Gas Related Problems related to Spacesuits

Jonathan B. Clark M.D., M.P.H.
jon@aerospacesafety.org
jbclarkmd@outlook.com

Foundation for Aerospace Safety and Training
Houston TX

U.S. SKC Program Spacesuit Medical Series

Learning Objectives

Understand how various atmospheric and metabolic gas 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

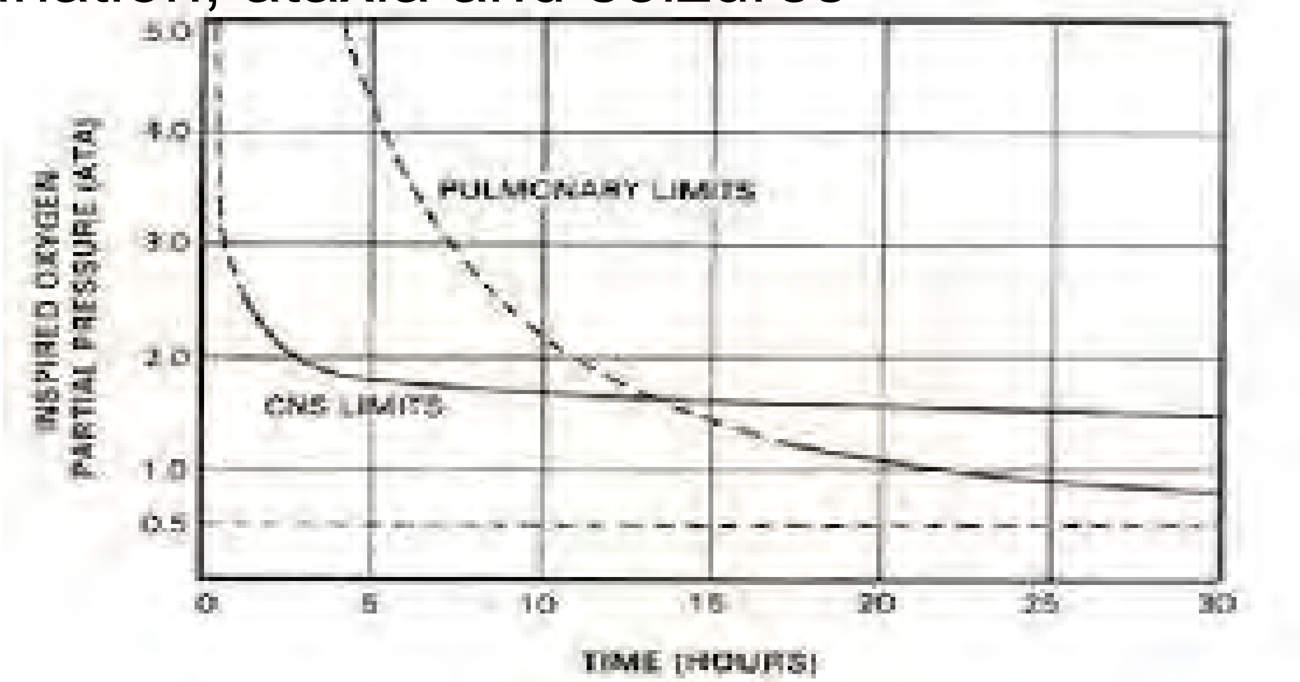
Earth Atmospheric Gas Composition

- 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 O_2 and causes alveolar collapse in less perfused lung
  - Pulmonary O2 Toxicity occurs above 60% O2 (FiO2)
- Nitrogen at high pressures is anesthetic (Nitrogen Narcosis)
  - Nitrogen (N_2) is inert at sealevel, 1 Atmosphere Absolute (ATA)
  - N_2 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

Oxygen can be toxic to pulmonary and/or central nervous system

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



So is Oxygen Toxicity a concern for Spacesuit Operations?

Scenario 1

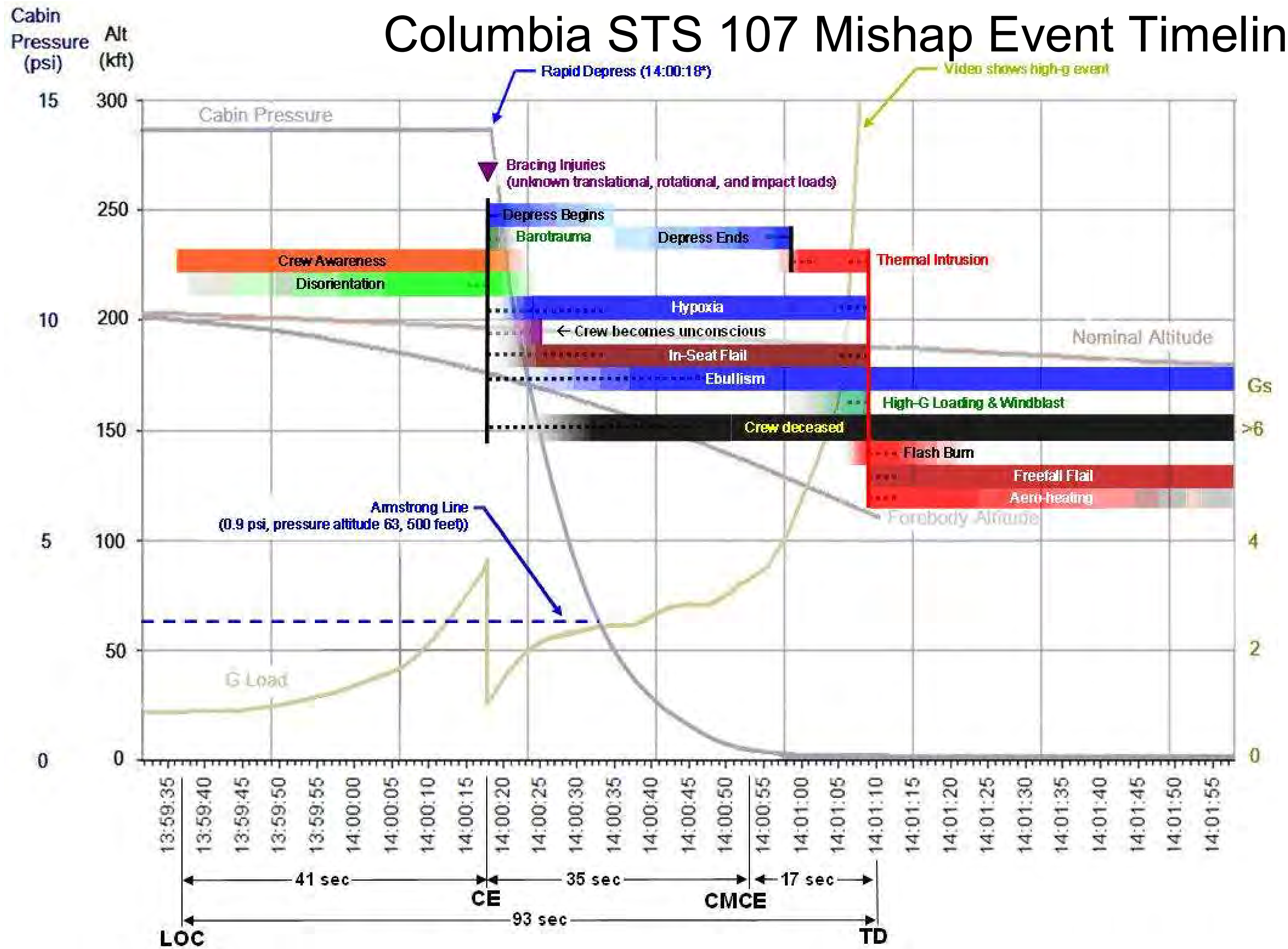
100% Oxygen used for O2 Prebreathe to wash out Nitrogen for DCS risk reduction, and 100% O2 in spacesuit for entire EVA

- 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)

Columbia STS 107 Mishap Event Timeline



Loss of Signal: Aeromedical Lessons Learned from the STS-107 Columbia Space Shuttle Mishap, Stepaniak PC, Lane HW (eds). Washington DC: US Government Printing Office, NASA/SP-2014-616, ISBN: 9780160923876, page 113.

Barometric Pressure Related Problems

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

Barotrauma

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

Ebullism

gas evolved from water (vapor pressure) below 47 mm Hg

severe lung damage within minutes

Human Health Threats and Countermeasures

Entry Phenomenon	Physical Characteristics	Altitude Range	Biologic Effect	Countermeasure
Plasma	Ionized molecular O2	> 130,000 Feet	Chemical / Thermal burn	Thermal Protection System
Excessive Acceleration Gradients	Delta G (dG/dT) x, y, z linear/ angular planes	Below Entry Interface (400K)	Organ/ Skeletal Damage, Body Fragmentation	Crew Compartment Stability System, Axial Restraint System
Shock Shock Interaction	Blast Wave Pressure	NA/ supersonic speeds	Organ Damage, Body Fragmentation	Aerodynamic Design, Crew Compartment Integrity
Dynamic Heating	C	> 150,000 feet	Thermal Burn	Thermal Protection System
Dynamic Pressure	Q		Organ/ Skeletal Damage, Body Fragmentation	Crew Protection System
Atmospheric Pressure	Atmosphere Absolute (ATA)	> 63,000 feet (< 0.06 ATA)	Tissue water vaporized to gas resulting in ebullism	Pressure Vessel, Pressure Suit, Pressure Breathing Mask
Atmospheric Pressure	Atmosphere Absolute (ATA)	> 18,000 feet (< 0.5 ATA)	Evolved tissue nitrogen resulting in decompression sickness (DCS)	Pressure Vessel, Pressure Suit, Pressure Breathing Mask
Pressure Differential	Delta pressure (dP)		Barotrauma in gas filled spaces (lung, ear, GI) resulting in arterial gas embolism	Pressure Vessel, Pressure Suit
Oxygen Partial Pressure	ppO2	> 10,000 feet	hypoxia and asphyxiation	Pressure Vessel, Pressure Suit, supplemental Oxygen
Intrusion of Habitable Space	Physical Trauma	NA	Fatal or severe organ damage due to penetration	Crew Compartment Protective System
Terrain Impact	Delta G (dG/dT) x, y, z linear planes	Surface	Injury due to Rapid Deceleration	Parachute, Lifting body, Airbag, Braking Rocket

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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, 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

Henry's Law: dissolved gas in liquid decrease as pressure around liquid decreases

DECOMPRESSION SICKNESS When pressure of liquid is reduced, gas comes out of solution as bubbles

Human Health Threats and Countermeasures

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Pressure Differential	Delta pressure (dP)		Barotrauma in gas filled spaces (lung, ear, GI) resulting in arterial gas embolism	Pressure Vessel, Pressure Suit
Oxygen Partial Pressure	**ppO2<182 mm Hg**	**> 10,000 feet**	**hypoxia and asphyxiation**	**Pressure Vessel, Pressure Suit, supplemental Oxygen**
Intrusion of Habitable Space	Physical Trauma	NA	Fatal or severe organ damage due to penetration	Crew Compartment Protective System
Terrain Impact	Delta G (dG/dT) x, y, z linear planes	Surface	Injury due to Rapid Deceleration	Parachute, Lifting body, Airbag, Braking Rocket

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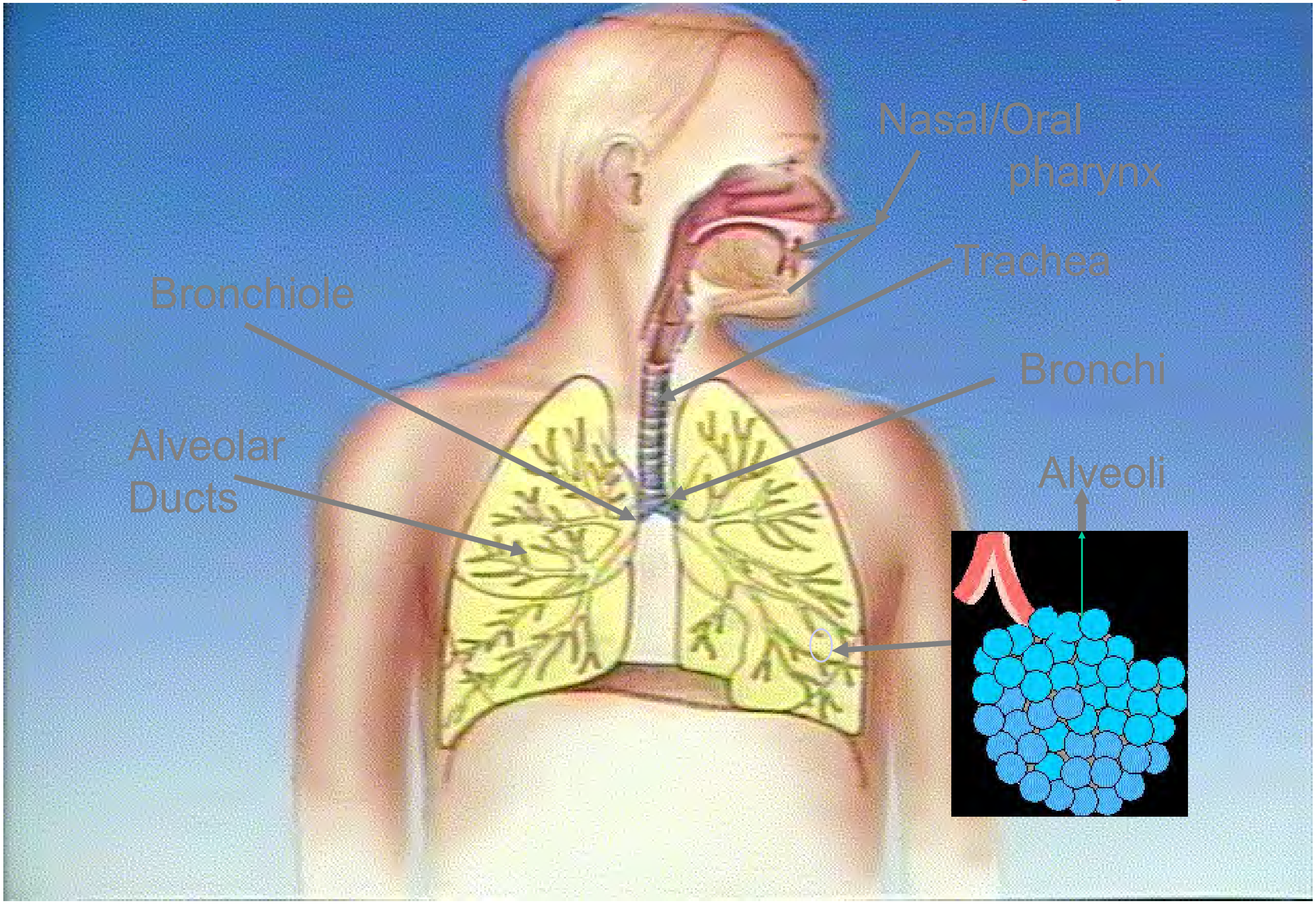
Hypoxia Overview

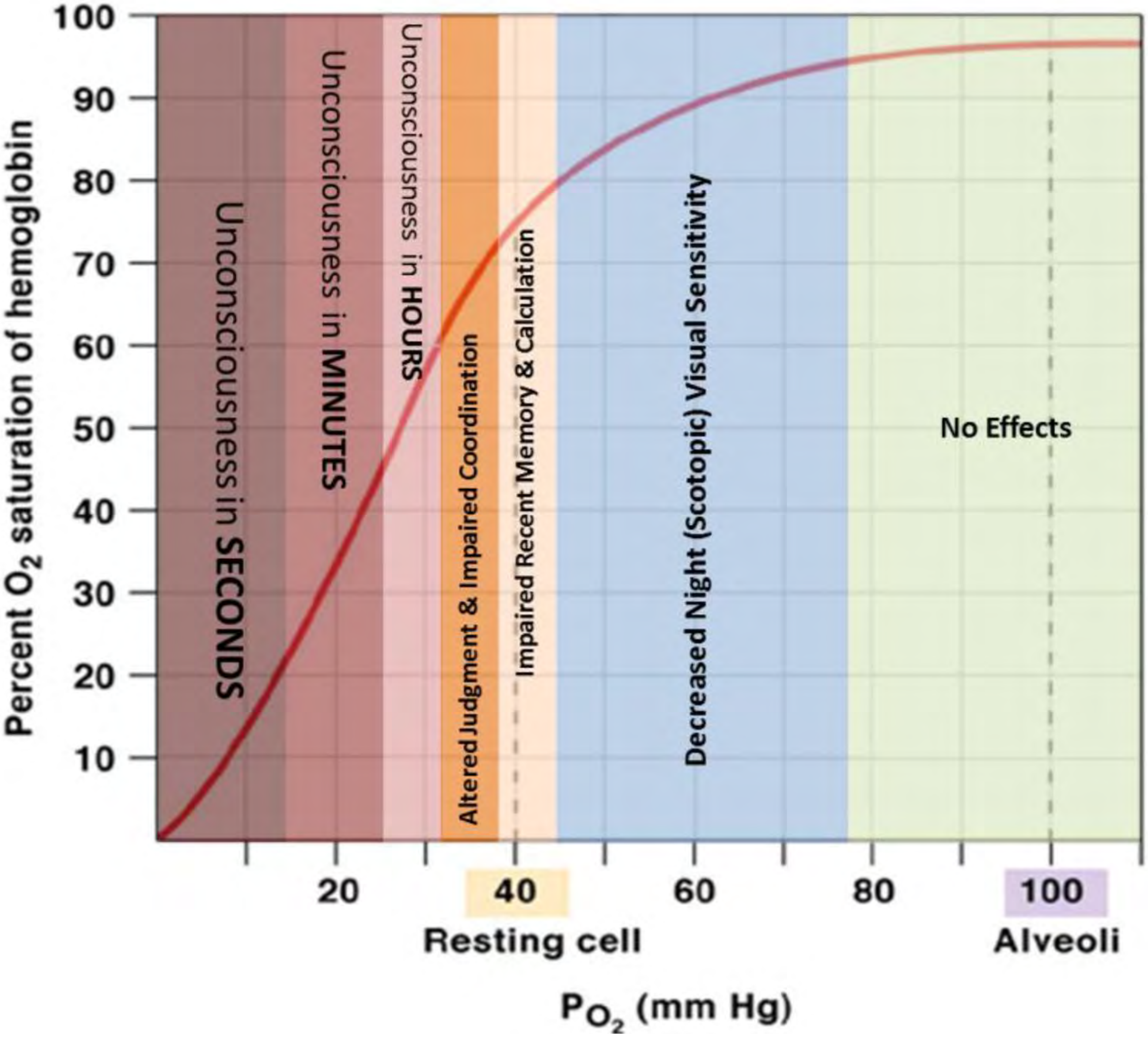
The deficiency of adequate oxygen to tissues resulting in functional impairment is termed hypoxia

The human brain is extremely sensitive and vulnerable to oxygen deprivation from whatever cause:

- **Hypoxic Hypoxia**: reduction in oxygen tension in the blood
- **Anemic Hypoxia**: reduction in the oxygen-carrying capacity of the blood (reduced hemoglobin)
- **Histotoxic Hypoxia**: interference with the ability of tissues to utilize oxygen
- **Ischemic (Stagnant) Hypoxia**: reduction in blood flow through tissues

Components Of The Respiratory System

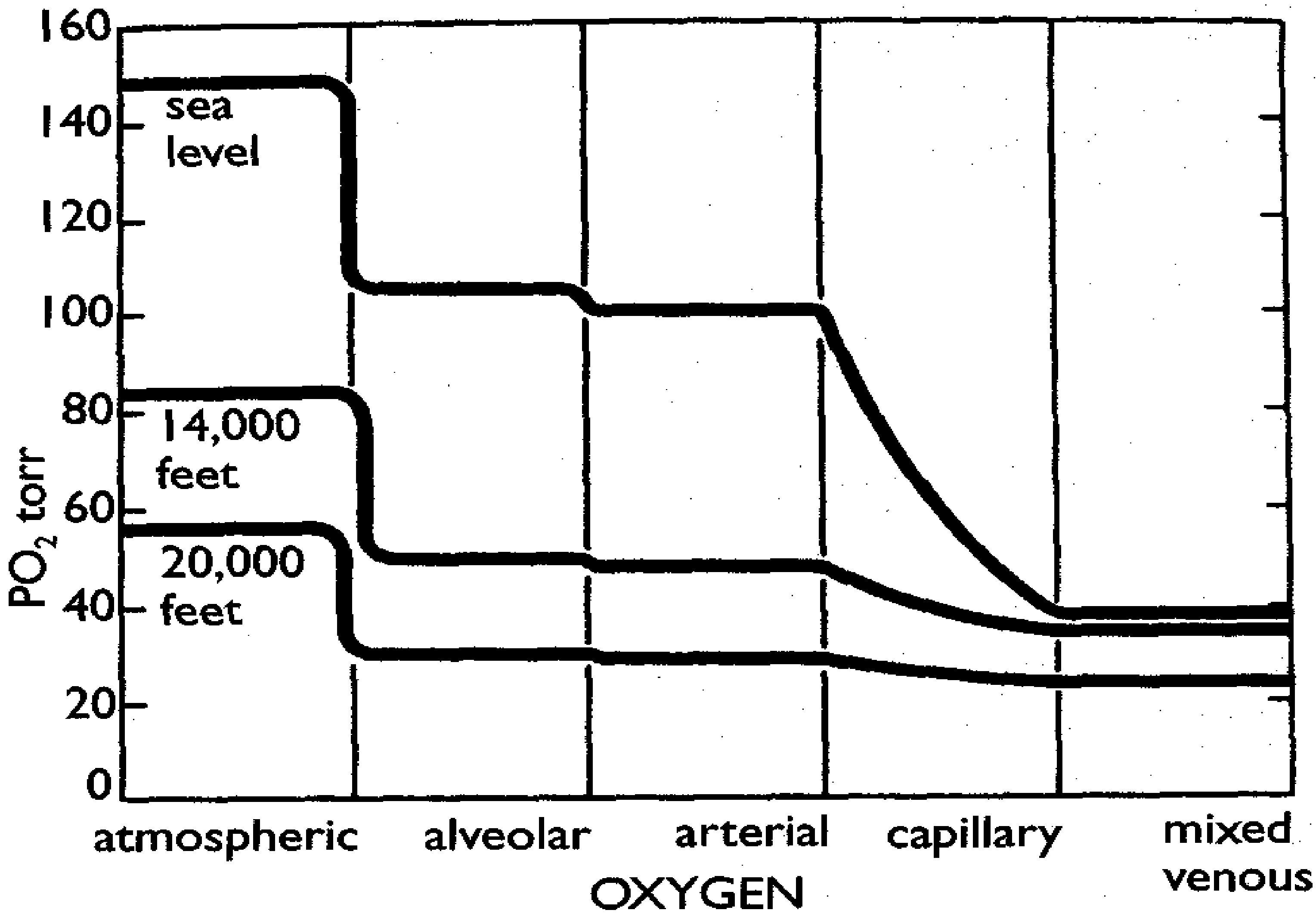




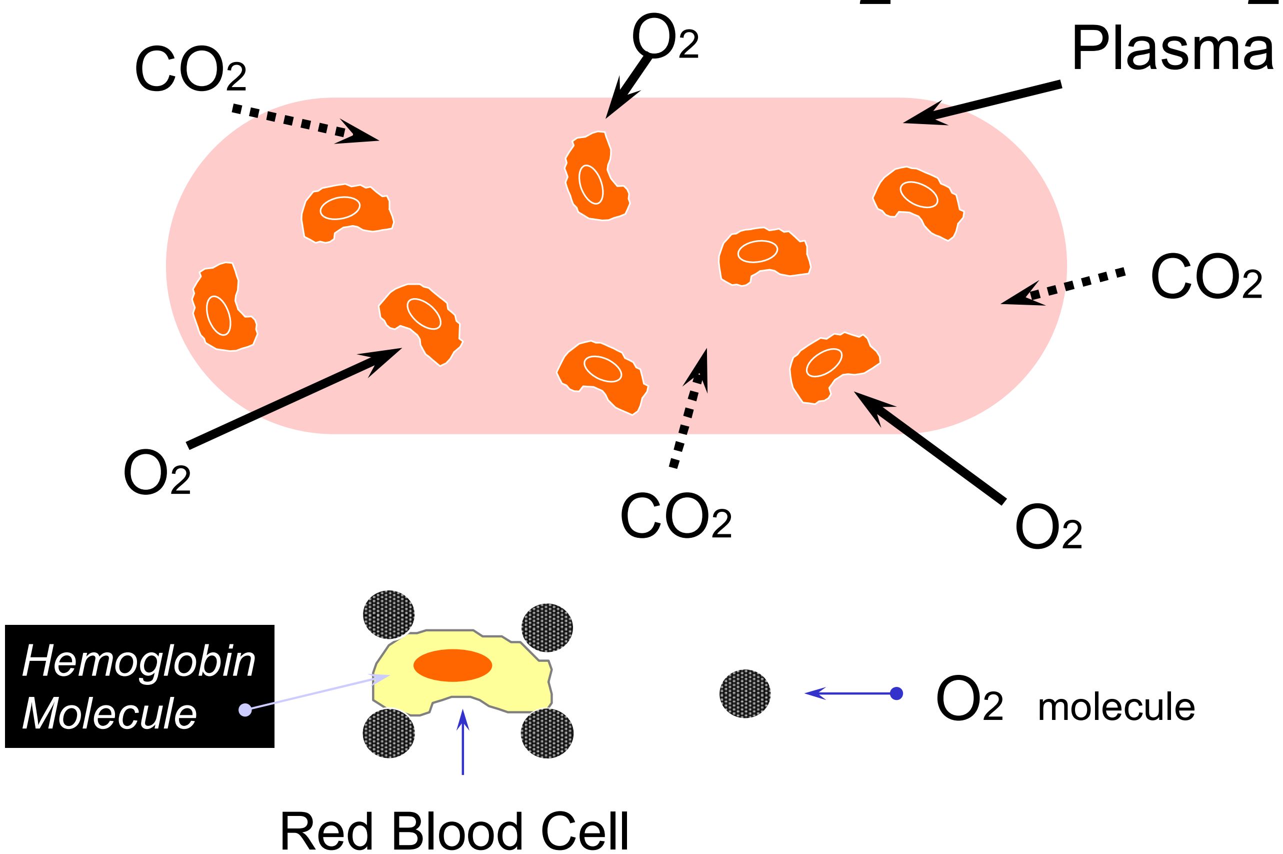
Effects of Hypoxia on Arterial Saturation and Body Function

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 3-1

The Oxygen Cascade



Blood transport of O_2 and CO_2



Atmosphere Verses Alveolus (Lung)

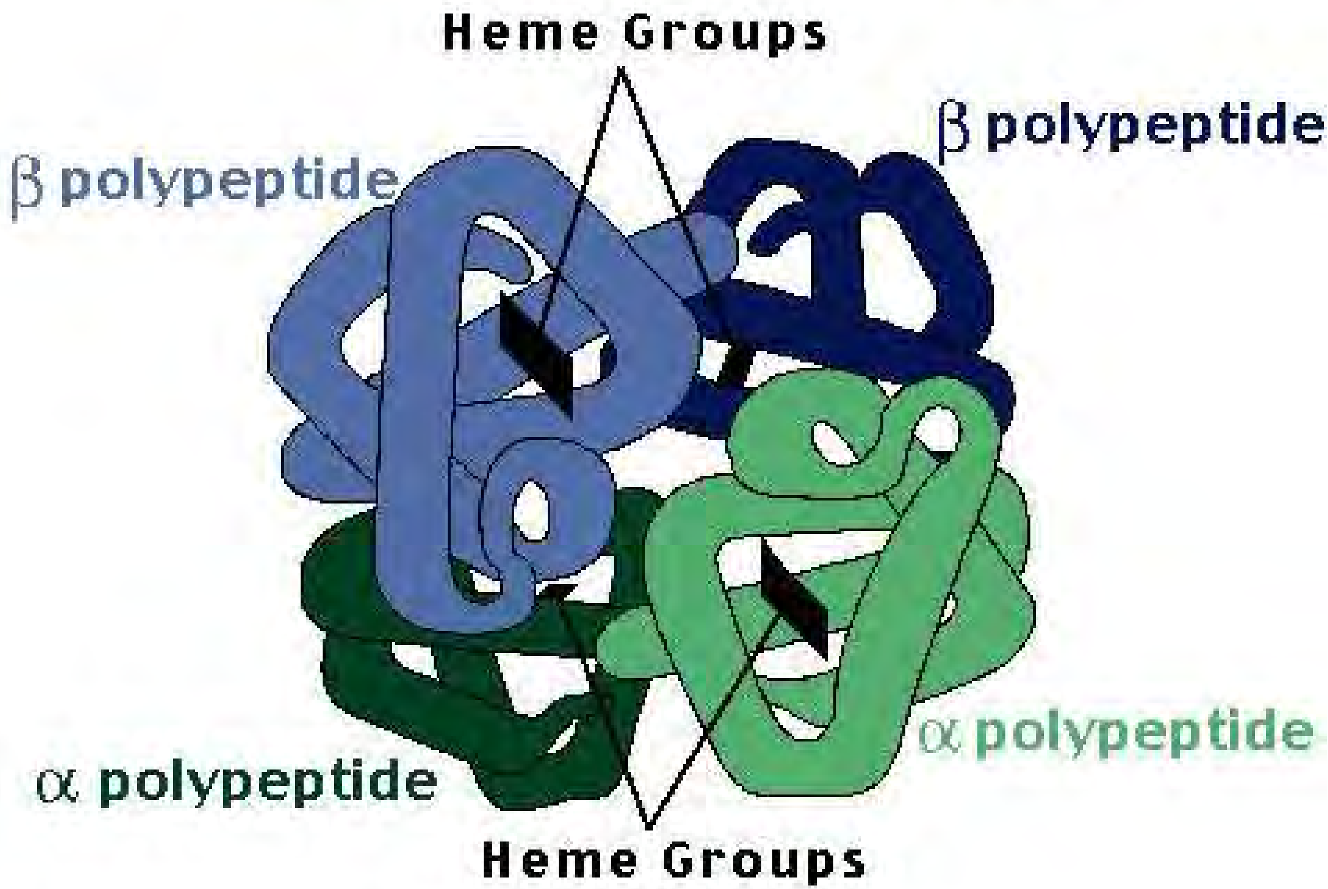
Atmosphere: 2 Gases

- Nitrogen
- Oxygen

Alveolus: 4 Gases

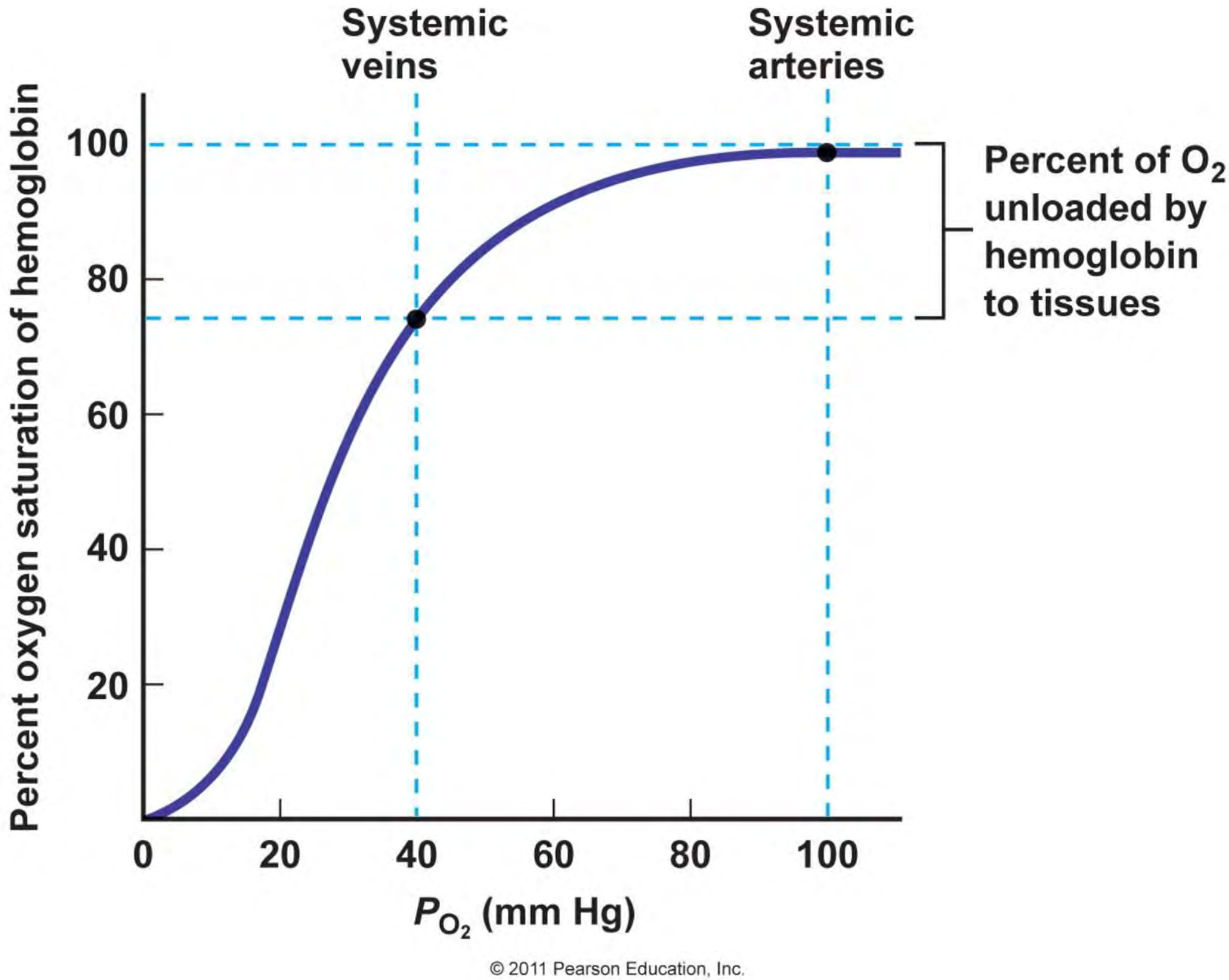
- Nitrogen
- Oxygen
- Carbon Dioxide
- Water

The Hemoglobin Molecule



Russell, P. J. 1996. *Genetics.* Harper Collins, NY.

Hemogl


Systemic
veins
Systemic
arteries
Percent of O_2 unloaded by hemoglobin to tissues
Percent oxygen saturation of hemoglobin
100
80
60
40
20
0
20
40
60
80
100
P_{O_2} (mm Hg)
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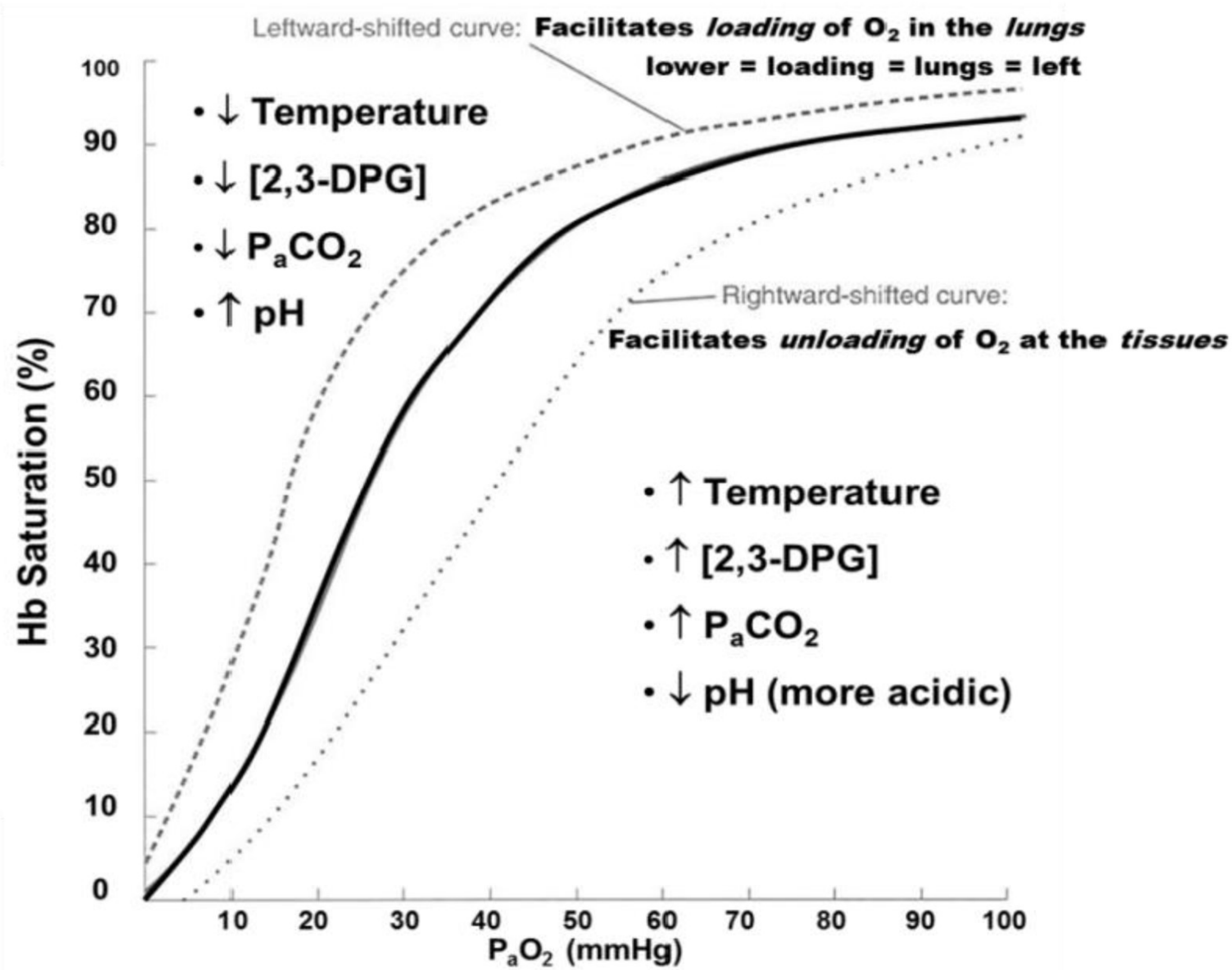
Factors Affecting the Oxygen-Hemoglobin Dissociation Curve

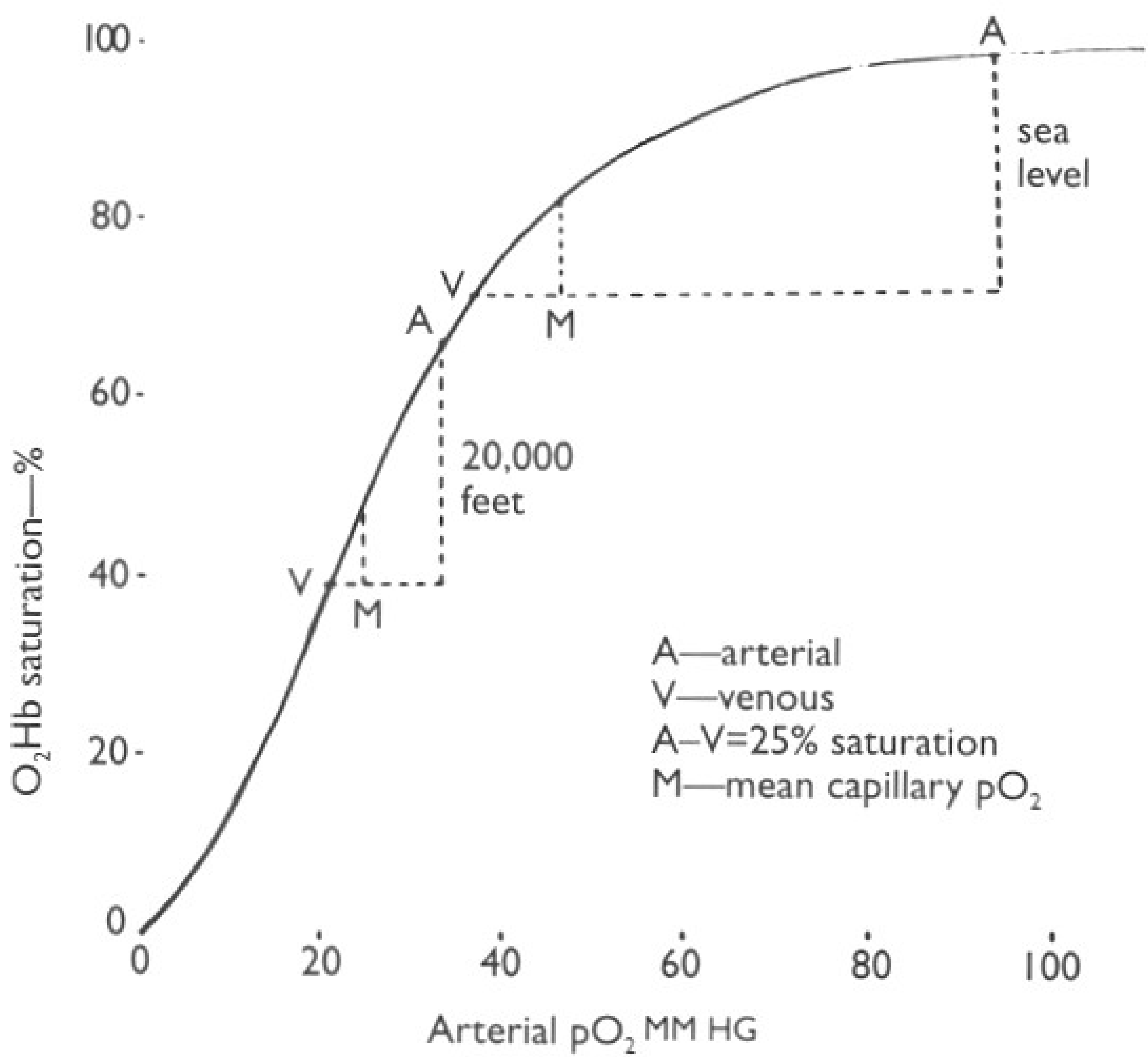


Oxyhemoglobin Dissociation Curve

Note that the change in saturation for every change in partial pressure is very little for $pO_2 \geq$ 60 mm Hg (i.e. HgB sat $\geq$ 90%)

However, the change in saturation for every change in partial pressure is much greater for 30 mmHg $<$ pO2 $<$ 60 mm Hg (i.e. 30% $<$ HgB sat $<$ 90%)

Relatively little change in saturation for every change in partial pressure for pO2 $\leq$ 30 mmHg (i.e. HgB $\leq$ 30%)



100
80
60
40
20
0
O2Hb saturation—%
A
sea level
V
A
M
20,000 feet
V
M
A—arterial
V—venous
A–V=25% saturation
M—mean capillary pO2
0
20
40
60
80
100
Arterial pO2 MM HG

Altitude, Alveolar pO_2 & Hgb Saturation

Ambient Air

Altitude (Feet)	Barometric Pressure (mmHg)	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

Altitude vs. Time of Useful Consciousness (TUC)

Altitude in Flight level	Time of Useful Consciousness	Altitude in meters	Altitude in feet
FL 150	30 min or more	4,500 m	15,000
FL 180	20 to 30 min	5,500 m	18,000
FL 220	5-10 min	6,700 m	22,000
FL 250	3 to 6 min	7,600 m	25,000
FL 280	2.5 to 3 mins	8,500 m	28,000
FL 300	1 to 3 mins	9,100 m	30,000
FL 350	30 sec to 1 min	10,700 m	35,000
FL 400	15 to 20 sec	12,200 m	40,000
FL 430	9 to 15 sec	13,100 m	43,000
FL 500 and above	6 to 9 sec	15,200 m	50,000

Effective Performance Time (Time of Useful Consciousness)

45,000 feet MSL	9 – 15 seconds
40,000 feet MSL	15-20 seconds
35,000 feet MSL	30-60 seconds
30,000 feet MSL	1 – 2 minutes
28,000 feet MSL	2 – 3 minutes
25,000 feet MSL	3 – 5 minutes
22,000 feet MSL	5 – 10 minutes
20,000 feet MSL	30 minutes or more

Hypoxia Symptoms

Lethargy

Poor coordination

Cyanosis

Poor judgment

Rapid breathing

Dizziness

Air hunger

Euphoria

Fatigue

Tingling

Periphery of visual field turns gray

Factors Affecting Hypoxia Symptoms

Pressure altitude
Rate of ascent
Time at altitude
Temperature
Physical activity
Individual factors
Physical fitness

Stages of Altitude-Induced (Hypoxic) Hypoxia

Indifferent Stage

Compensatory Stage

Disturbance Stage

Critical Stage

Indifferent Stage

Altitudes

- Air: 0 - 10,000 feet
- 100% O_2: 34,000 - 39,000 feet

Symptoms: Decrease in night vision at 4000 feet

- Acuity
- Color perception

Compensatory Stage

Altitude

Air: 10,000 - 15,000 feet

100% O_2: 39,000 - 42,000 feet

Symptoms: Impaired efficiency, drowsiness, poor judgment & decreased coordination

Disturbance Stage

Altitudes

Air: 15,000 - 20,000 feet

100% O_2: 42,000 - 44,800 feet

Signs & Symptoms

Hyperventilation & Cyanosis

Memory, Judgment, Reliability impairment

Understanding (information processing) decreased

Coordination & Flight Control less precise

Speech slurred; Handwriting sloppy

Critical Stage

Altitudes

Air:	20,000 feet and above
100% O_2:	44,800 feet and above

Signs: Loss of consciousness, convulsions & death

Key Altitudes (Feet)

5,000: Night vision impaired

8,000: (Airline cabin altitude) 93% sat

10,000: 89% Sat

12,500: 87% Sat; per FAA crew must use oxygen after 30 minutes

14,000: 83% Sat; per FAA O2 required for crew and passengers

15,000: 80% Sat

20,000: 65% Sat; TUC is 10 minutes

25,000: 60% Sat; TUC is 2.5 minutes

37,000: TUC is 18 seconds; Requires 100% oxygen supplement

45,000: TUC is 15 sec; Requires pressurized O_2

63,000: Armstrong's Line; blood begins to off-gas

Hypoxia: Insidious Onset

In aviation, the *insidious onset* of hypoxia is a problem because one may not experience symptoms, or the symptoms may not be noticed (especially if they are subtle, or the individual is preoccupied with other things, like an inflight emergency)

Prevention of hypoxia therefore becomes critical, because there may not be sufficient warning symptoms when it occurs

Respiratory Limit: 50,000 Feet

Atmospheric Pressure = 87 mm Hg

Alveolar pressures:

- P_ACO_2 = 40 mm Hg
- Vapor Pressure of Water = 47 mm Hg

Therefore, no atmospheric air (nitrogen & oxygen) can get into the alveolus

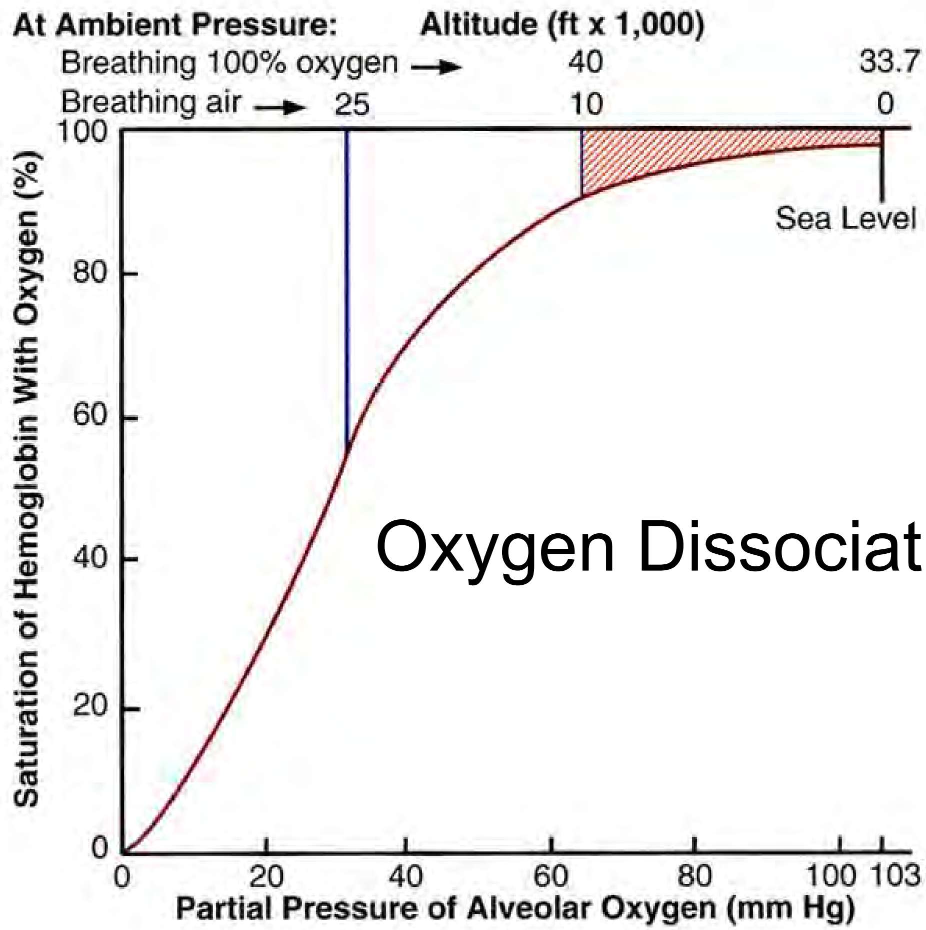
Above 50,000 Feet: Pressure Suit Needed

Returning blood from tissue has p_aO_2 approximately 40 mm Hg

O_2 diffuses towards lower partial pressure in lungs (Graham's Law)

Oxygen gradient results in O_2 actually LEAVING the blood into the alveolus

Reduced Oxygen Partial Pressure
Hypoxic Hypoxia



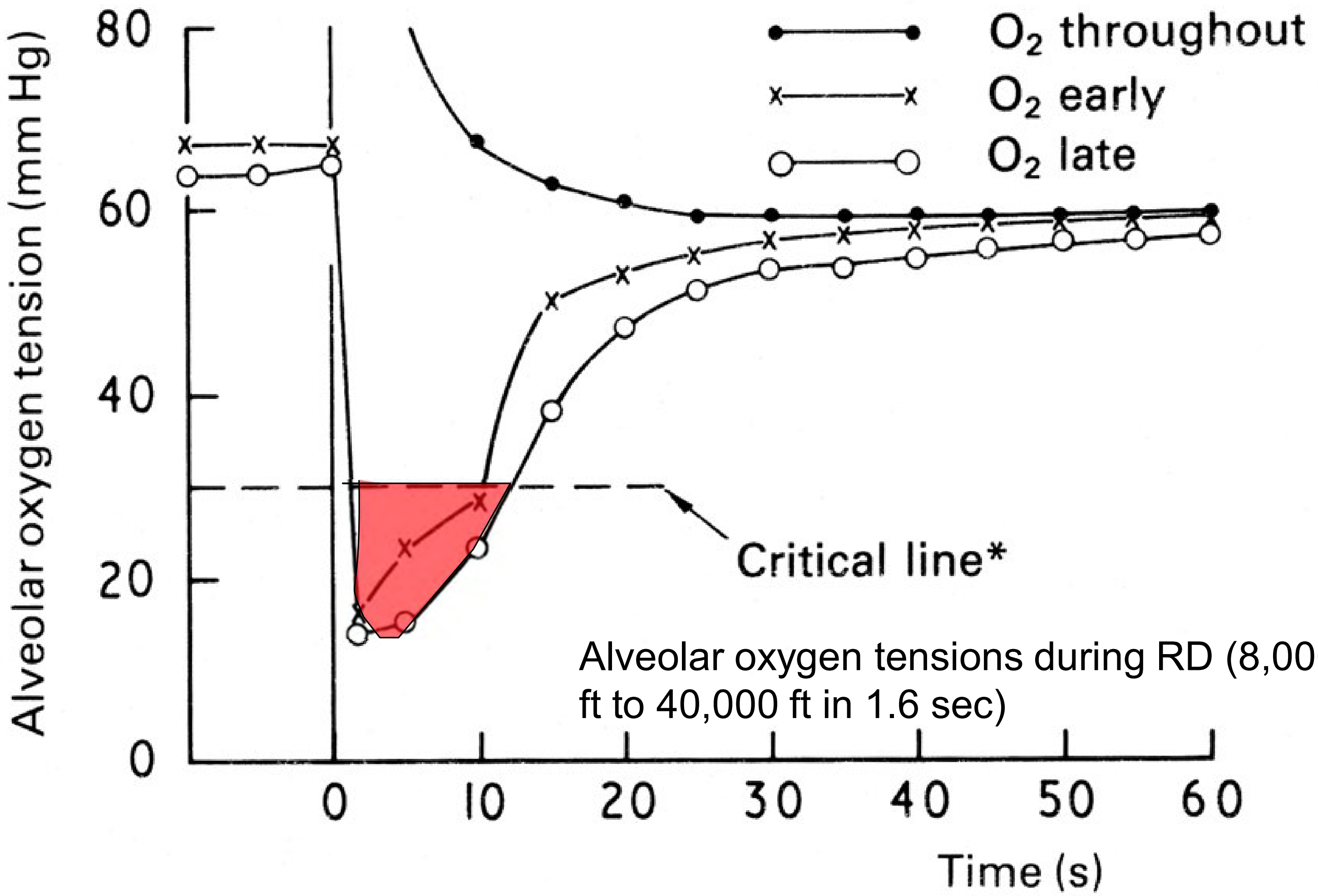
Oxygen Dissociation Curve

Rapid Decompression (RD) and Hypoxia

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

As oxygen tension in the blood is higher than that in the lungs, oxygen passes from the blood into the alveoli, that is **oxygen passes out of the body**.

Rapid Decompression and Hypoxia



Alveolar oxygen tensions during RD (8,000 ft to 40,000 ft in 1.6 sec)

Rapid Decompression and Hypoxia

The greater the final altitude and the longer the delay in re-establishing adequate oxygenation, the greater will be the degree of hypoxia.

Catastrophic hypoxia-induced neurological consequences of RD occur if alveolar oxygen falls below ~30 mmHg.

Such a fall is inevitable during and after RD to a final altitude above 30,000 ft ***even if*** 100% oxygen is delivered to the respiratory tract at the moment of decompression.

Rapid Decompression and Hypoxia

So, in order to avoid neurological consequences *after* RD, an oxygen-enriched breathing gas must be being breathed *before* it.

Consciousness will almost certainly be lost if the time course of changes in alveolar oxygen tension during RD exceeds 140 mm Hg/sec.

Severe and unacceptable hypoxia occurs within a few seconds of exposure to altitudes above 40,000 - 43,000 ft, even when 100% oxygen is breathed.

Rapid Decompression and Hypoxia

In such exposures the blood loses oxygen to the atmosphere and so oxygen tension in the blood falls abruptly.

As a result, blood entering the capillaries of the brain (and other tissues) has a very low oxygen tension within 5 - 6 sec of the start of RD (*eg* to 40,000 ft).

Rapid Decompression and Hypoxia

This, combined with the very limited capacity of brain tissue to store oxygen, produces impairment of performance in 9 - 12 sec and unconsciousness in 20 sec.

These times do not change significantly with final altitudes greater than 52,000 ft because cerebral hypoxia is determined primarily by lung-to-brain circulation time (cerebral storage capacity being relatively constant).

Time of Useful Consciousness (TUC)

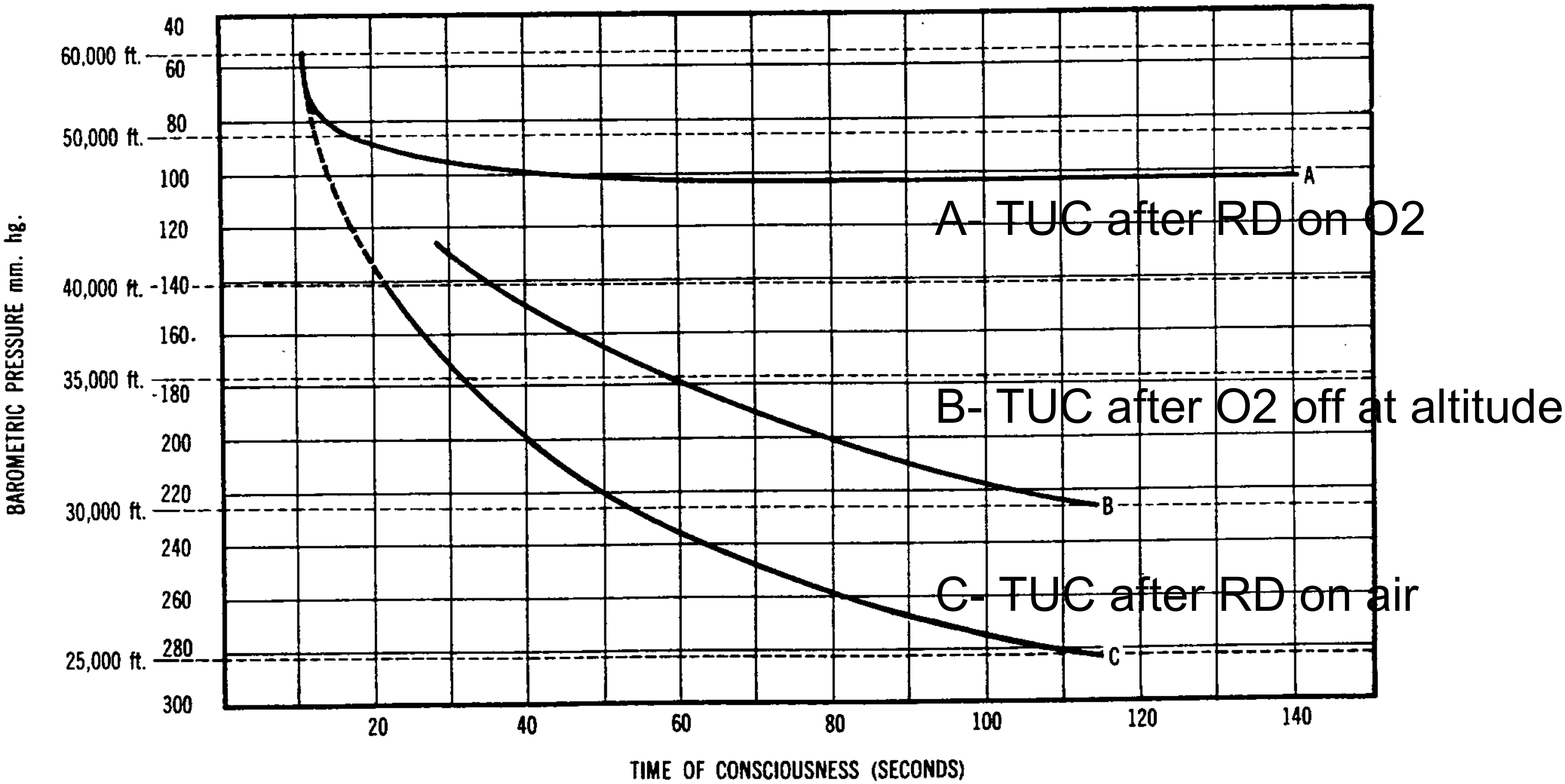
a.k.a. Effective Performance Time (EPT)

TUC is the time interval between a reduction in inspired oxygen tension and the point at which there is a specified degree of impairment of performance.

The most useful and practical concept is to regard the TUC as the period during which an affected individual can act to correct his or her predicament.

At altitudes above 43,000 ft the TUC is 9 - 12 sec.

Altitude vs. Time of Useful Consciousness



Differences between Hypoxic Hypoxia and Hyperventilation

Signs/ Symptoms	Hypoxic (Altitude) Hypoxia	Hyperventilation
Onset of signs/ symptoms	Rapid (altitude dependent)	Gradual
Muscle activity	Flaccid, limp	Spasm
Appearance	Cyanosis	Pale, clammy
Tetany	Absent	Present

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

Hypoxia vs Hyperventilation

HYPOXIA

Headache

Decreased Reaction Time

Impaired Judgment

Euphoria

Visual Impairment

Drowsiness

Lightheadedness

Tingling in Fingers Toes

Numbness

Blue Fingernails & Lips

Limp Muscles

HYPERVENTILATION

Headache

Decreased Reaction Time

Impaired Judgment

Euphoria

Visual Impairment

Drowsiness

Lightheadedness

Tingling in Fingers Toes

Numbness

Pale, Clammy Appearance

Muscle Spasms

Hyperventilation

Definition: An excessive rate & depth of respiration leading to the abnormal loss of CO_2 from the blood

Can be triggered by anxiety, fear, stress causing higher levels of adrenaline

LOWERS carbon dioxide (CO_2) levels

Can be intentional

May result in unconsciousness

Hyperventilation vs Hypoxia

Above 10,000 feet: Possible hypoxia

Below 10,000 feet: Probable hyperventilation

Treatment is to slow down rate and depth of breathing--talking may help

If not sure if hyperventilation or hypoxia: Give oxygen

Health and Performance Consequences of Elevated Carbon Dioxide

CO_2 is a 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)

Visual symptoms occur at CO_2 concentrations near 9 mmHg

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% and 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)

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

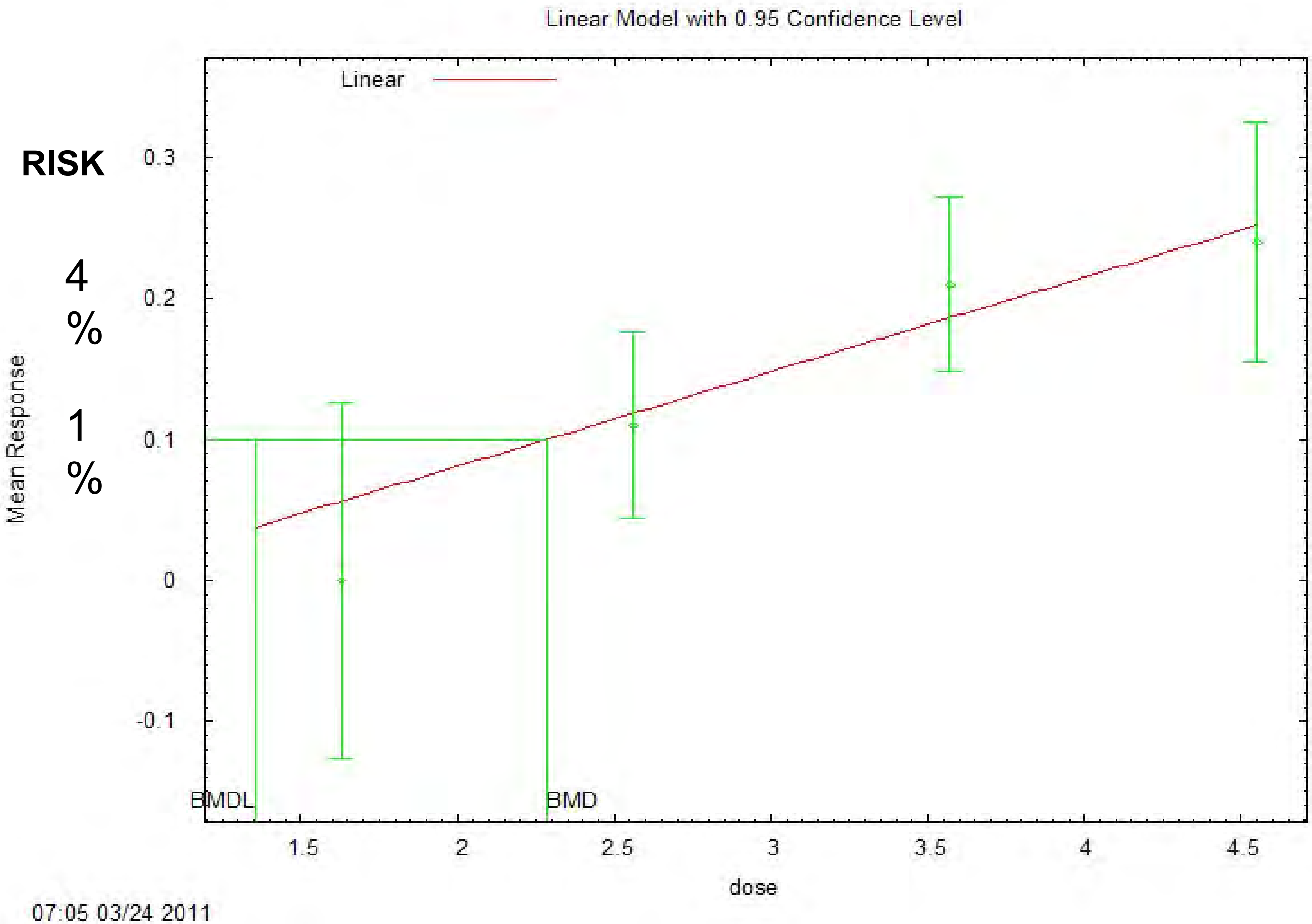
Current Status

State of Knowledge (New Evidence)

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).

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*

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



24-h CO_2 mmHg

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).

Ground-based Evidence

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

Usha Satish,[1] Mark J. Mendell,[2] Krishnamurthy Shekhar,[1] Toshifumi Hotchi,[2] Douglas Sullivan,[2] Siegfried Streufert,[1] and William J. Fisk[2]

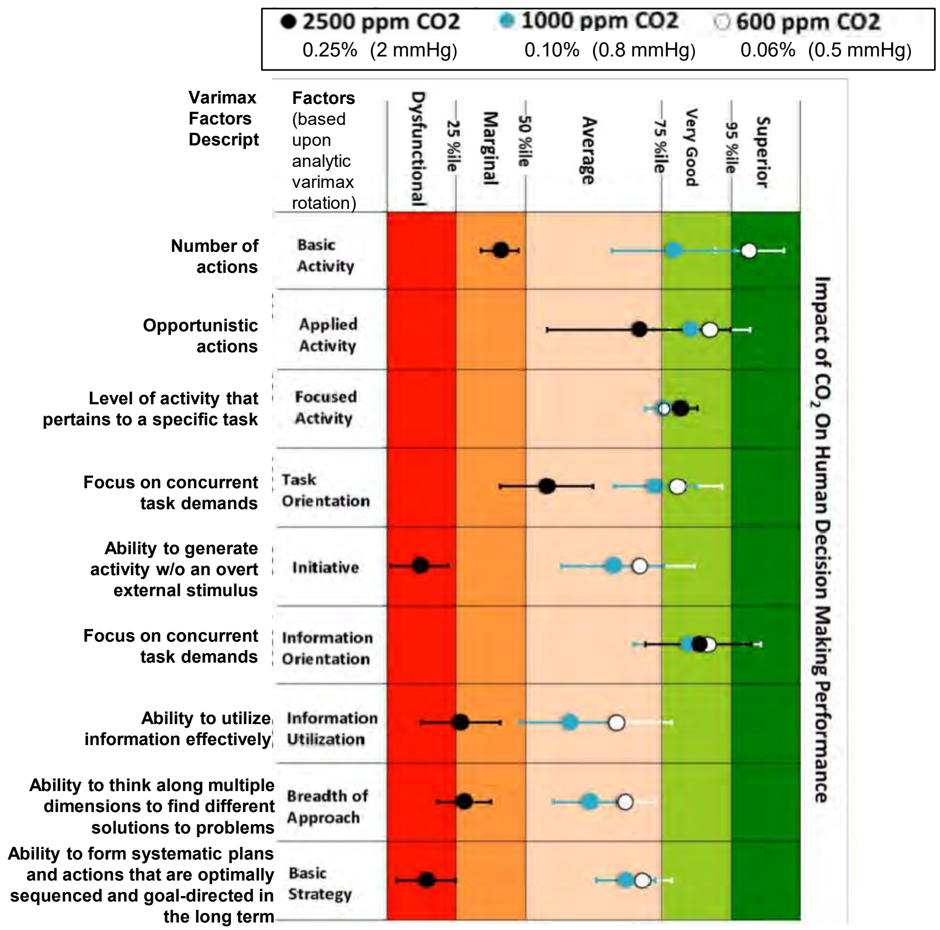
[1]Department of Psychiatry and Behavioral Science, Upstate Medical University, State University of New York, Syracuse, New York, USA; [2]Indoor Environment Department, Lawrence Berkeley National Laboratory, Berkeley, California, USA

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)

Current Status

Decision-Making Decrements (Satish et al. 2012)



Relevance to Operations:

- Decision Making
- Situational Awareness

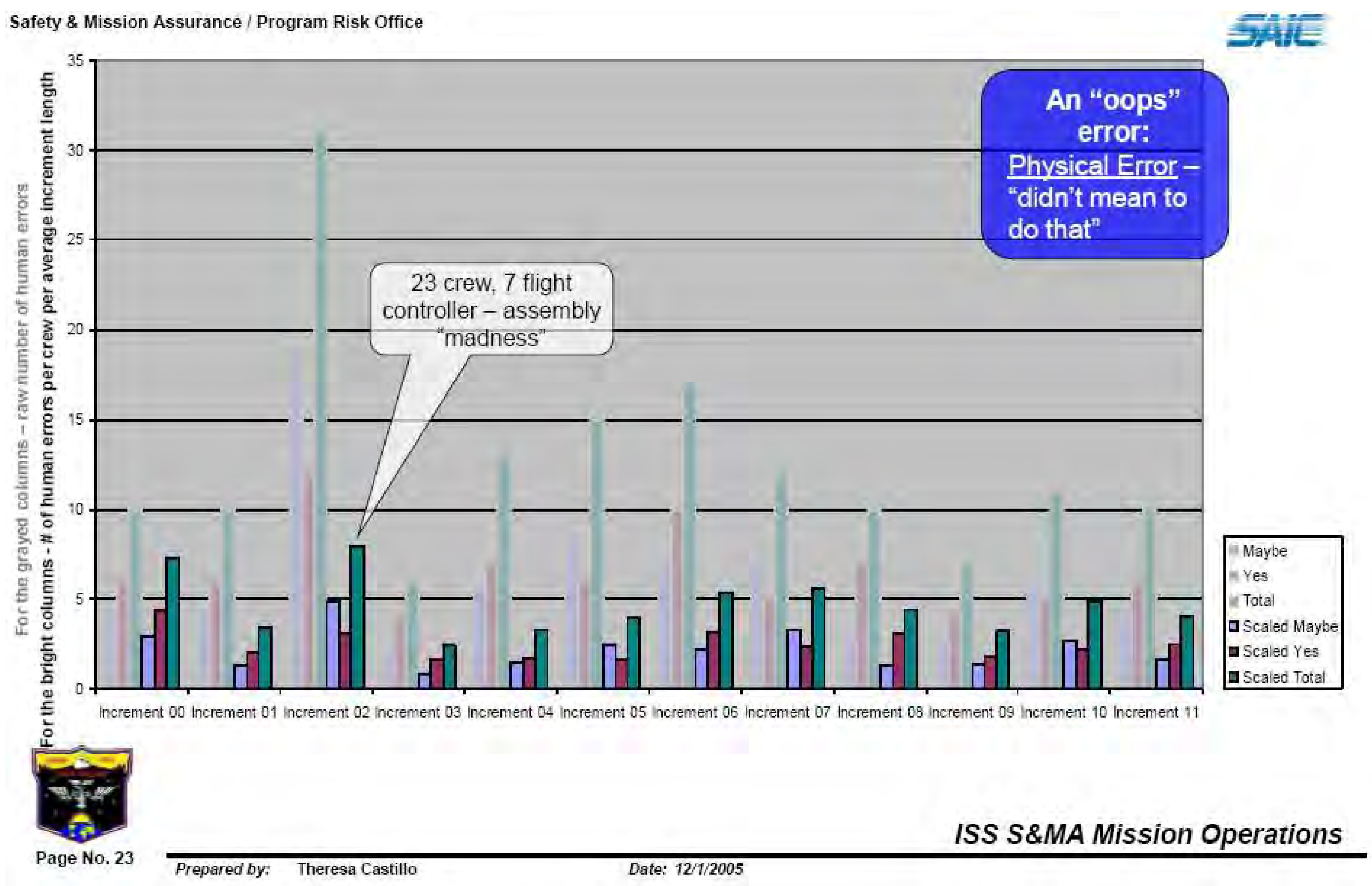
The Challenge of Aviation Emergency and Abnormal Situations

Barbara K. Burian, Immanuel Barshi and Key Dismukes

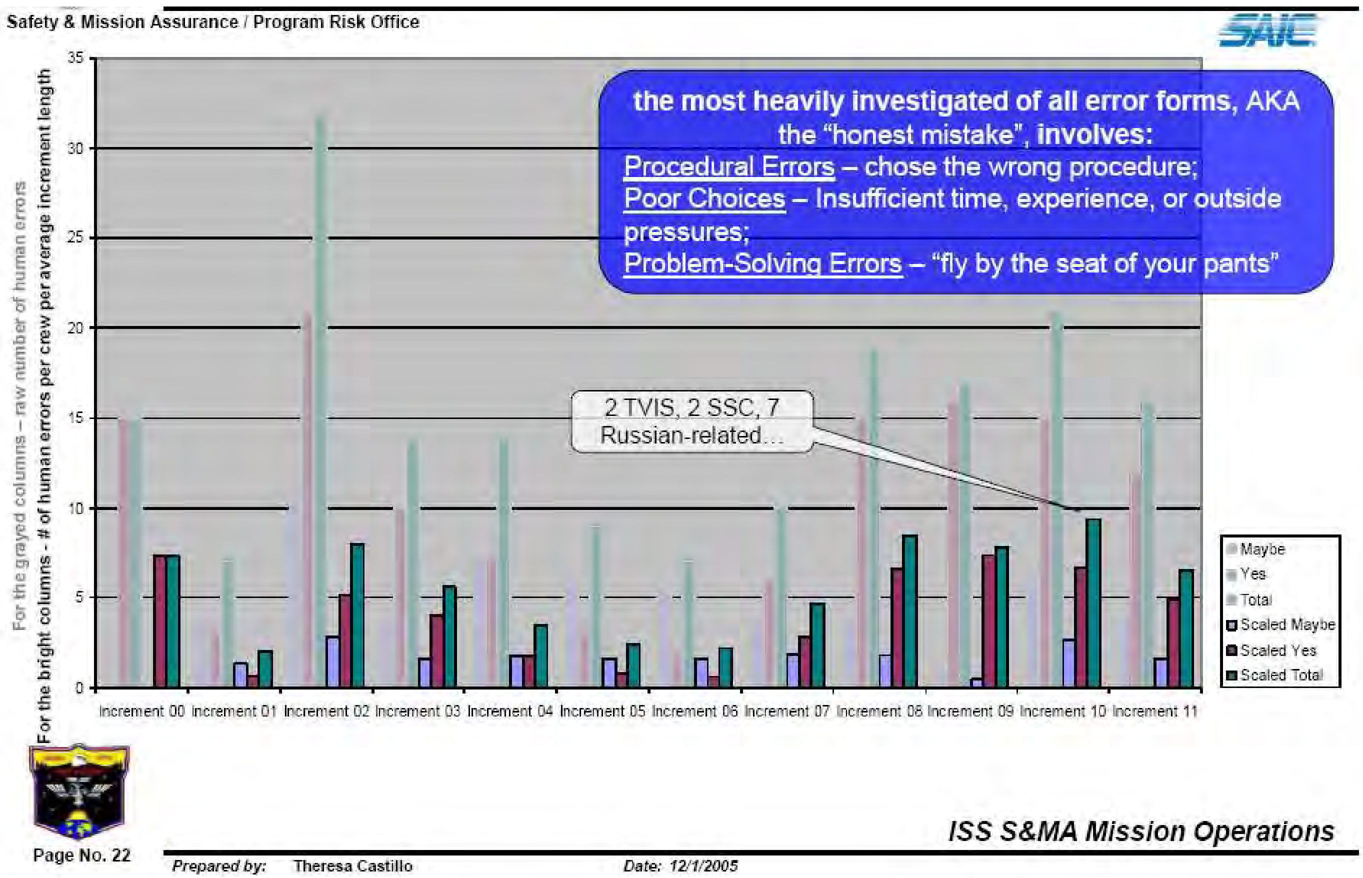
when experiencing <u>stress and high workload</u>, crews are vulnerable to <u>missing important cues related to their situation</u> and are likely to experience <u>difficulty pulling together disparate pieces of information and making sense of them</u>. This is especially true when some of that information is incomplete, ambiguous, or contradictory. Pilots' <u>problem-solving abilities may be impaired</u>, and they will generally have difficulty performing complex mental calculations (Hendy, Farrell, & East, 2001)… In contrast, <u>well-learned motor skills</u>, such as those demonstrated by experienced pilots when operating flight controls, <u>are quite robust and are much less affected by stress</u> (Cohen & Weinstein, 1981).

See Slides 19 & 20: Skill v. Prob. Solving

Skill-Based Error (Involving Hardware)

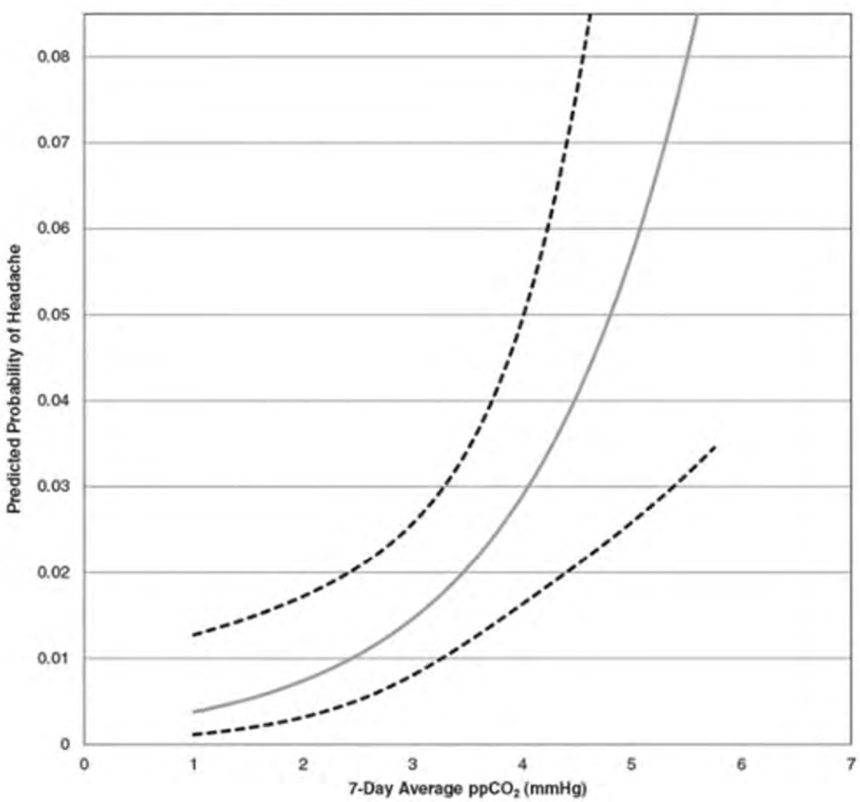


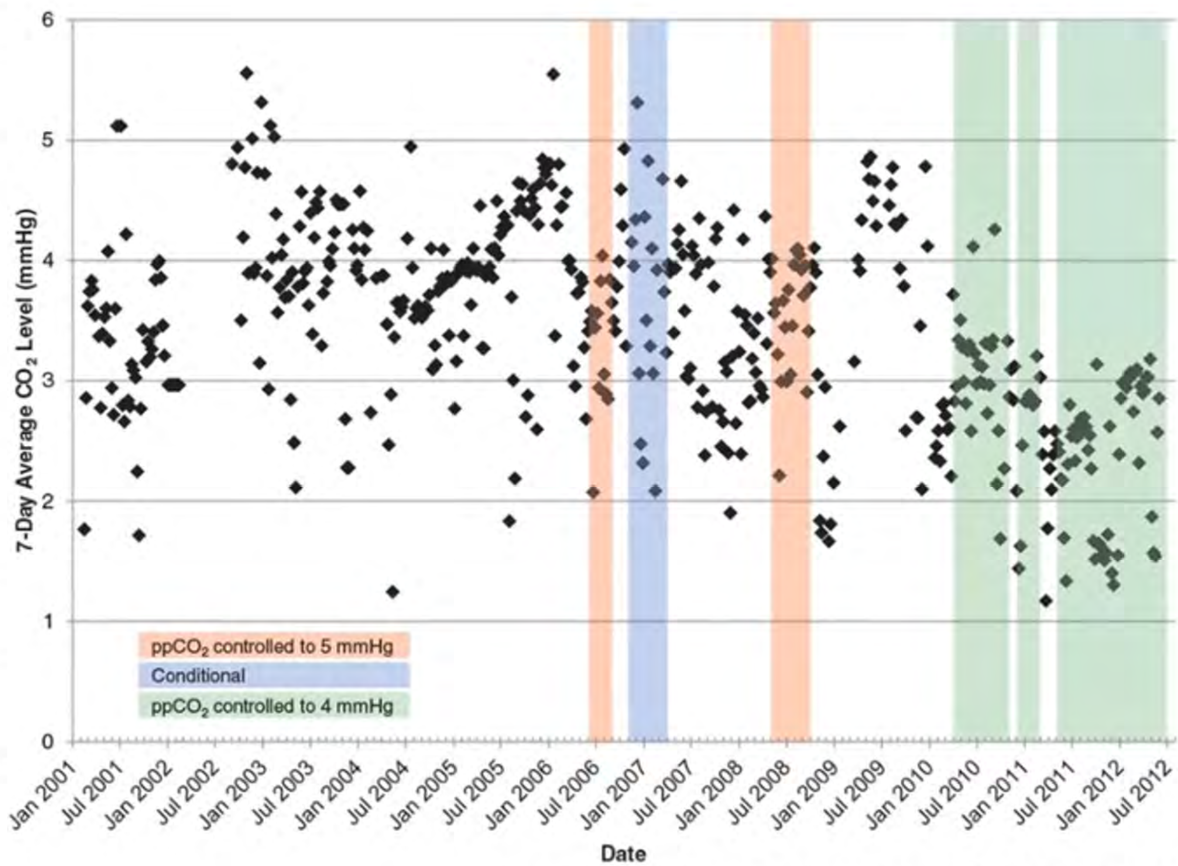
Decision Error (Involving Hardware)



Headache Probability increases with CO2 concentration

CO2 limits on ISS





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Conclusions

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 and 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

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