMACs = 0.7%. (ppCO_2 5.3mmHg/ 7000 ppm)

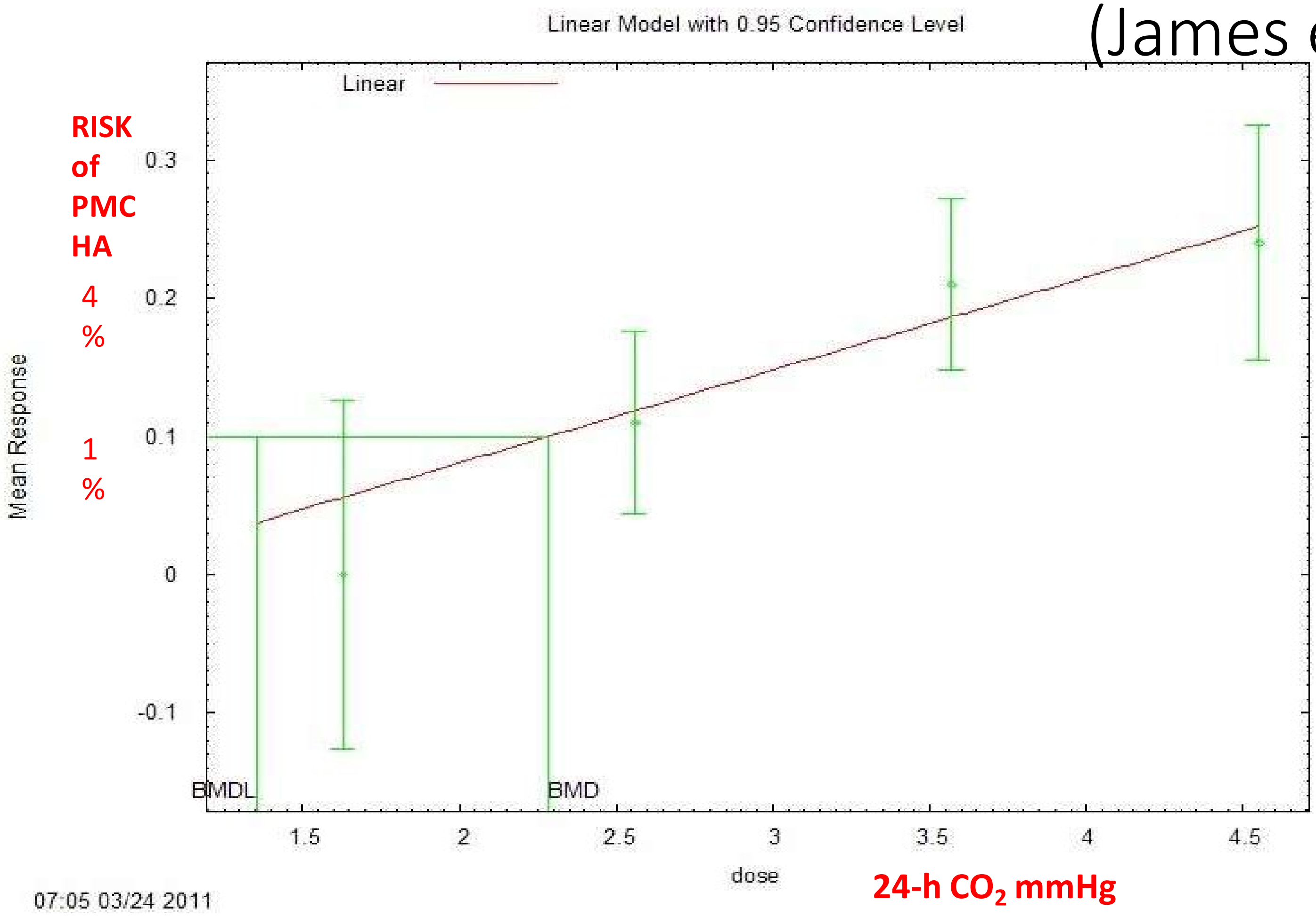
Chronic risks - prolonged, continuous elevated CO_2 for months to less than 3 years

180-d SMAC = 0.7%

1000-d SMAC = 0.5%)

International Space Station (ISS) crews report symptoms consistent with acute CO_2 toxicity (headaches, lethargy) at CO_2 concentrations below SMAC values

Headache Risk Reported during Private Medical Conference (James et al. 2011)



Risk of headache being reported during a PMC increases with increasing 24-hr average levels of CO_2 in the range of 2-5 mmHg aboard ISS

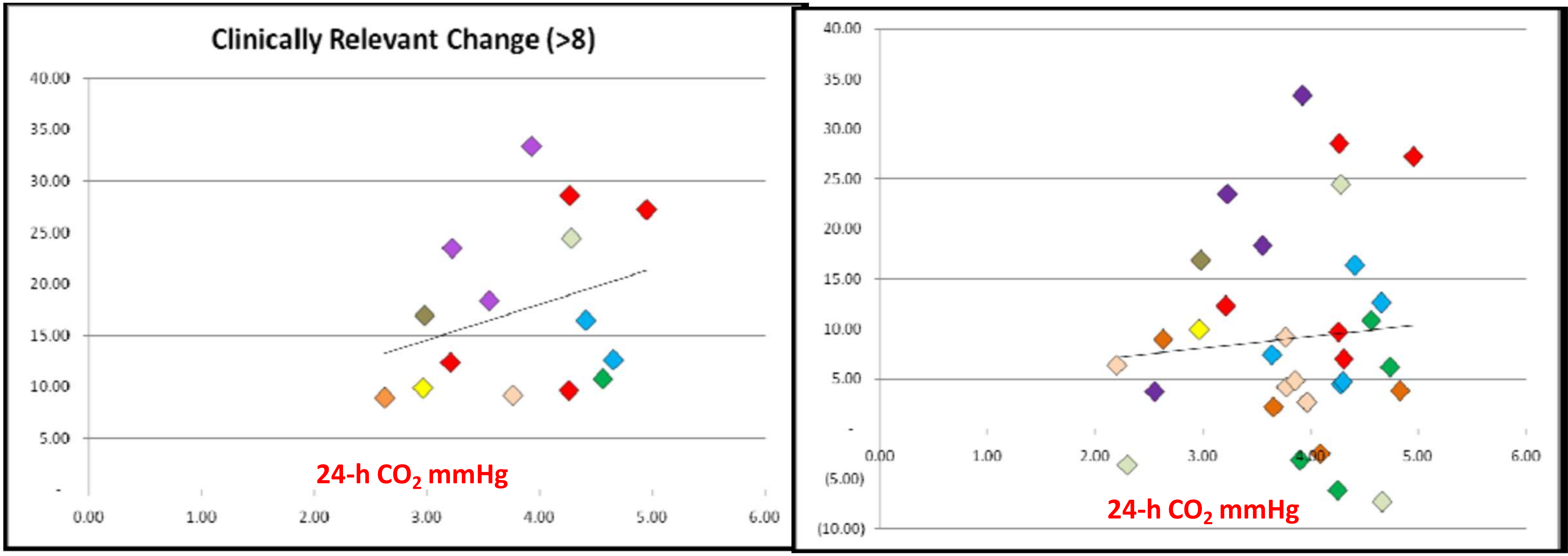
Occurrence of numerous *"space viscosity"* events aboard ISS*

Maintaining a CO2 level of 2-2.5 mmHg will result in a 1% risk that headaches could be reported during a PMC and a 4% risk if kept at ~4 mmHg CO2

Operational limits below 3 mmHg CO2 are not practical from a hardware standpoint

James J, Matty C, Meyers V, Sipes W, Scully R. 2011, July. Crew health and performance improvements with reduced carbon dioxide levels and the resource impact to accomplish those reductions. In *41st International Conference on Environmental Systems* (p. 5047).

24 hr CO2 Levels and Effect on Cognitive Performance Task (winSCAT) in 9 ISS astronauts (James et al 2011)



James J, Matty C, Meyers V, Sipes W, Scully R. 2011, July. Crew health and performance improvements with reduced carbon dioxide levels and the resource impact to accomplish those reductions. In *41st International Conference on Environmental Systems* (p. 5047).

Is CO_2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO_2 Concentrations on Human Decision-Making Performance

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Environmental Health Perspectives • VOLUME 120 | NUMBER 12 | December 2012

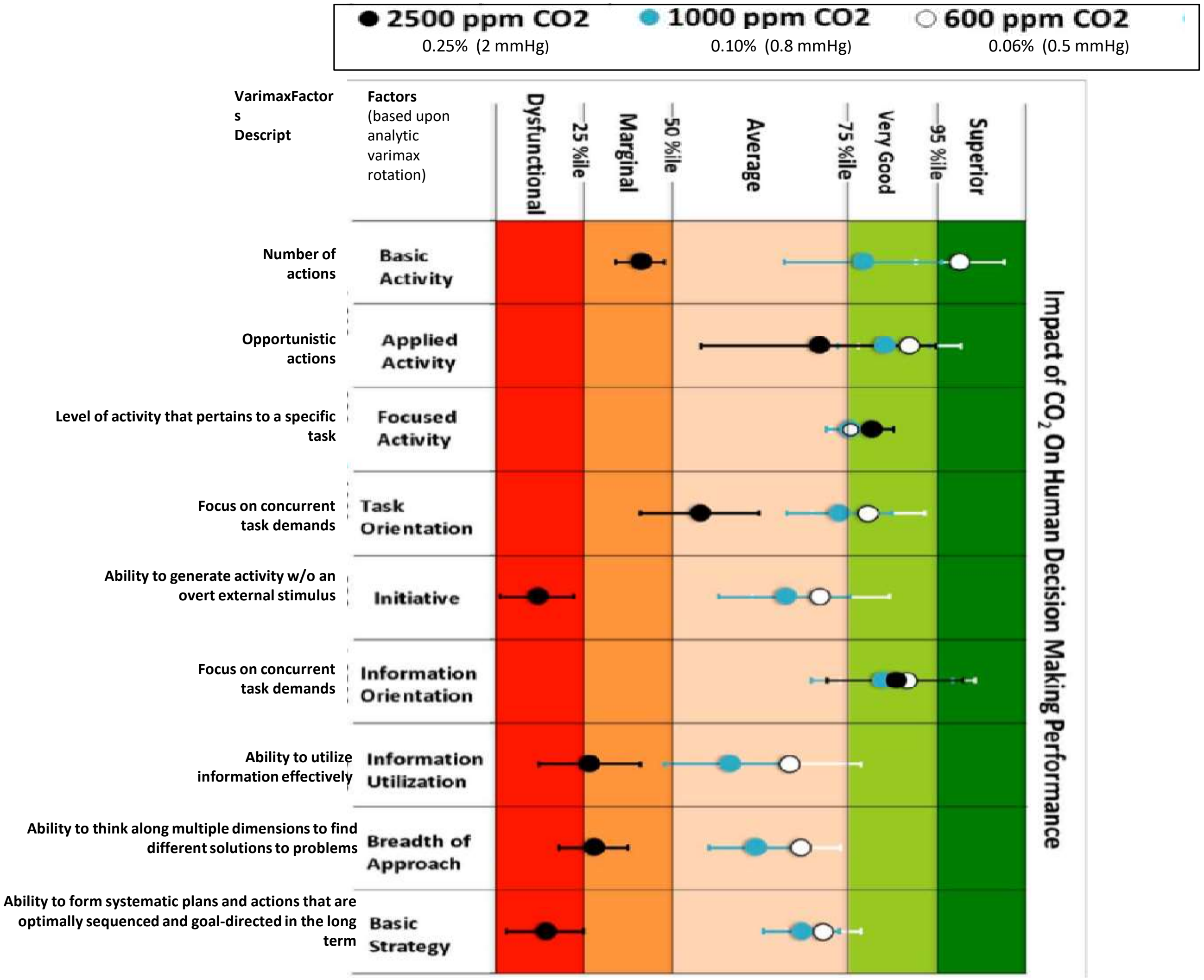
Decision-making performance (n=22) reaches dysfunctional levels for several measures during 2 ½ hour exposures to CO_2 at 1.9 mmHg

Visual effects reported in subjects (n=3) exposed for ~30 min to19 mmHg

CO_2 Depth perception decreased (Sun, et al., 1996)

Motion detection decreased (Yang, et al., 1997)

Effects of CO^2 on decision-making performance (Satish et al. 2012)

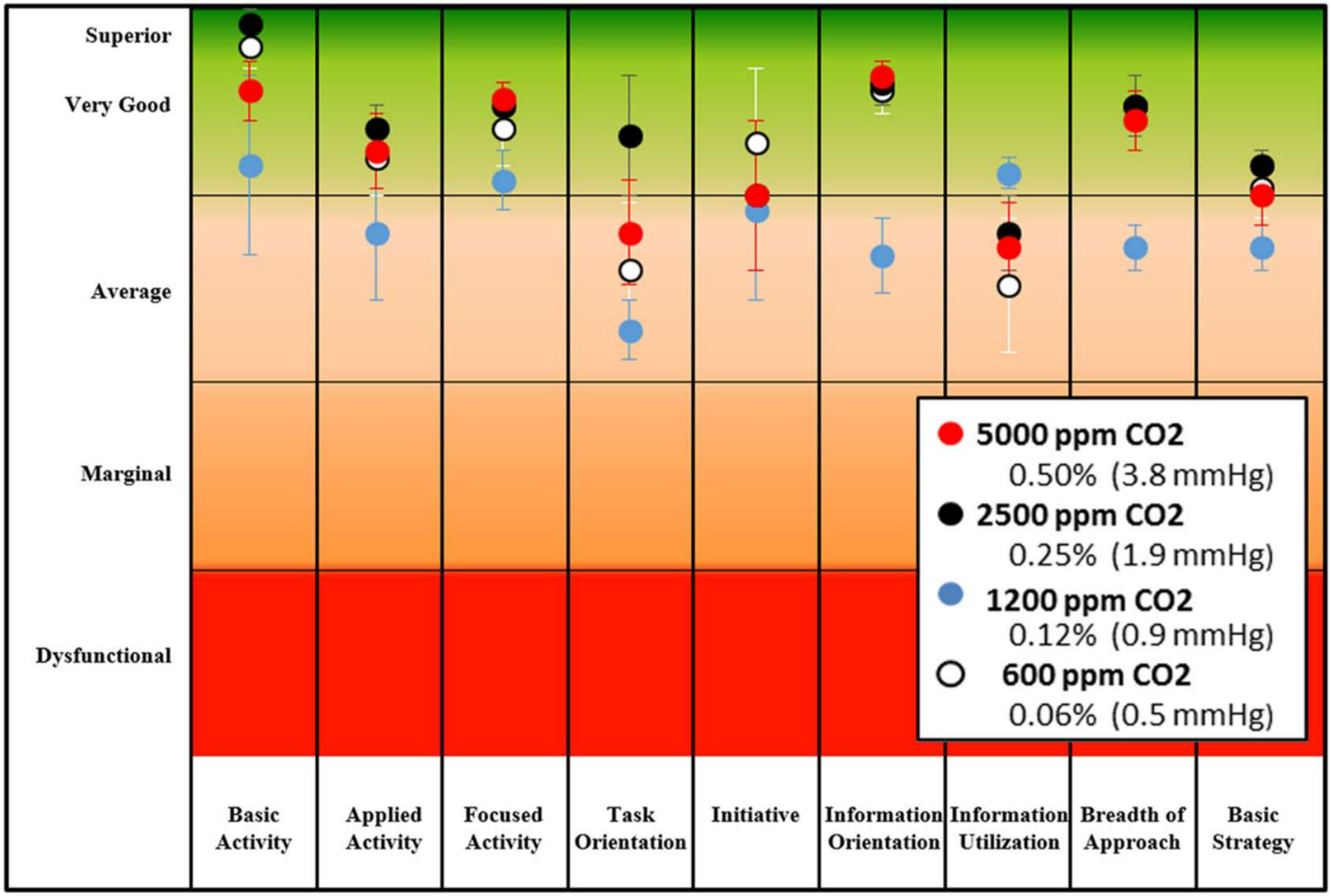


Relevance to Operations:

- Decision Making
- Situational Awareness

The Challenge of Aviation Emergency and Abnormal Situations
Barbara K. Burian, Immanuel Barshi and Key Dismukes
when experiencing stress and high workload, crews are vulnerable to missing important cues related to their situation and are likely to experience difficulty pulling together disparate pieces of information and making sense of them. This is especially true when some of that information is incomplete, ambiguous, or contradictory. Pilots' problem-solving abilities may be impaired, and they will generally have difficulty performing complex mental calculations (Hendy, Farrell, & East, 2001)… In contrast, well-learned motor skills, such as those demonstrated by experienced pilots when operating flight controls, are quite robust and are much less affected by stress (Cohen & Weinstein, 1981).
See Slides 19 & 20: Skill v. Prob. Solving

Effects of acute exposures to carbon dioxide on decision making and cognition in astronaut-like subjects



Scully RR, Basner M, Nasrini J, Lam CW, Hermosillo E, Gur RC, Moore T, Alexander DJ, Satish U, Ryder VE, 2019. Effects of acute exposures to carbon dioxide on decision making and cognition in astronaut-like subjects. *npj Microgravity*, *5*(1), pp.1-15.

Effects of acute exposures to carbon dioxide on decision making and cognition in astronaut-like subjects

There were no clear dose–response patterns for performance on either SMS or Cognition. Performance on most SMS measures and aggregate speed, accuracy, and efficiency scores across Cognition tests were lower at 1200 ppm than at baseline (600 ppm); however, at higher CO2 concentrations performance was similar to or exceeded baseline for most measures.

These outcomes, which conflict with those of other studies, likely indicate differing characteristics of the various subject populations and differences in the aggregation of unrecognized stressors

Scully RR, Basner M, Nasrini J, Lam CW, Hermosillo E, Gur RC, Moore T, Alexander DJ, Satish U, Ryder VE, 2019. Effects of acute exposures to carbon dioxide on decision making and cognition in astronaut-like subjects. *npj Microgravity*, *5*(1), pp.1-15.

Carbon Dioxide as Medical Therapy

Carbogen is prescribed medical therapy for improving blood flow in certain conditions such as sudden sensorineural hearing loss and central retinal artery occlusion

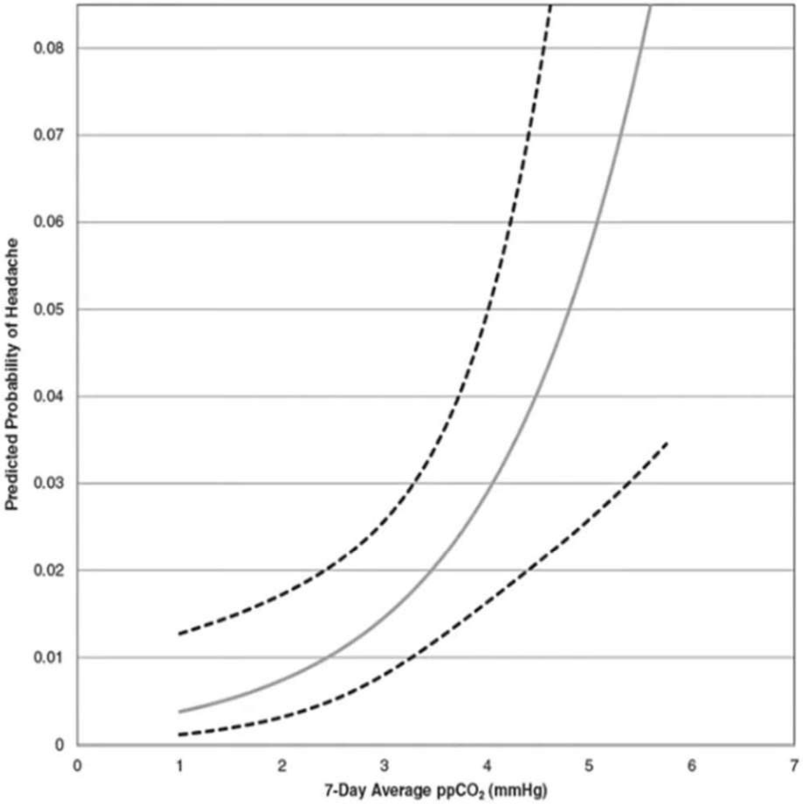
Carbogen is Carbon Dioxide (1.5%-50%) and Oxygen

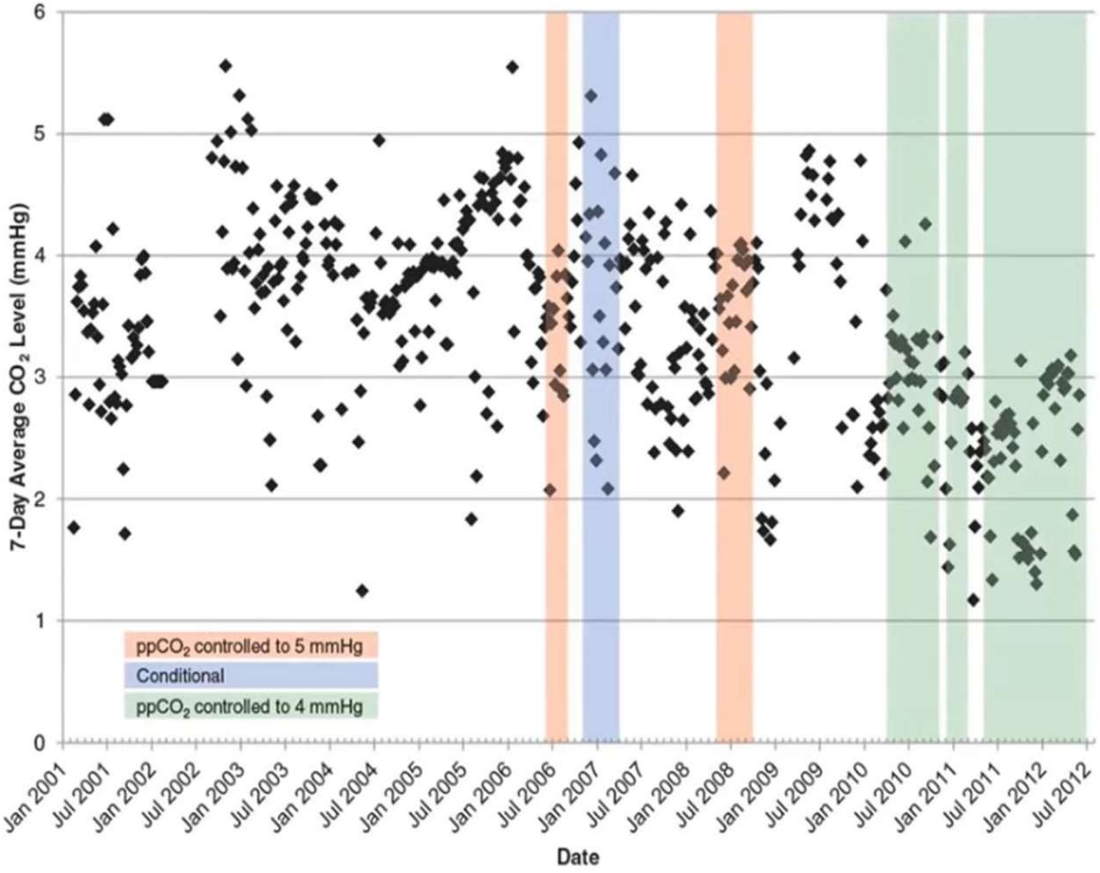
It was used in an astronaut following sudden sensorineural hearing loss related to otic barotrauma during an NBL EVA run and astronaut was returned to flight status

Alford BR, Clark JB, Danielson RW. Ear, nose and throat and auditory issues (Chapter 4.2) in: Biomedical Results of the Space Shuttle Program, Risin D, Stepaniak PC (eds.), Washington DC: U.S. Government Printing Office, NASA/SP-2013-607. ISBN: 978-0-615-86613-0, pp.59-72.

Headache Probability increases with CO2 concentration

CO2 limits on ISS





Law J, et al. J Occup Environ Med. 2014;56(5):477-483.

Space CO2 Concerns

Levels of CO_2 on ISS are chronically above the level shown by Satish et al., (2012) to have profound effect upon ability to make decisions

Preliminary ISS inflight data indicate that an increase in headaches reported by crews during Private Medical Conferences with increasing 24-hr CO_2 levels in the range of 2-5mmHg (0.26-0.66%).

These headaches are not controlled by ordinary medications

Crews on exploration class missions will have to rely on their decision-making ability to deal with many off-nominal conditions expected during long missions.

Summary

Ambient pressure reduction decreases oxygen partial pressure (hypoxic hypoxia) that can lead to human performance decrements, incapacitation, or death

Hypoxic hypoxia consequences are influenced by degree, rate, and duration of pressure reduction

Hypoxic Hypoxia due to ambient atmospheric pressure reduction may occur concurrently with bubble related disorders (evolved gas/ decompression sickness, trapped gas/ barotrauma, and/ or water vaporization/ ebullism

Hyperventilation reduces CO_2 levels resulting in blood vessel vasoconstriction which mimic hypoxia symptoms

Elevated CO_2 levels cause cerebral vasodilatation, may result in headache, irritability, and/ or cognitive effects

Hypoxia and Depressurization References

Clark JB. *"Decompression Related Disorders II: Pressurization Systems, Depressurization, Barotrauma and Altitude Sickness"* in Principles of Clinical Medicine for Space Flight, Chapter 10; 1st edition. Barratt MR, Pool SL, eds. New York: Springer-Verlag (2008) ISBN: 978-0-387-98842-9

Maresh RW, Woodrow AD, Webb JT. 2016. *Handbook of Aerospace and Operational Physiology*. AFRL-SA-WP-SR-2016-0018..School Of Aerospace Medicine Wright Patterson AFB OH United States.

Pilmanis AA, Clark JB. "Decompression-Related Disorders.“ Chapter 16 in *Principles of Clinical Medicine for Space Flight* 2nd edition Barratt MR, Baker ES, Pool SL, eds. New York: Springer-Verlag (2019): 481-518.

Clark JB. (2020) The Space Environment: An Overview. In: Young LR. Sutton JP. (eds) Handbook of Bioastronautics. Springer, Cham. https://doi.org/10.1007/978-3- 319-10152-1_127-1

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Satish U, Mendell MJ, Shekhar K, Hotchi T, Sullivan D, Streufert S, Fisk WJ, 2012. Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. *Environmental health perspectives*, *120*(12), pp.1671-1677.

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