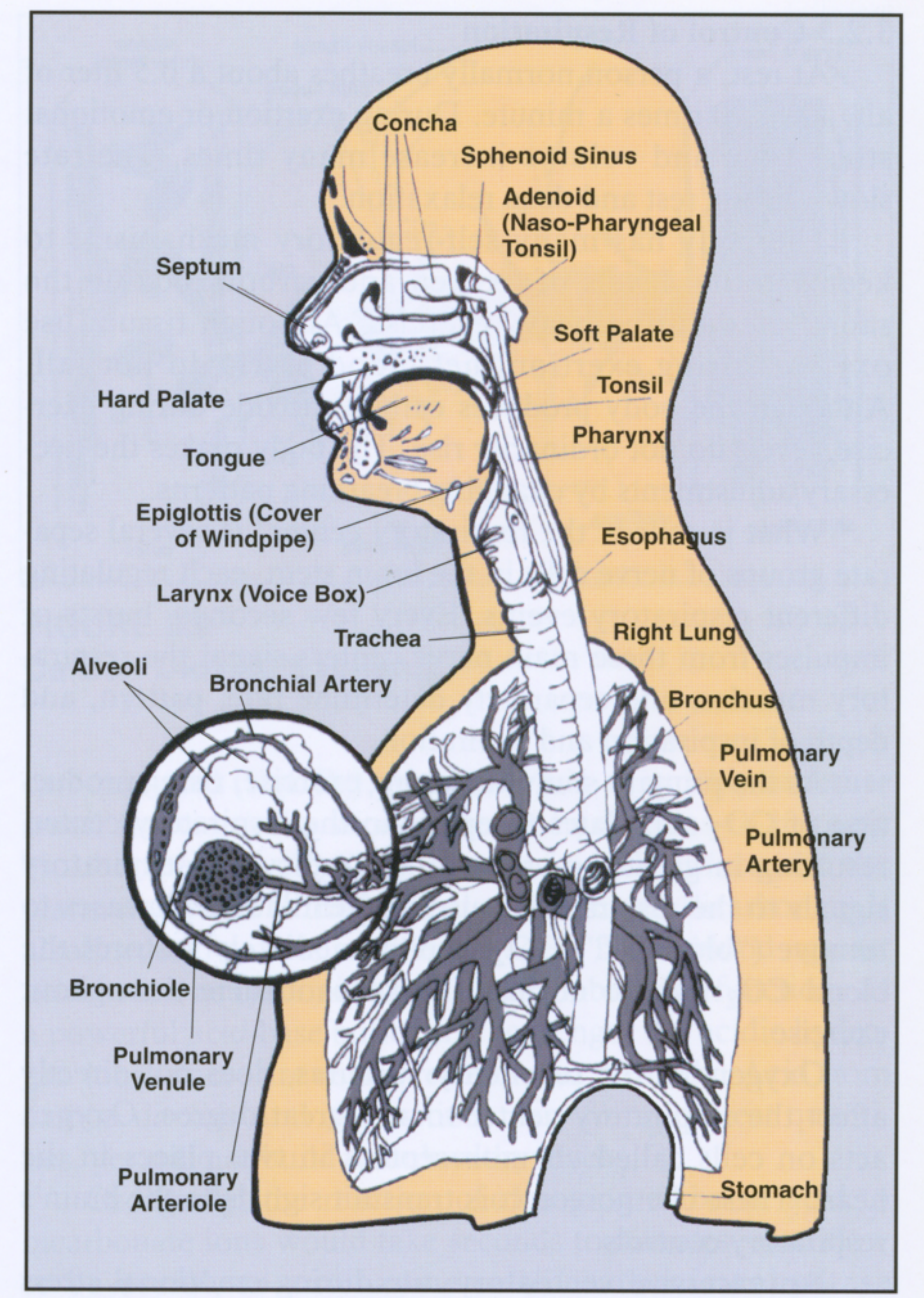
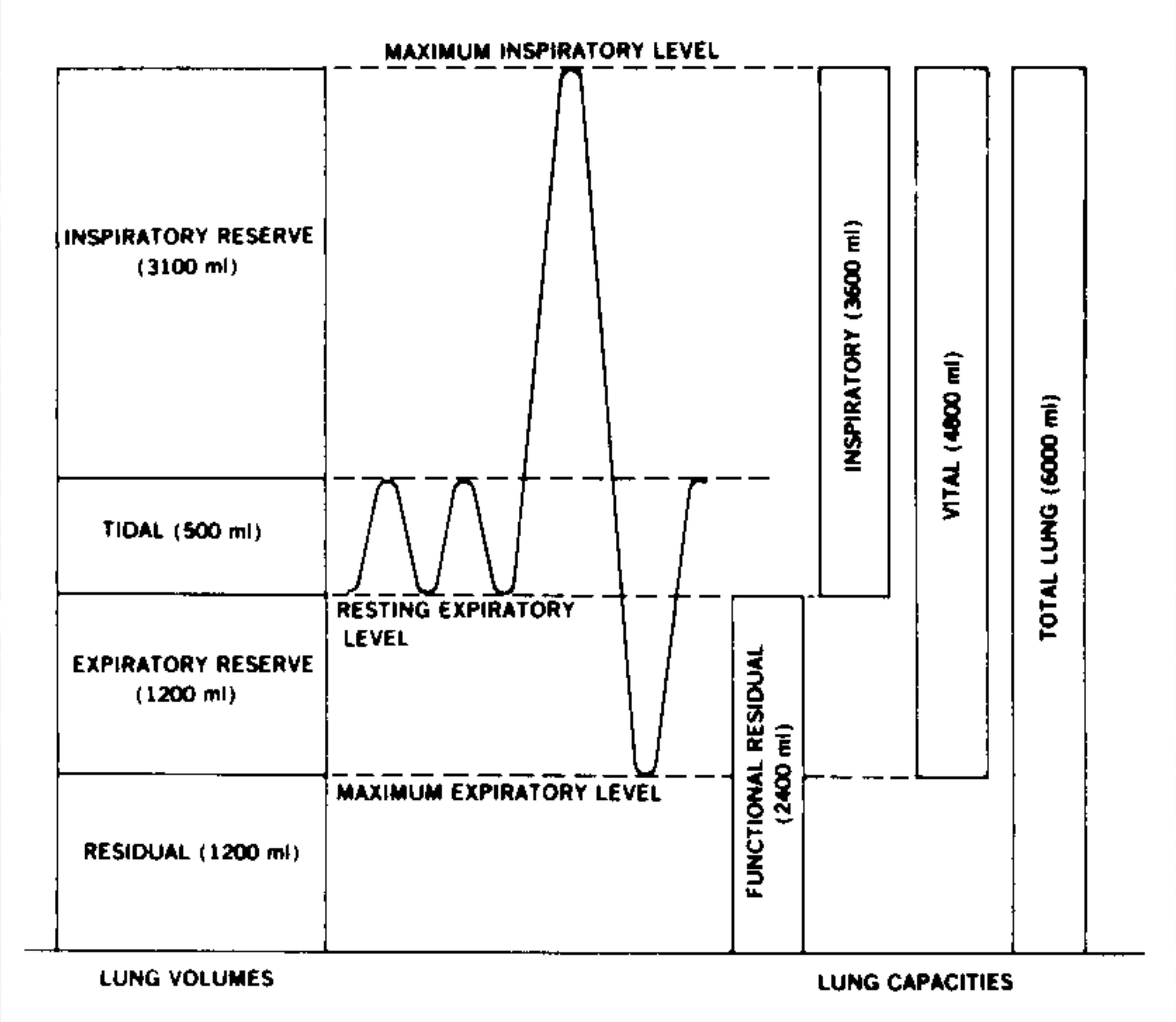
# Aerospace Physiology

- Lecture #11 – October 2, 2023
- Cardiopulmonary physiology
  - Respiratory
  - Cardiovascular
- Musculoskeletal
- Vestibular
- Neurological
- Environmental Effects

# The Human Respiratory System



# Lung Measurements




From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

# Metabolic Processes

- Respiratory Quotient (“RQ”)

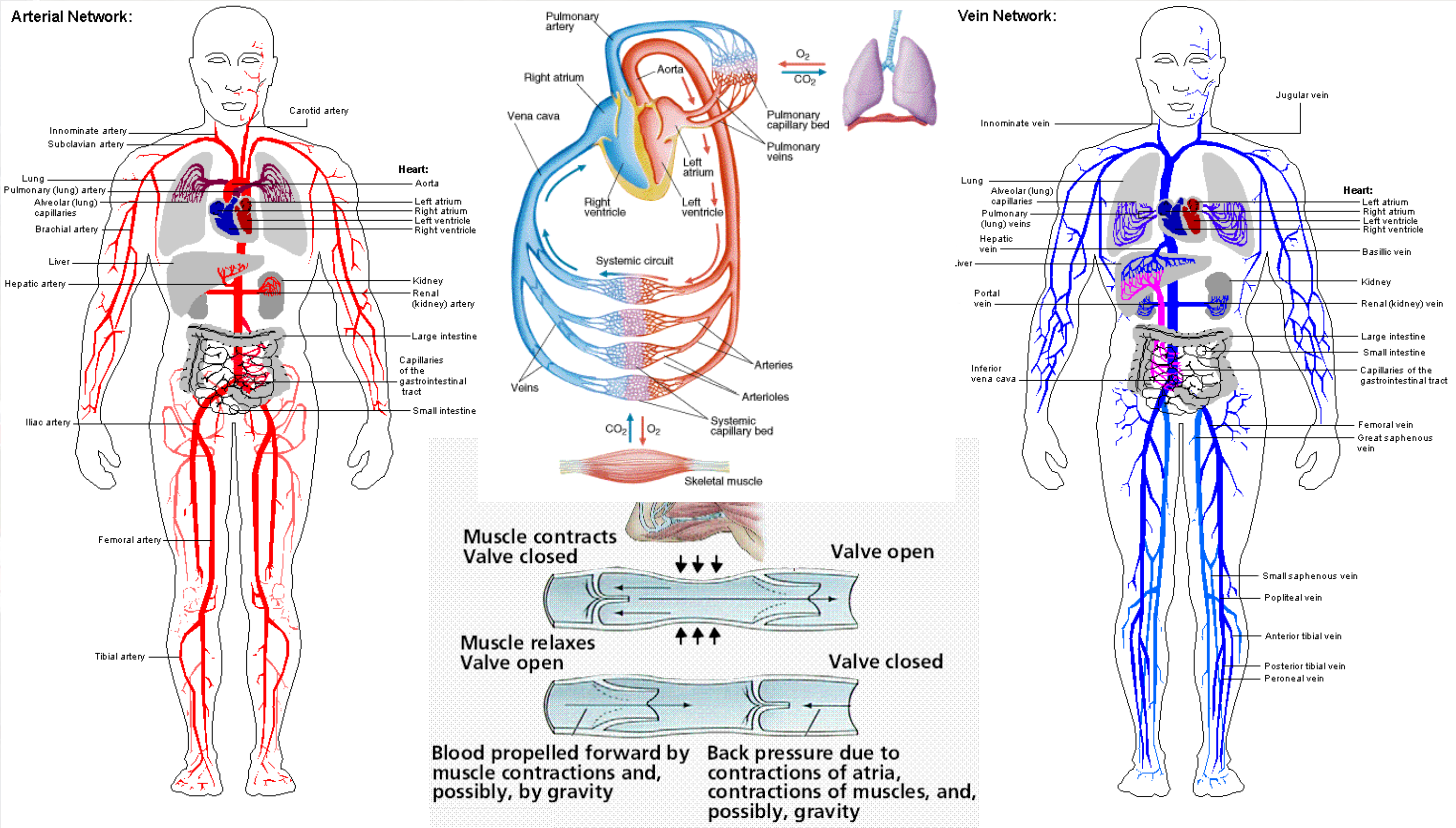
$$RQ = \frac{Exhaled\ volume\ of\ \mathrm{CO_2}}{Inhaled\ volume\ of\ \mathrm{O_2}}$$

- Function of activity and dietary balance
  - Sugar: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \quad (RQ = 1.0)$
  - Protein: $2C_3H_7O_2N + 6O_2 \rightarrow 5CO_2 + 5H_2O \quad (RQ = 0.83)$
  - Fat: $C_{57}H_{104}O_6 + 80O_2 \rightarrow 57CO_2 + 52H_2O (RQ = 0.71)$
- For well-balanced diet, RQ~0.85

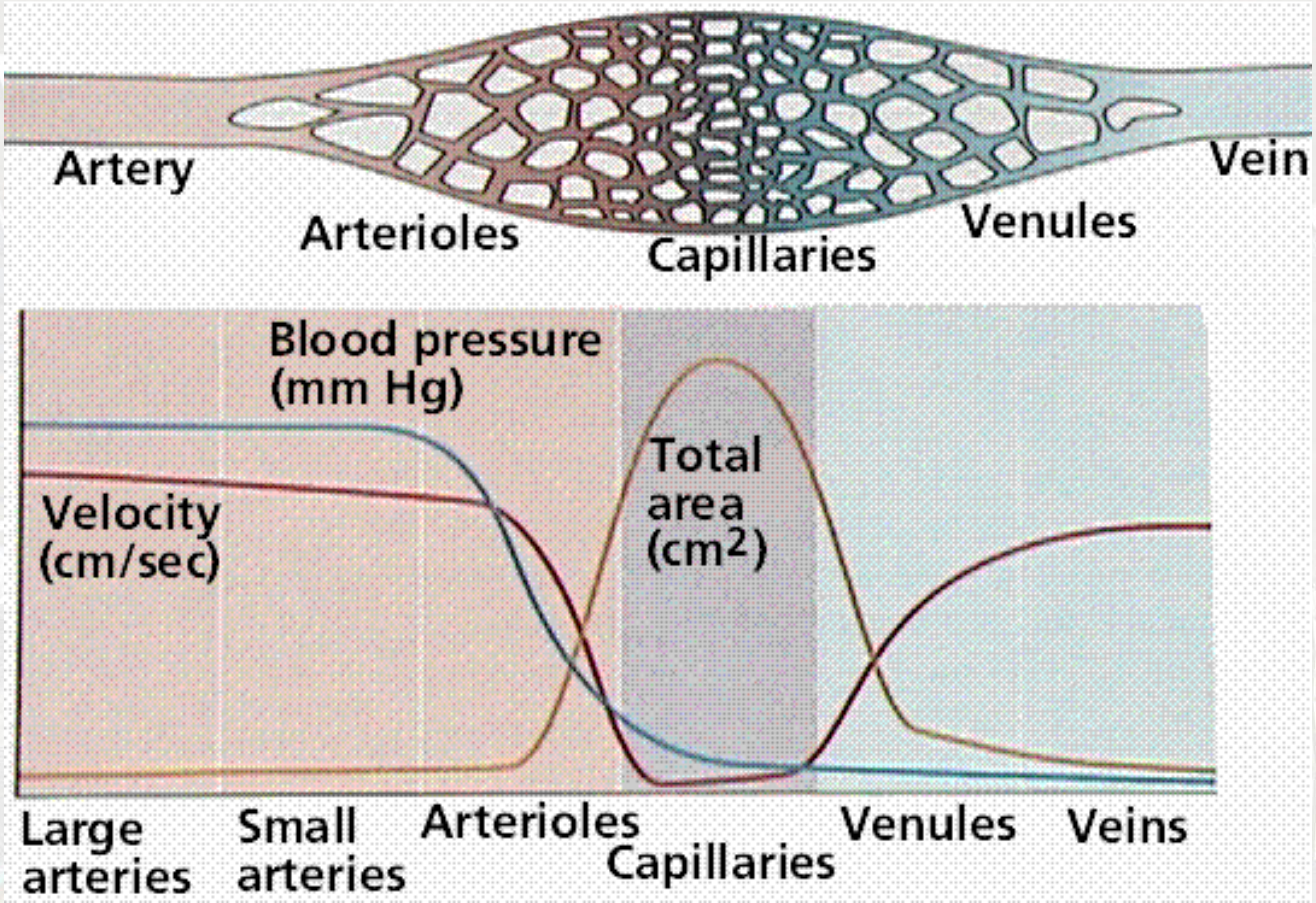
# VO2 Metabolic Workload Measurement

# VO2 Measurement in (Simulated) Suit

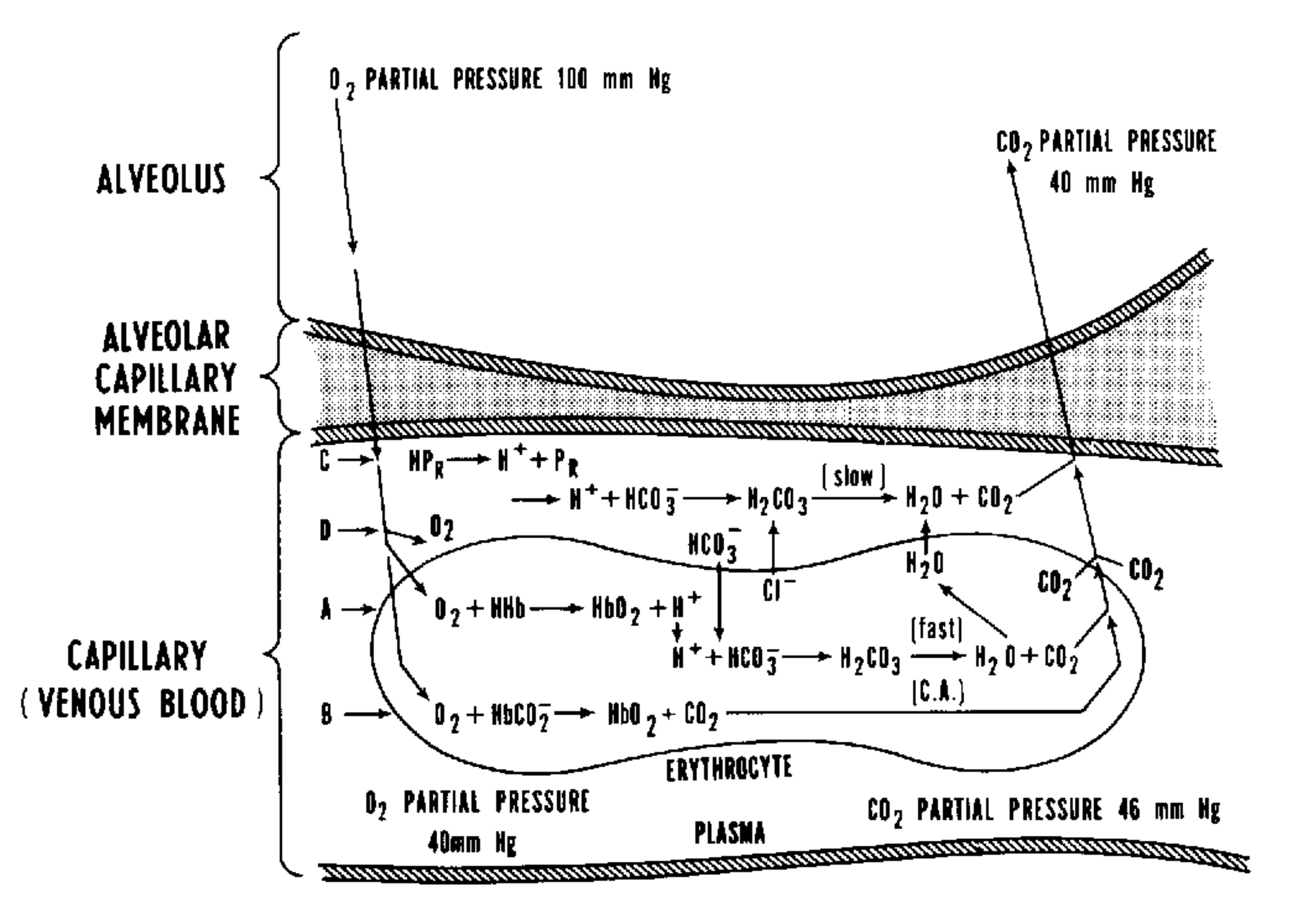
# The Human Circulatory System



# Blood Pressure in Circulatory System

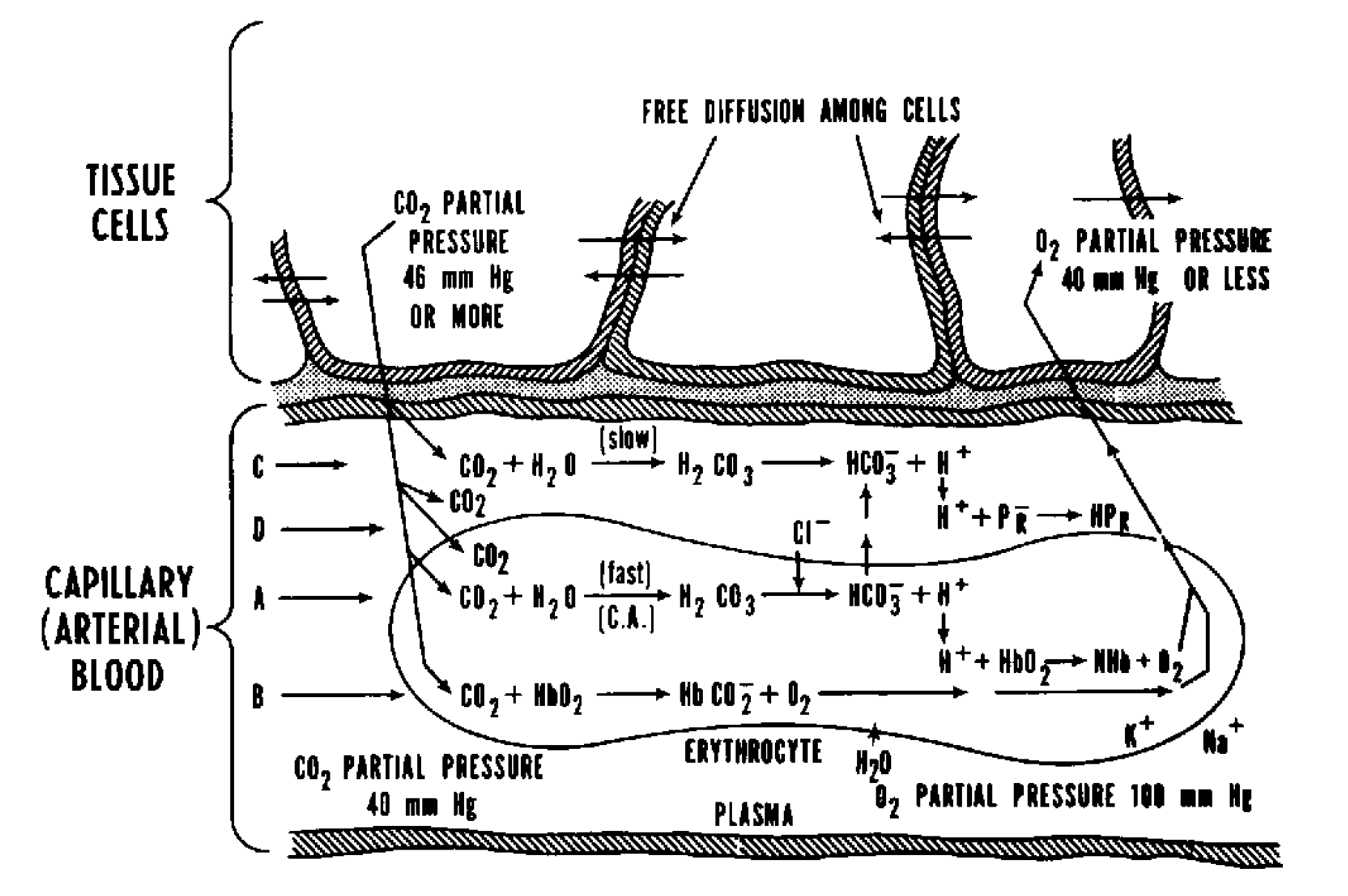


# Gas Exchange in the Lungs




From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

# Gas Exchange in the Tissues




From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

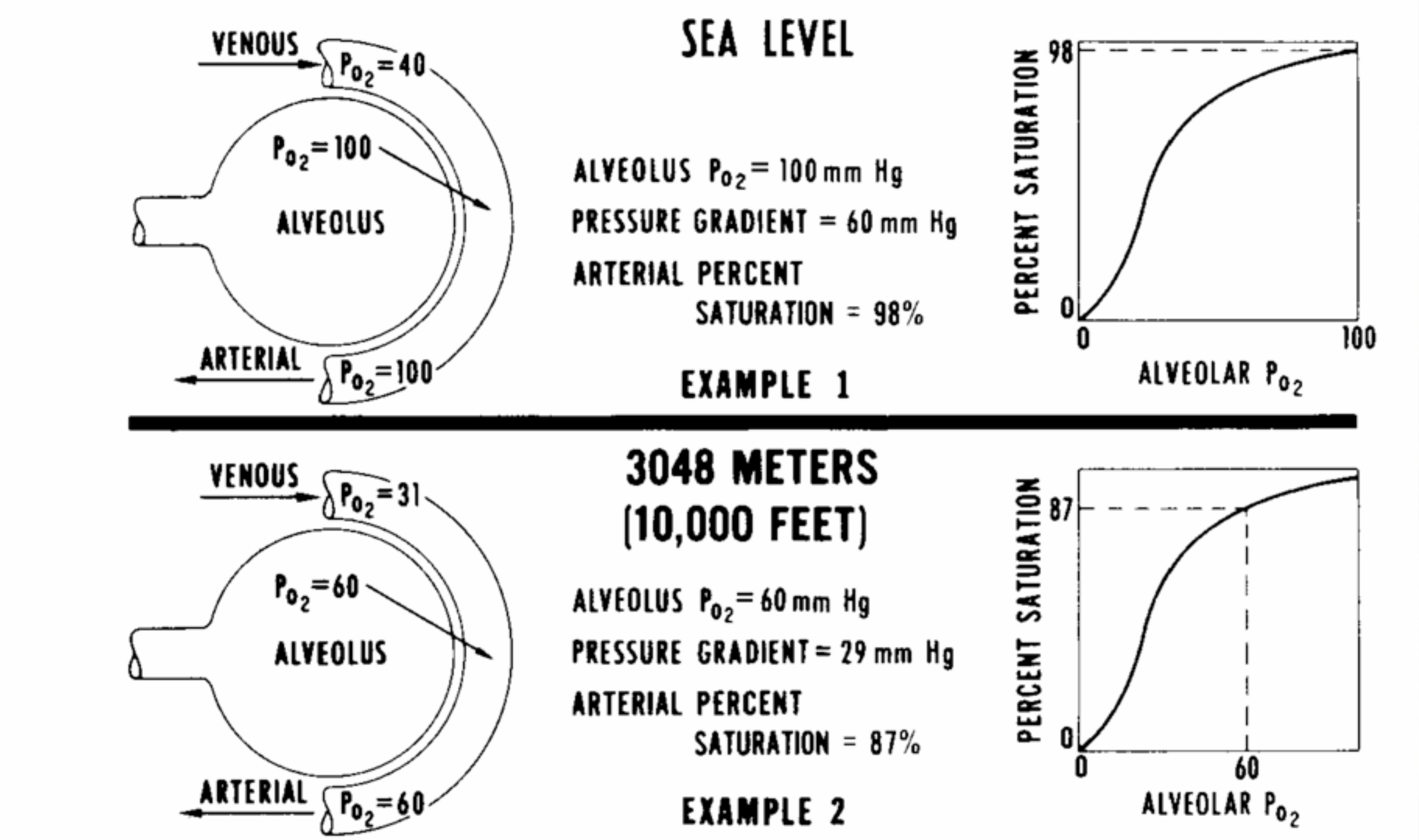
# Respiratory Problems

- Hypoxia
  - Hypoxic
  - Hypemic
  - Stagnant
  - Histotoxic
- Hyperoxia
- Hypocapnia
- Hypercapnia

# Types of Hypoxia

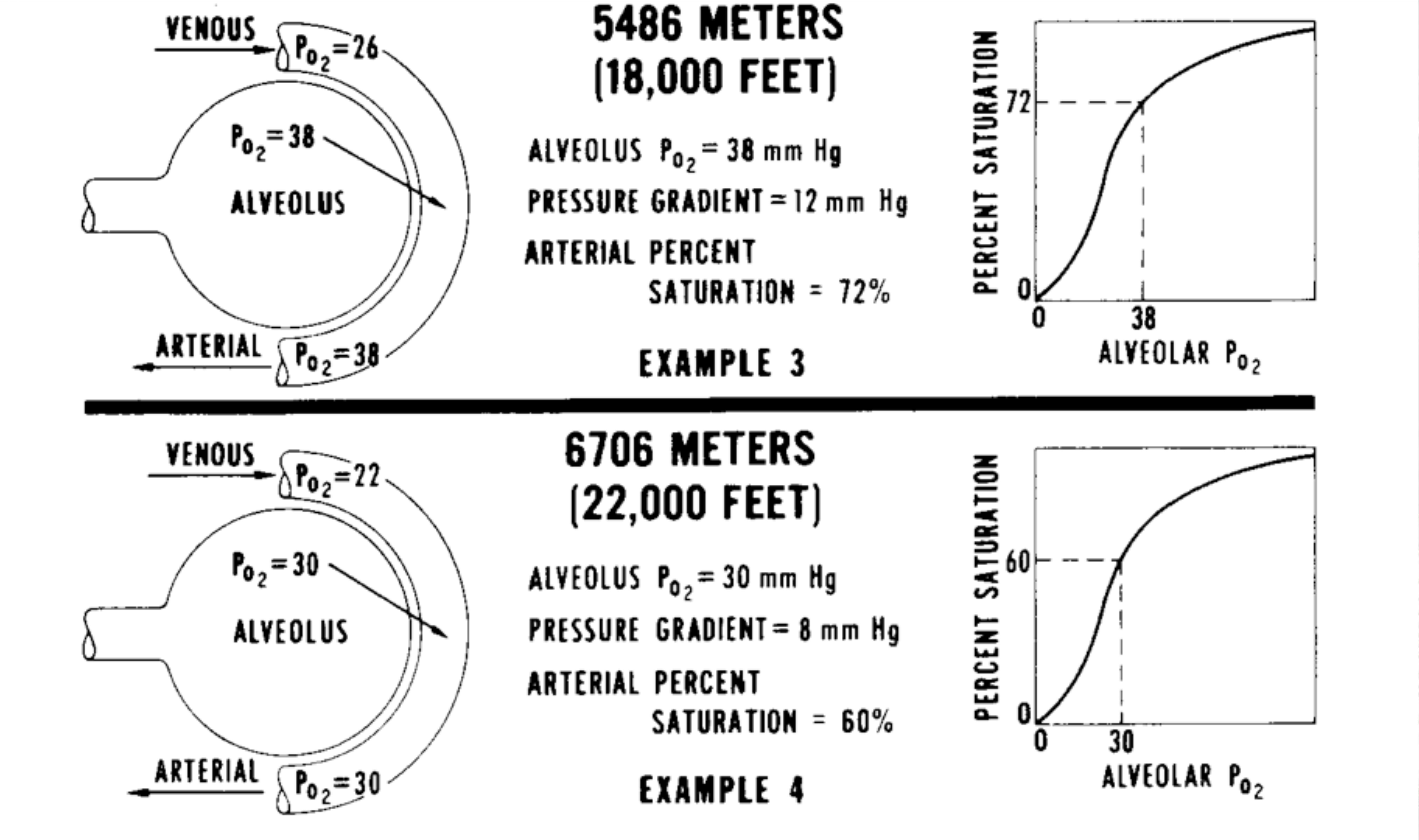
- Hypoxic (insufficient O2 present)
  - Decompression
  - Pneumonia
- Hypemic (insufficient blood capacity)
  - Hemorrhage
  - Anemia
- Stagnant (insufficient blood transport)
  - Excessive acceleration
  - Heart failure

# Pressure Effects on Blood Oxygenation



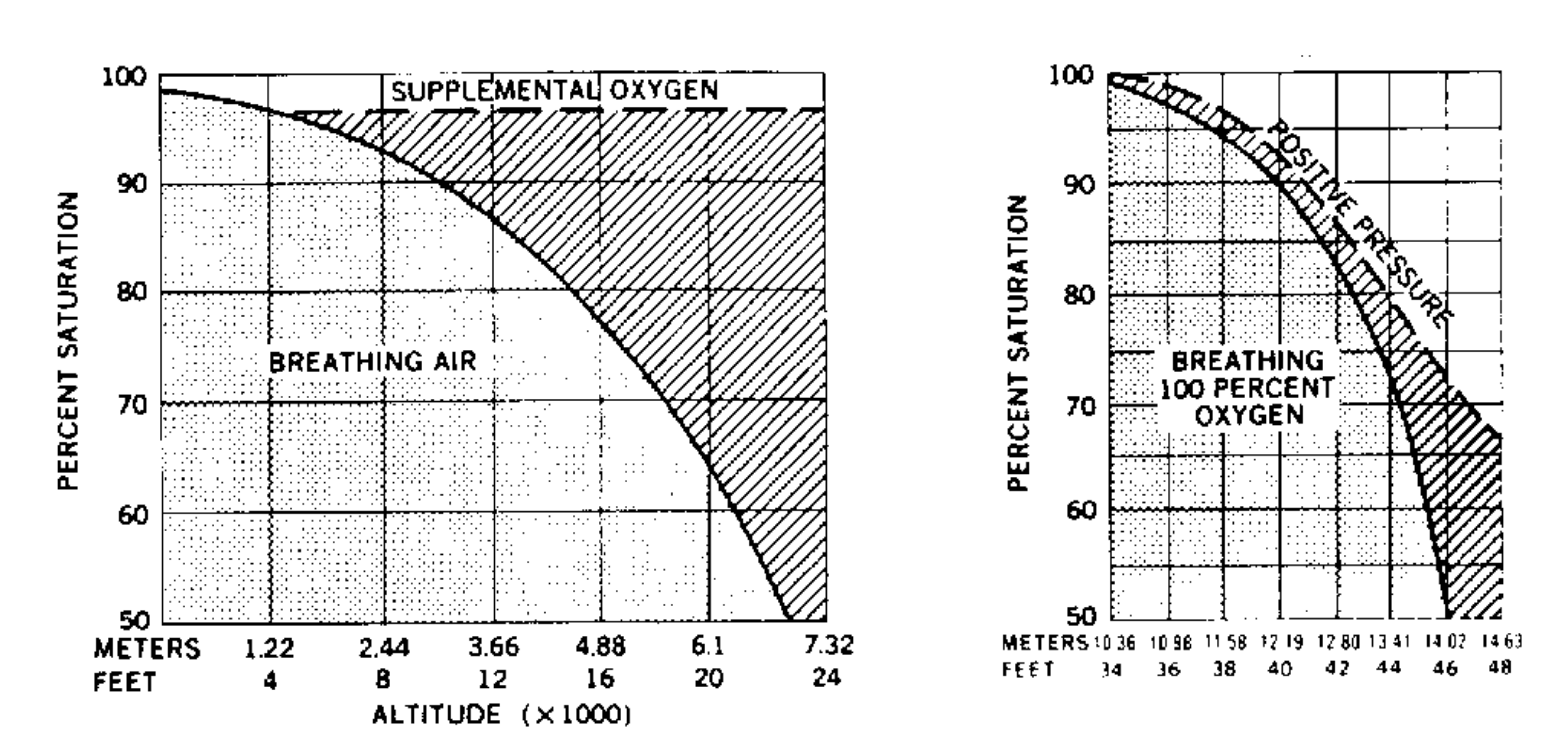

From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1996

# Pressure Effects on Blood Oxygenation



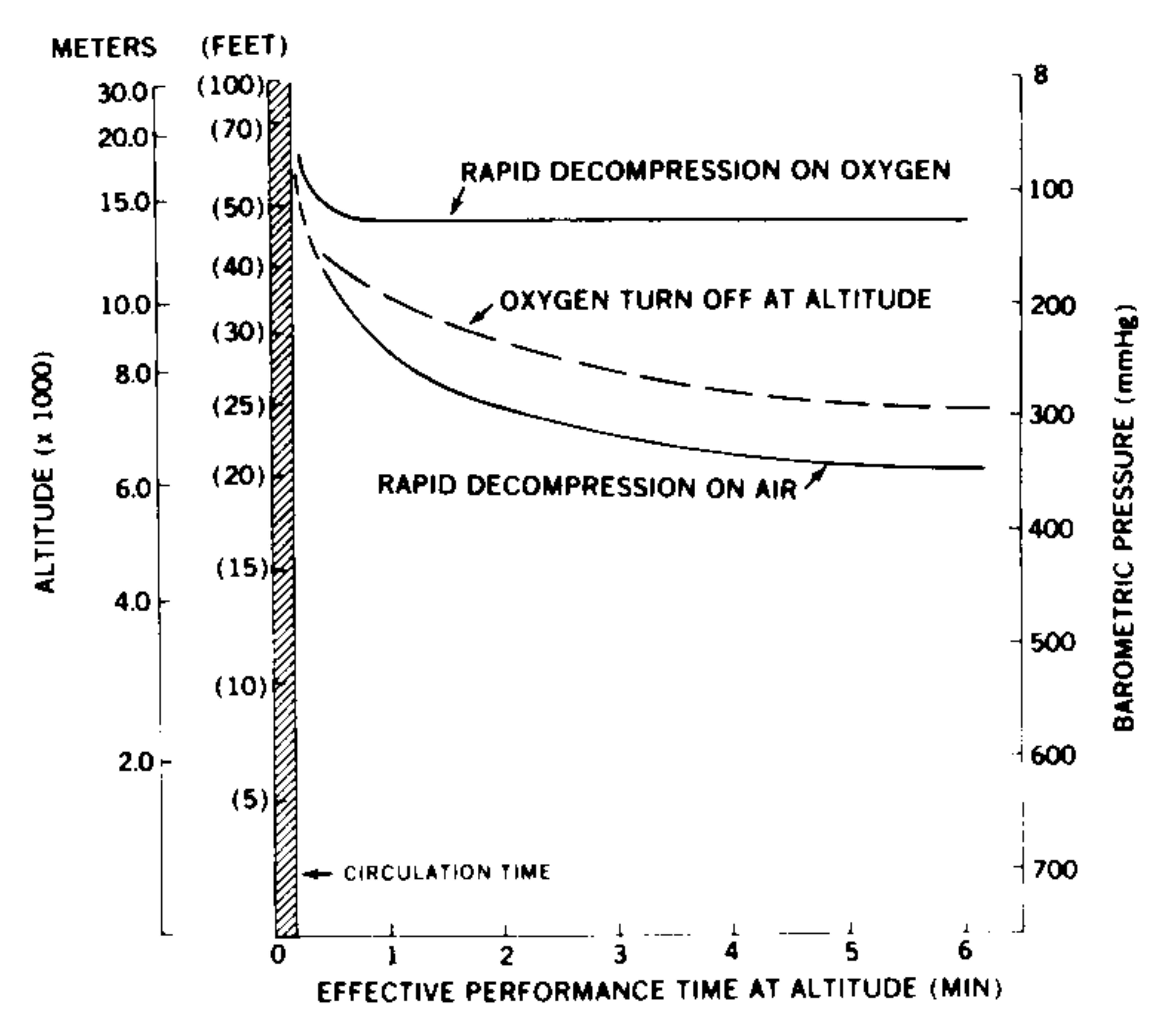

From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1996

# Effects of Supplemental Oxygen



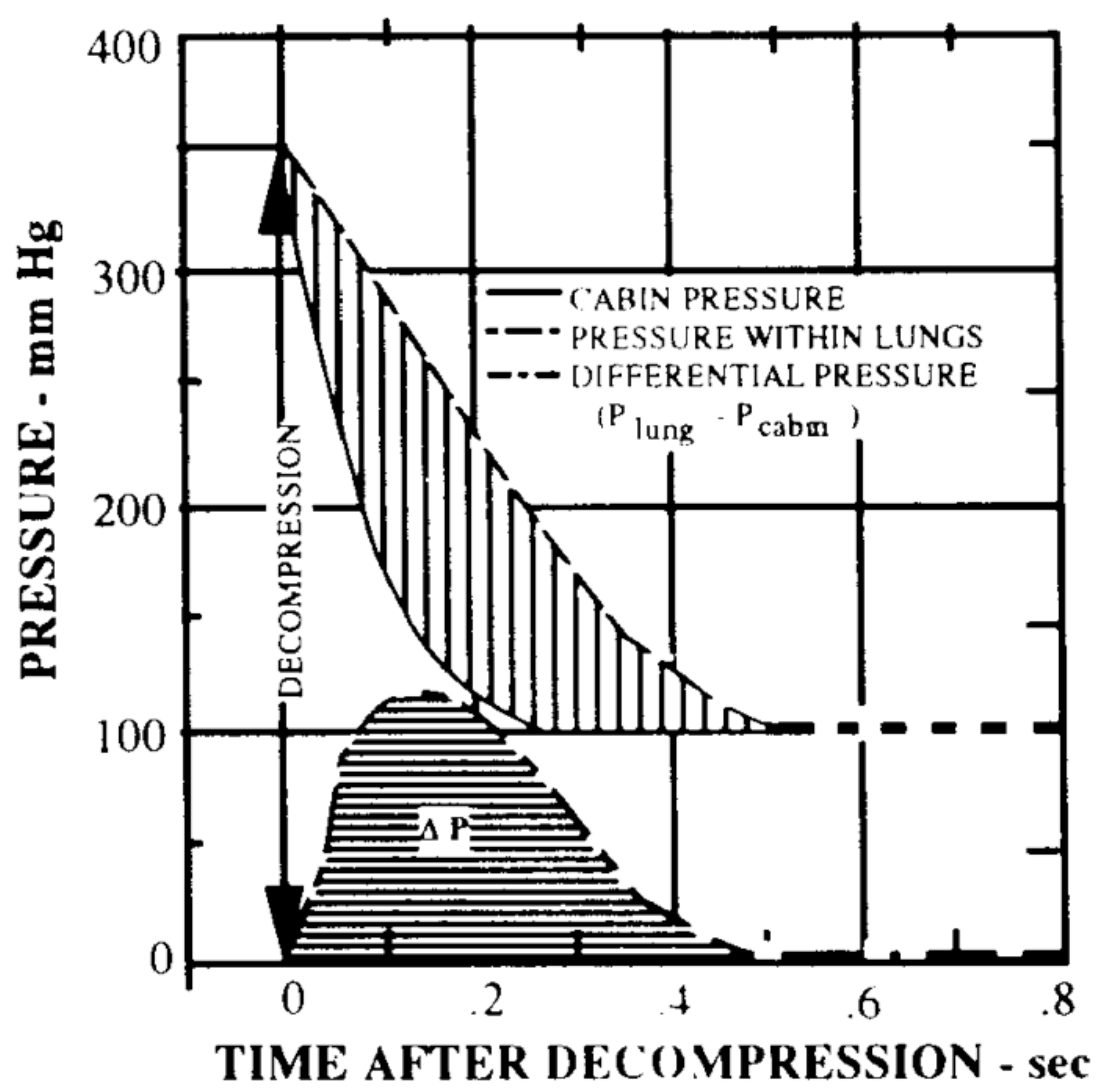

From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

# Hypoxia Effective Performance Time



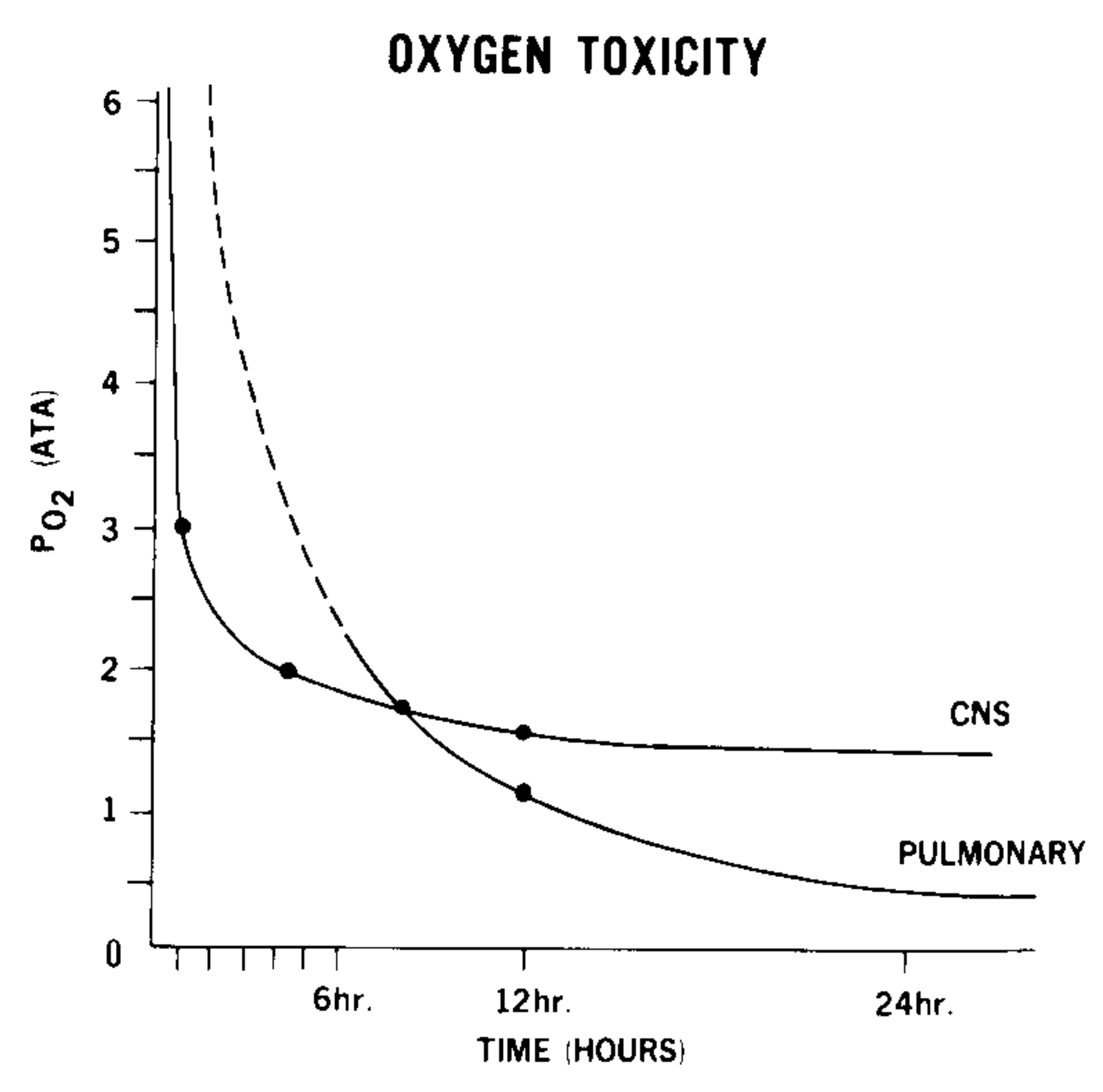

From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

# Lung Overpressure Following Decompression



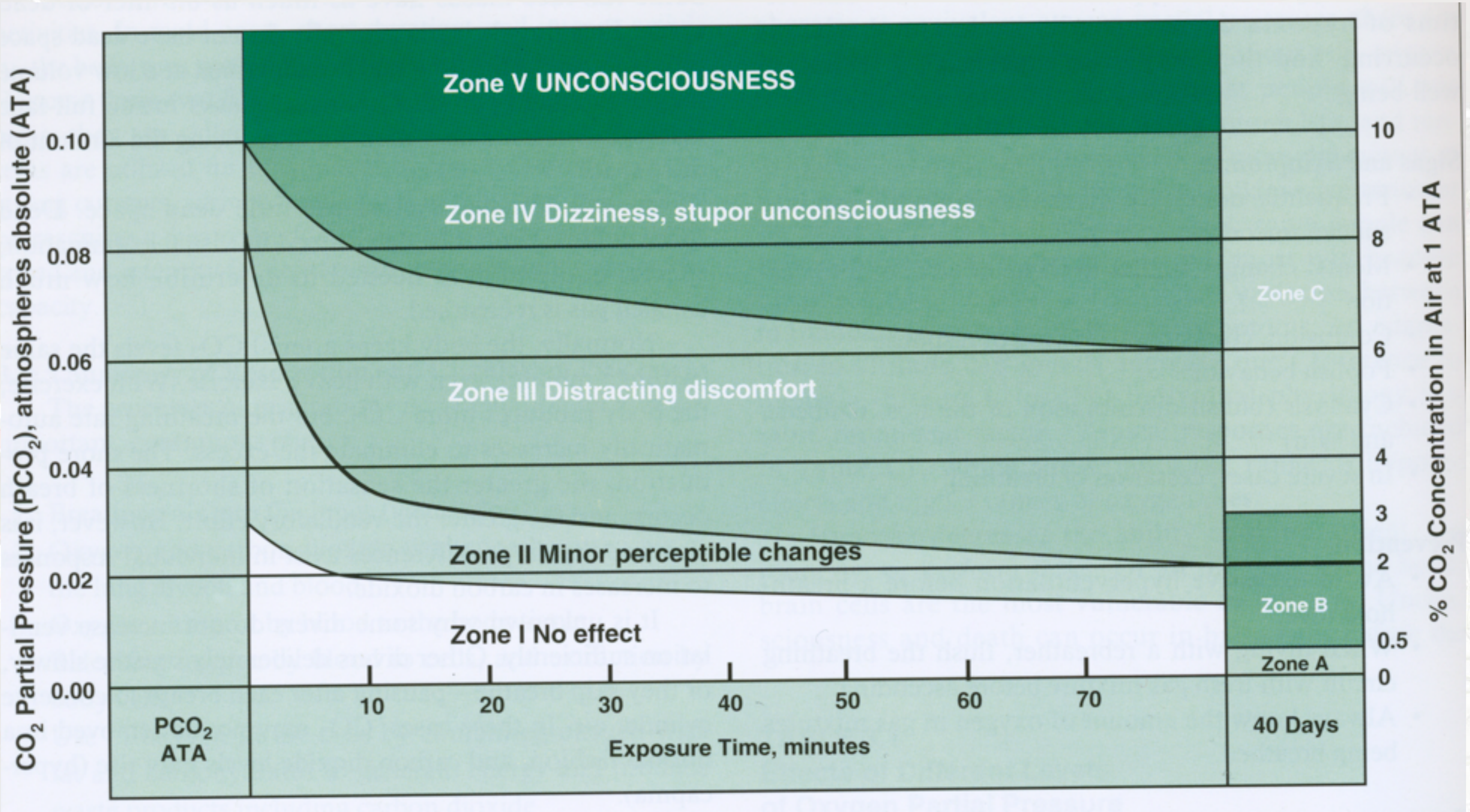

From Nicogossian and Gazenko, *Space Biology and Medicine - Volume II: Life Support and Habitability*, AIAA 1994

# Oxygen Toxicity



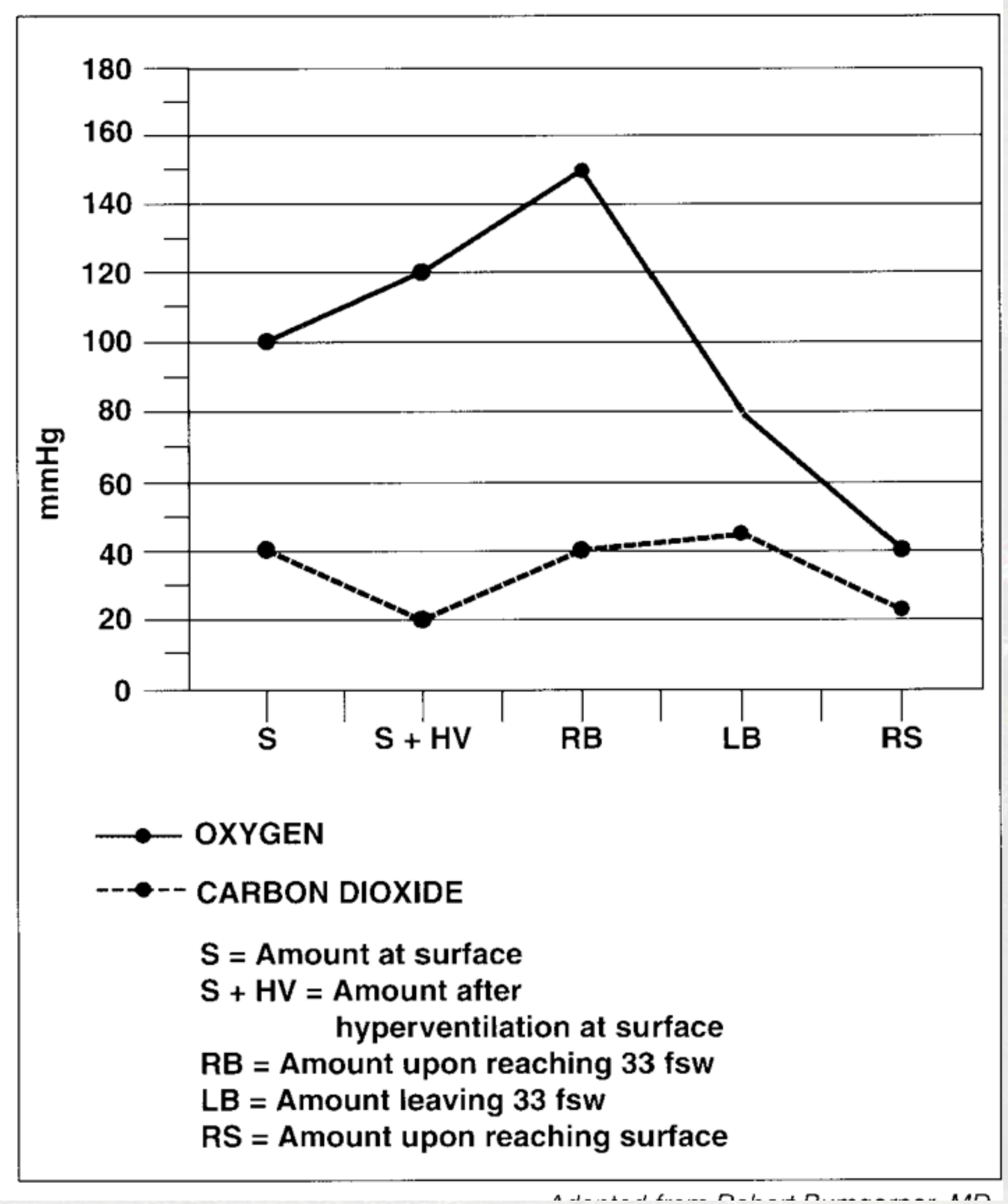

From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

# Effects of ppCO2



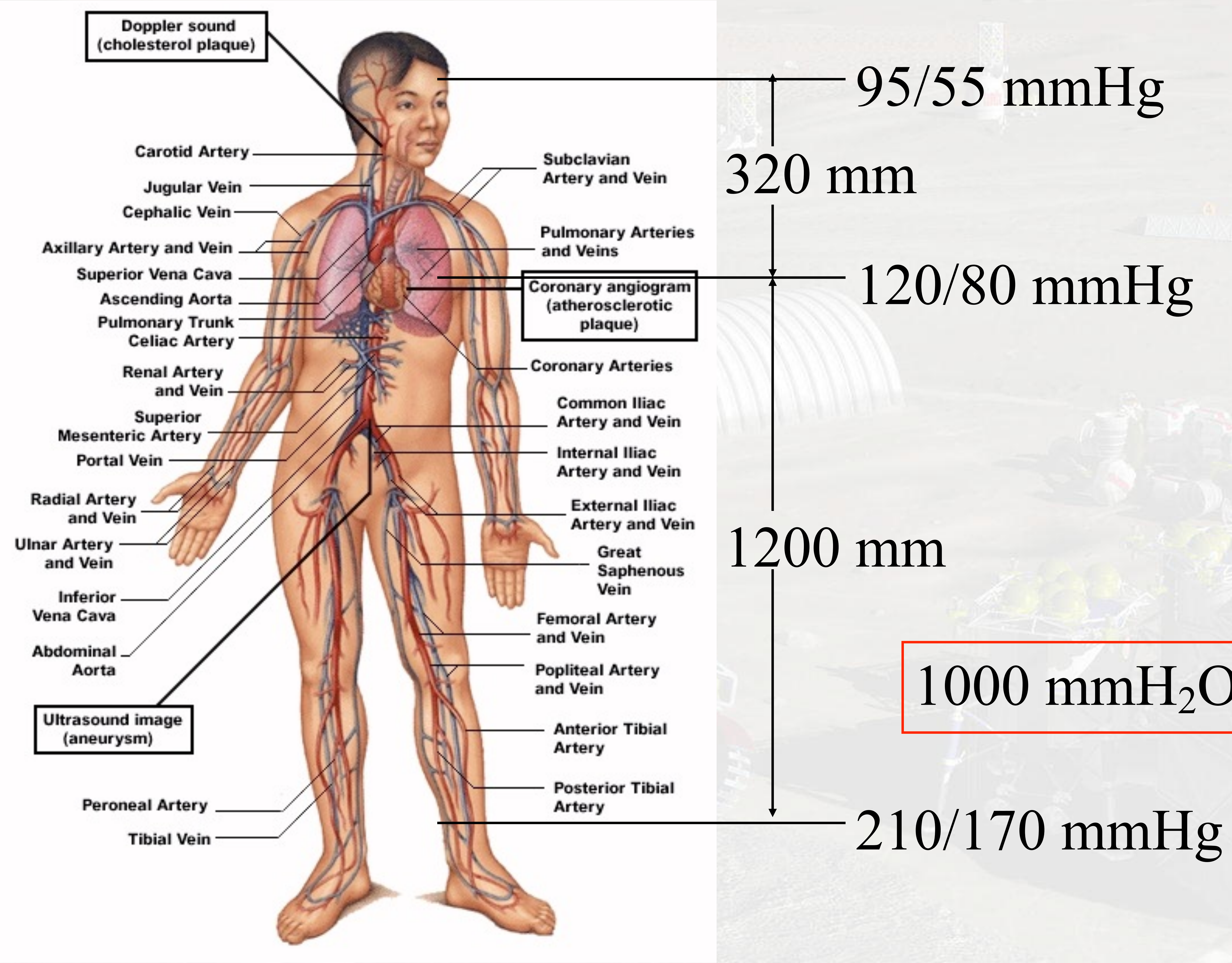

From James T. Joiner, *NOAA Diving Manual*, Fourth Edition, 2001

# Acute Effects of Hyperventilation



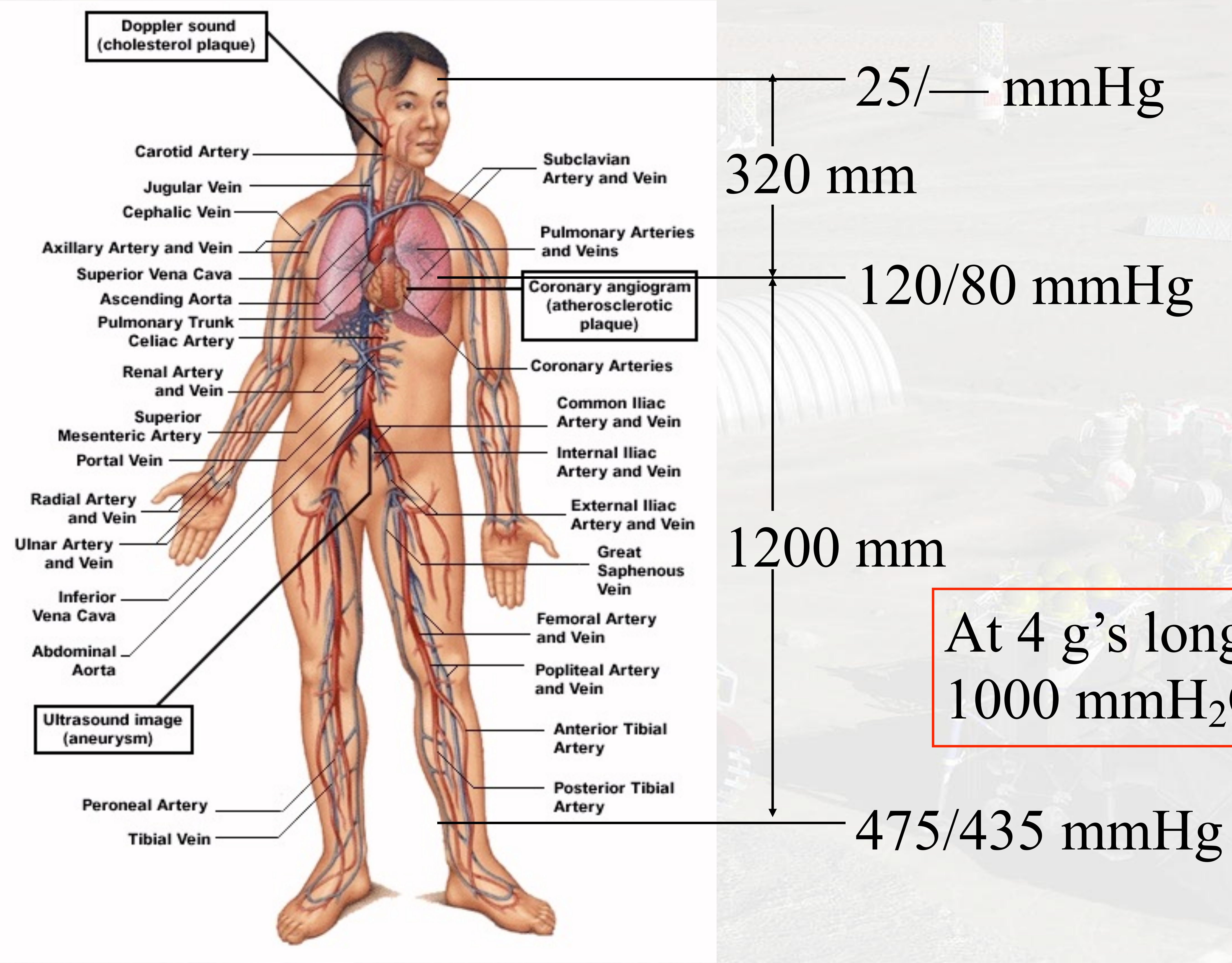

From James T. Joiner, *NOAA Diving Manual*, Fourth Edition, 2001

# Gravity Effects on Arterial Pressure




1000 mm$H_2O$ = 74.1 mmHg

# Acceleration Effects on Arterial Pressure




At 4 g's longitudinal:
1000 $mmH_2O$ = 296 mmHg

# Cardiovascular Effects of Microgravity

- Cardiovascular deconditioning
- Upper body blood pooling
- Changes in blood volume
- Increased calcium content

# Supersaturation of Blood Gases

- Early observation that "factor of two" (50% drop in pressure) tended to be safe
- Definition of tissue ratio R as ratio between saturated pressure of gas compared to ambient pressure

$$R = \frac{P_{N2}}{P_{ambient}} = 0.79 \text{ (nominal Earth value)}$$

- 50% drop in pressure corresponds to R=1.58 (R values of ~1.6 considered to be "safe")

# Tissue Models of Dissolved Gases

- Issue is dissolved inert gases (not involved in metabolic processes, like N2 or He)
- Diffusion rate is driven by the gradient of the partial pressure for the dissolved gas

$$\frac{dP_{tissue}(t)}{dt} = k\left[P_{alveoli}(t) - P_{tissue}(t)\right]$$

where k=time constant for specific tissue ($min^{-1}$)

P refers to partial pressure of dissolved gas

# Solution of Dissolved Gas Differential Eqn.

- Assume ambient pressure is piecewise constant (response to step input of ambient pressure)
- Result is the Haldane equation:

$$P_{tissue}(t) = P_{tissue}(0) + \left[P_{alveoli}(0) - P_{tissue}(0)\right]\left(1 - e^{-kt}\right)$$

- Need to consider value of $P_{alveoli}$

$$P_{alveoli} = (P_{ambient} - P_{H2O} - P_{CO2} + \Delta P_{O2})\,Q$$

$$P_{alveoli} = \left(P_{ambient} - P_{H2O} + \frac{1 - RQ}{RQ} P_{CO2}\right) Q$$

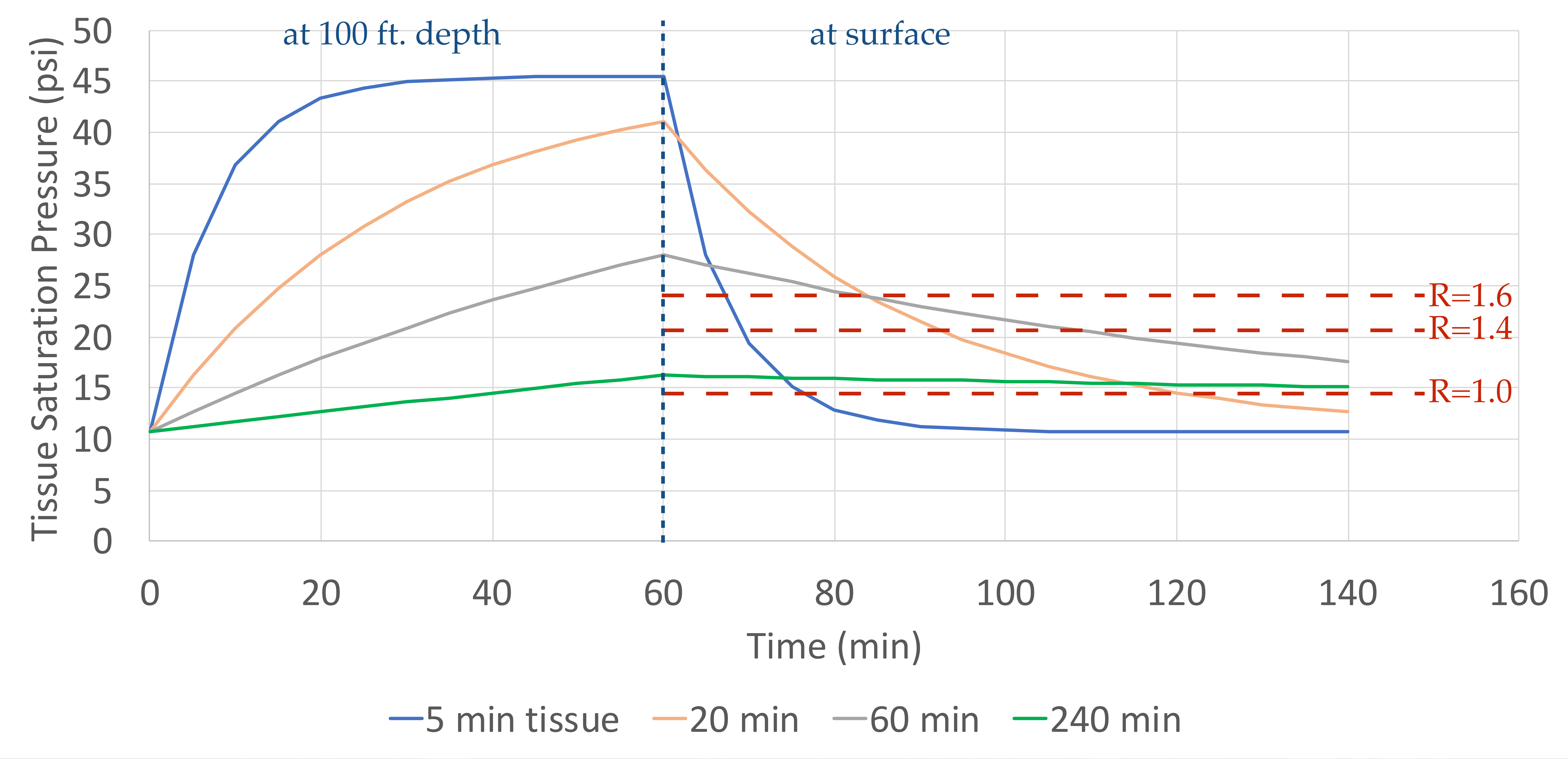
where Q=fraction of dissolved gas in atmosphere

$\Delta P_{O2}$=change in ppO2 due to metabolism

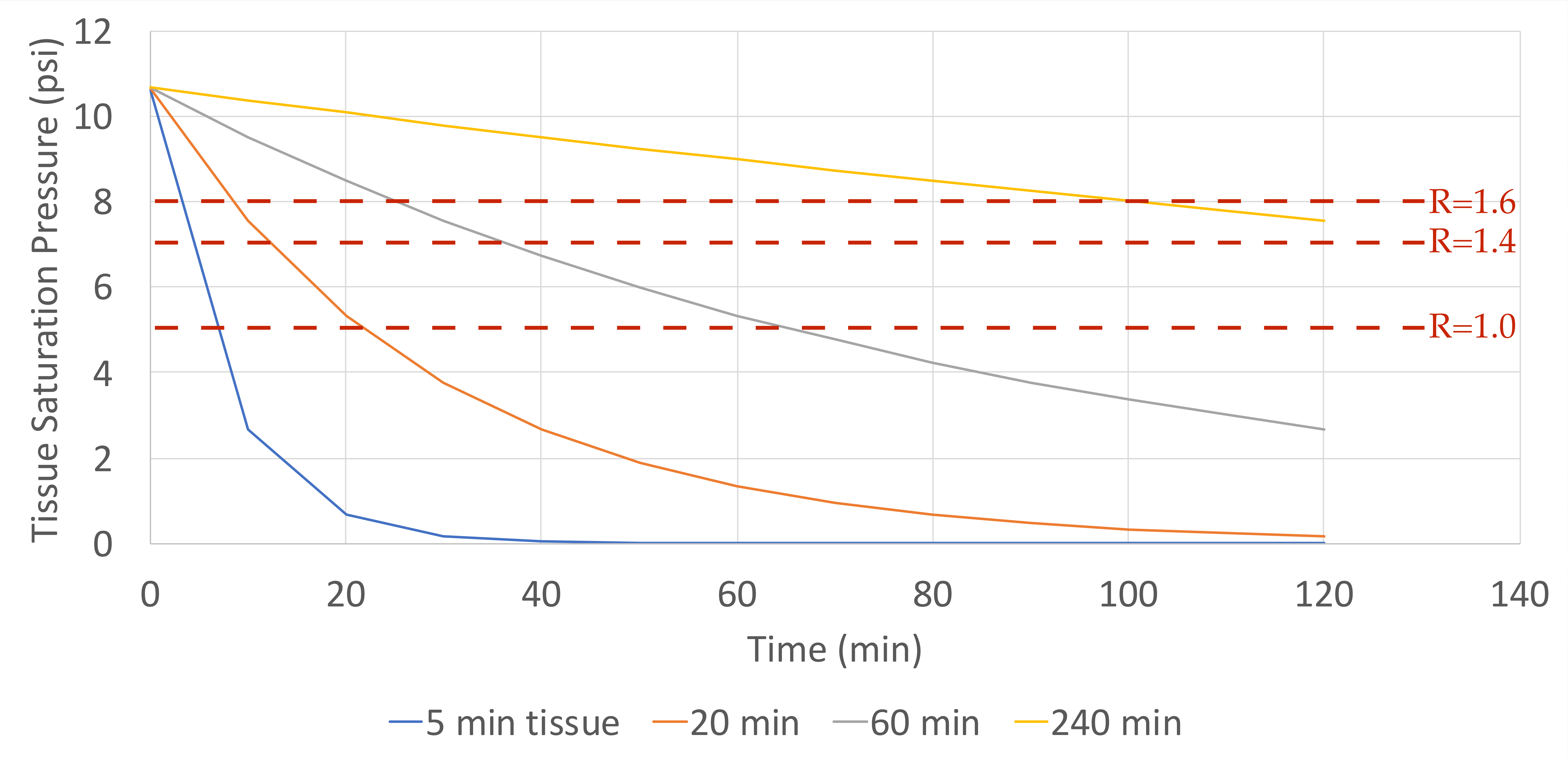
# Alveolar Pressure Corrections

- At body temperature (37°C=98.6°F), 100% humidified air has a partial pressure of 47 mmHg=6.3 kPa=0.91 psi – this is independent of total pressure or atmospheric composition
- Earth atmosphere=78% N2=Q, 0.04% CO2 (ISS limit ≤0.5% (negligible for these calculations)
- $P_{N_2,alveoli}(sea\ level) = (14.7 - 0.97)\,0.78 = 10.7\ psi$
- $P_{N_2,alveoli}(8.2\ psi/32\,\%\,O_2) = (8.2 - 0.97)\,0.68 = 4.9\ psi$

# Scuba Diving Decompression



# Apollo Pre-Launch Decompression




Transitioning from Earth sea level to 5psi 100% O2

# Solving for Time to Denitrogenate

$$P_{N_2,alveoli} = \left(P_{ambient} - P_{H_2O}\right) f_{N_2}$$

$$P_{N_2,tissue}(t) = P_{N_2,tissue}(0) + \left[\left(P_{ambient} - P_{H_2O}\right) f_{N_2} - P_{N_2,tissue}(0)\right]\left(1 - e^{-kt}\right)$$

$$e^{-kt} = 1 - \left[\frac{P_{N_2,tissue}(t) - P_{N_2,tissue}(0)}{\left(P_{ambient} - P_{H_2O}\right) f_{N_2} - P_{N_2,tissue}(0)}\right]$$

$$e^{-kt} = 1 - \left[\frac{\frac{P_{N_2,tissue}}{P_{ambient}}(t) - \frac{P_{N_2,tissue}}{P_{ambient}}(0)}{\left(1 - \frac{P_{H_2O}}{P_{ambient}}\right) f_{N_2} - \frac{P_{N_2,tissue}}{P_{ambient}}(0)}\right]$$

# Time to Reach Denitrogenation

$$\frac{P_{N_2,tissue}}{P_{ambient}}(t) \equiv R(t)$$

$$t = -\frac{1}{k}\ln\left[1 - \frac{R(t) - R(0)}{\left(1 - \frac{P_{H_2O}}{P_{ambient}}\right) f_{N_2} - R(0)}\right]$$

For Apollo case, 240 min tissue

$$t = -\frac{1}{0.002888}\ln\left[1 - \frac{1.4 - 2.14}{\left(1 - \frac{0.97}{5}\right) 0 - 2.14}\right] = 147\ min$$

# Haldane Tissue Models

- Rate coefficient frequently given as time to evolve half of dissolved gases:

$$T_{1/2} = \frac{\ln(2)}{k} \qquad k = \frac{\ln(2)}{T_{1/2}}$$

- Example: for 5-min tissue, k=0.1386 min$^{-1}$
- Haldane suggested five tissue "compartments": 5, 10, 20, 40, and 75 minutes
- Basis of U. S. Navy tables used through 1960's
- Three tissue model (5 and 10 min dropped)
- 1950's: Six tissue model (5, 10, 20, 40, 75, 120)

# Physics of Bubbles

- Pressure inside a bubble is balanced by exterior pressure and surface tension

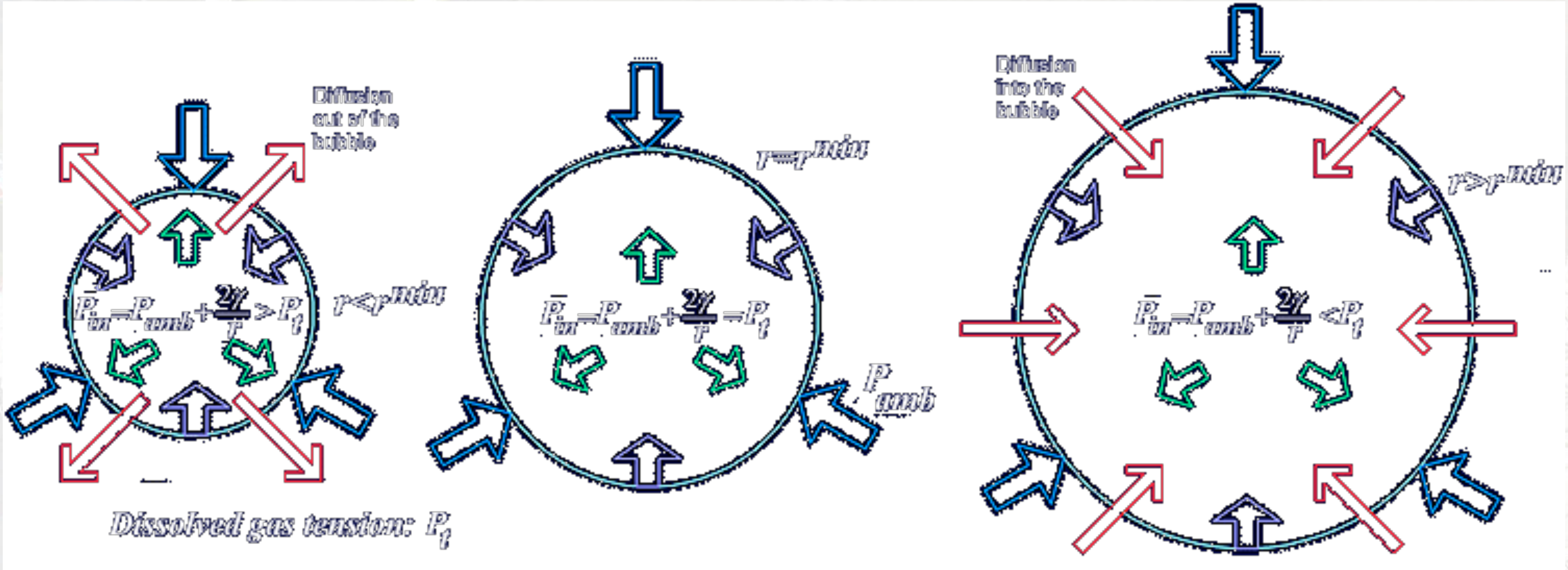
$$P_{internal} = P_{ambient} + P_{surface} = P_{ambient} + \frac{2\gamma}{r}$$

where $\gamma$=surface tension in J/m$^2$ or N/m (=0.073 for water at 273°K)

- Dissolved gas partial pressure $P_g$=$P_{amb}$ in equilibrium
- Gas pressure in bubble $P_{int}$>$P_{amb}$ due to $\gamma$
- All bubbles will eventually diffuse and collapse

# Bubble Formation and Growth

- In equilibrium, external pressure balanced by internal gas pressure and surface tension
- Surface tension forces inversely proportional to radius



# Critical Bubble Size

- Minimum bubble size is defined by point at which interior pressure $P_{int}$ = gas pressure $P_g$

$$r_{min} = \frac{2\gamma}{P_g - p_{ambient}}$$

- $r < r_{min}$ - interior gas diffuses into solution and bubble collapses
- $r > r_{min}$ - bubble will grow
- $r = r_{min}$ - unstable equilibrium

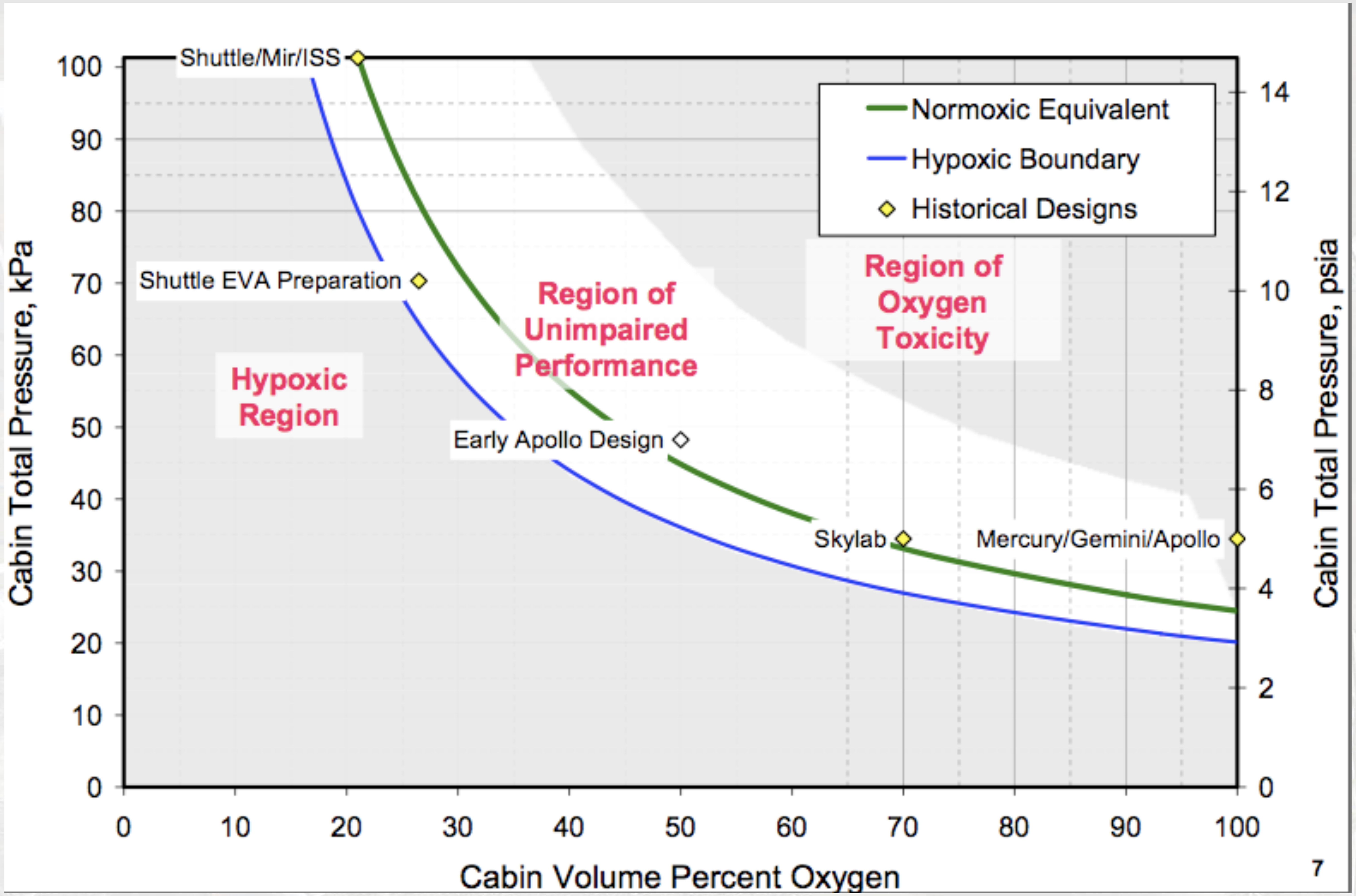
# Historical Data on Cabin Atmospheres

| Program | Cabin Pressure, kPa (psia) | Cabin Oxygen Concentration, volume % | EVA Suit Pressure,[1] kPa (psia) | EVA $O_2$ Pre-breathe Time, minutes | EVA Prebreathe Conditions |
|---|---|---|---|---|---|
| Mercury | 34.5 (5) | 100 | - | - | - |
| Gemini/Apollo | 34.5 (5) | 100 | 25.8 (3.75) | 0 | - |
| Skylab | 34.5 (5) | 70 | 25.8 (3.75) | 0 | - |
| Shuttle | 70.3 (10.2) | 26.5 | 29.6 (4.3) | 40 | In-suit (after 36 hours at 70.3 kPa) |
| | 101.3 (14.7) | 21 | 29.6 (4.3) | 240[3] | In-suit |
| ISS/US | 101.3 (14.7) | 21 | 29.6 (4.3) | 120-140 | Mask and in-suit; staged w/exercise |
| | | | | 240[3] | In-suit |
| Salyut, Mir, ISS/Russian | 101.3 (14.7) | 21 | 40.0 (5.8)[2] | 30 | In-suit |

References: Carson, et al. (1975), McBarron, et al. (1993), Waligora, et al. (1993), NASA (2002), NASA (2003).
(1) 100% oxygen.
(2) In earlier versions of the Orlan suit, the pressure could be reduced to 26.5 kPa (3.8 psia) for short-duration work regime.
(3) Under emergency conditions, a minimum of 150 minutes of unbroken prebreathe is recommended.

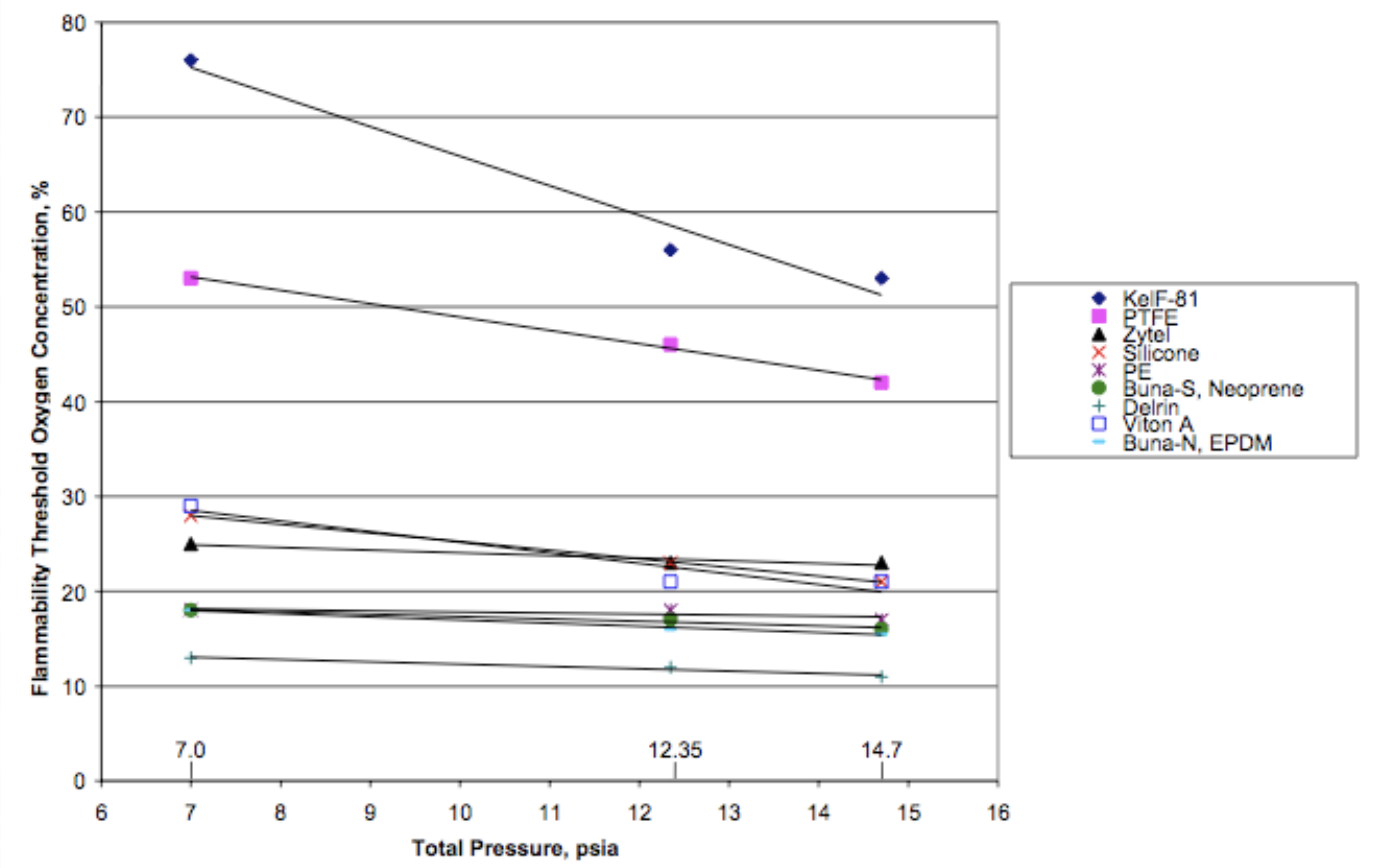
from Scheuring et. al., "Risk Assessment of Physiological Effects of Atmospheric Composition and Pressure in Constellation Vehicles" 16th Annual Humans in Space, Beijing, China, May 2007

# Spacecraft Atmosphere Design Space



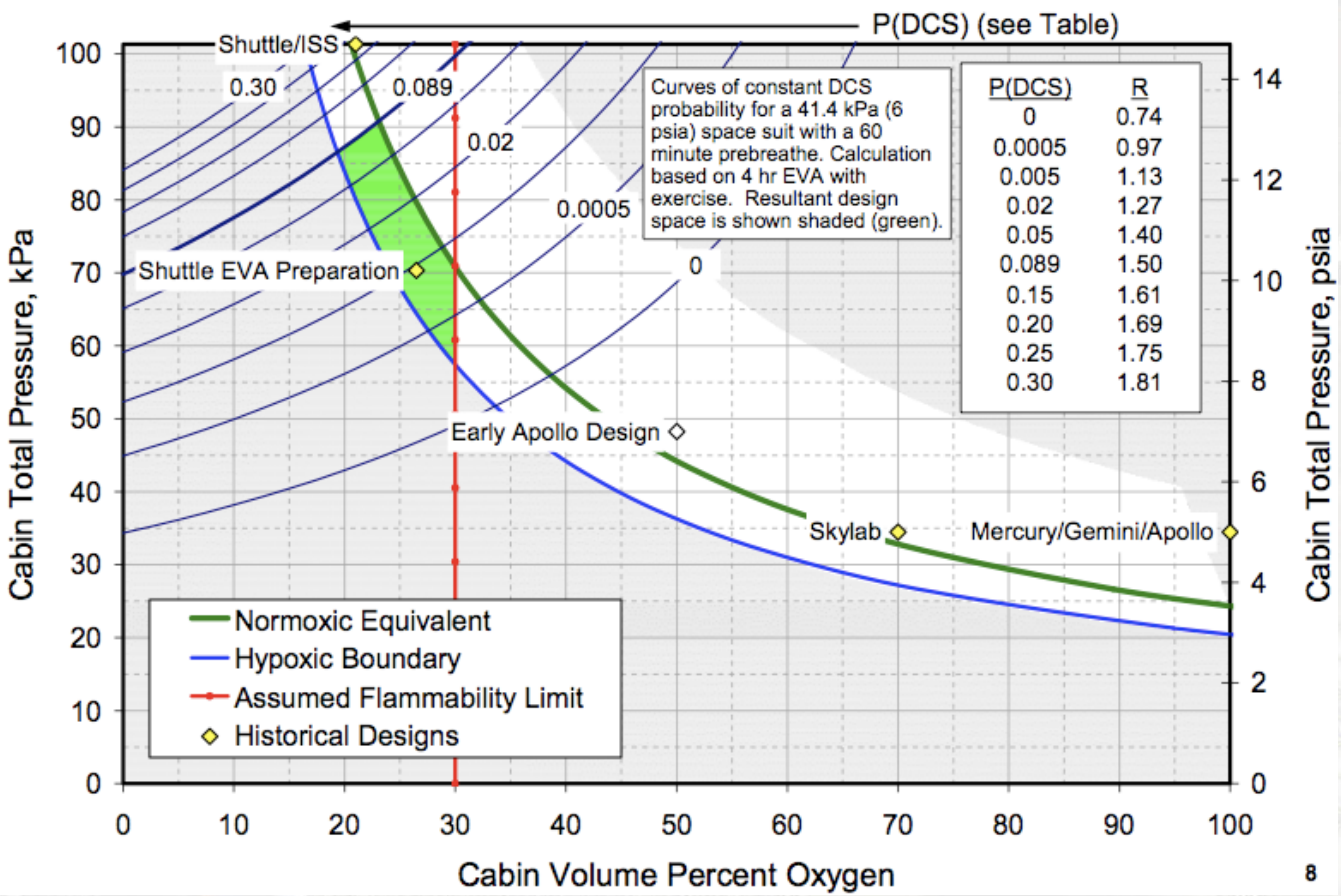

from Scheuring et. al., “Risk Assessment of Physiological Effects of Atmospheric Composition and Pressure in Constellation Vehicles” 16th Annual Humans in Space, Beijing, China, May 2007

# Effect of Pressure and %$O_2$ on Flammability



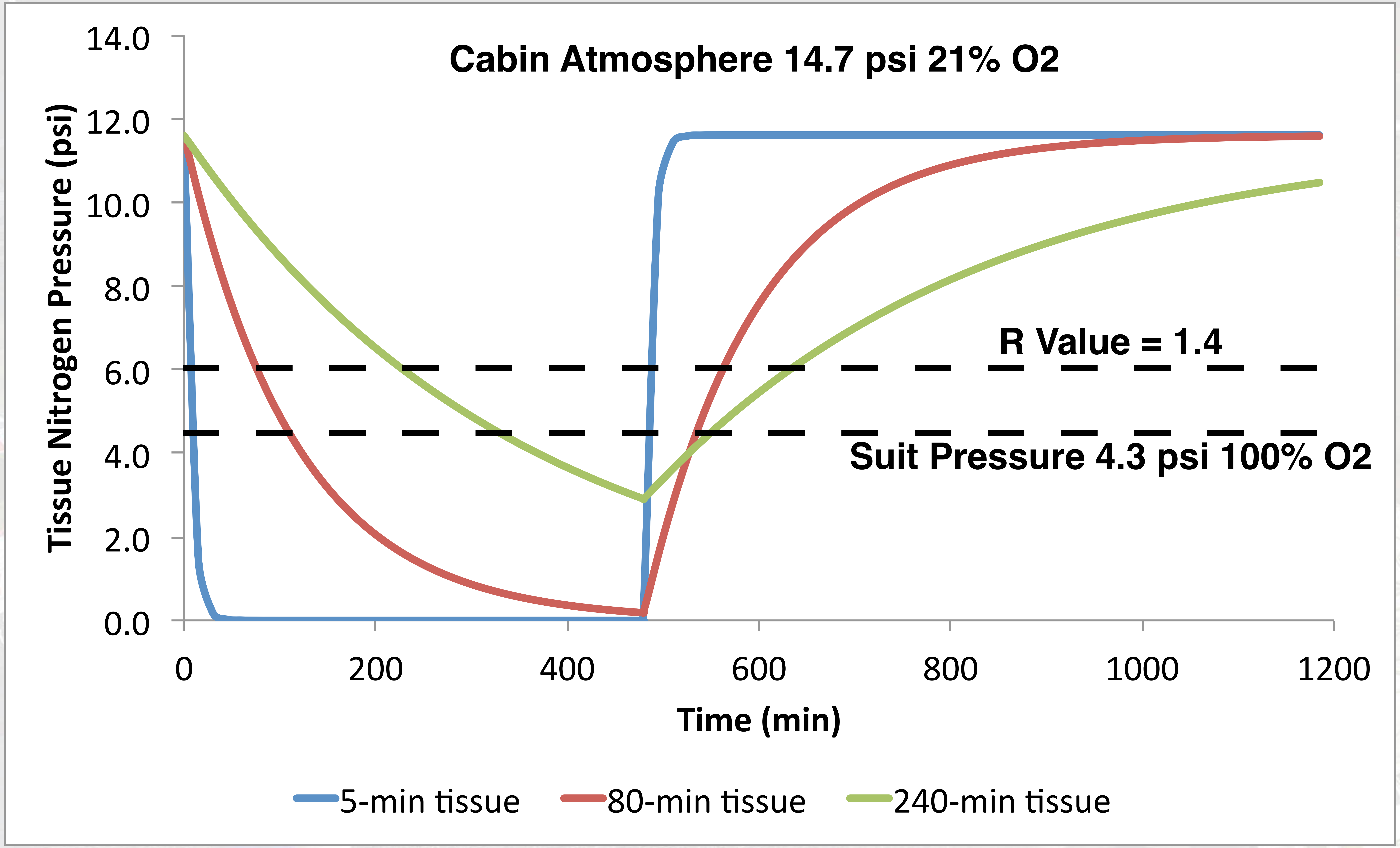

from Hirsch, Williams, and Beeson, "Pressure Effects on Oxygen Concentration Flammability Thresholds of Materials for Aerospace Applications" J. Testing and Evaluation, Oct. 2006

# Atmosphere Design Space with Constraints

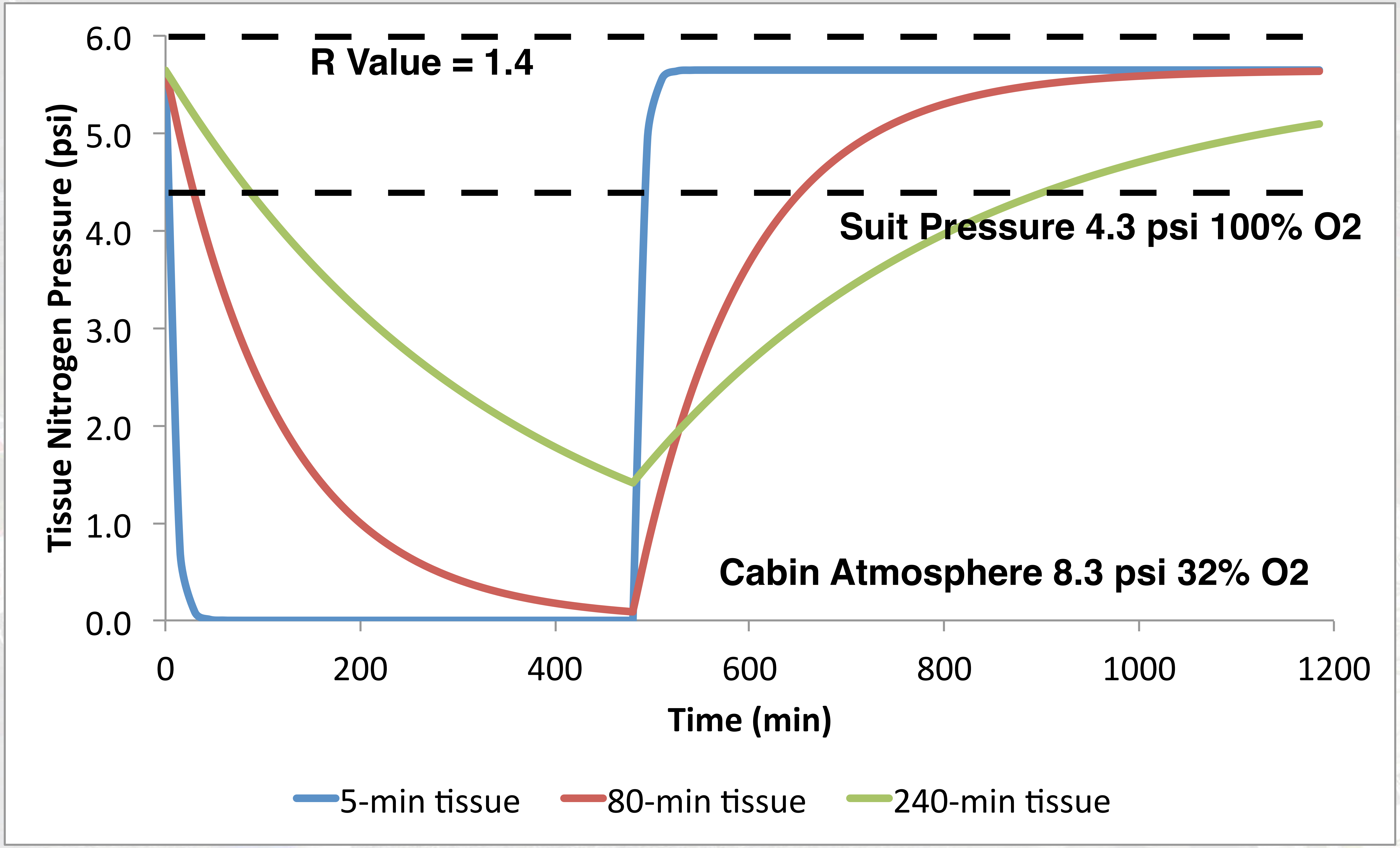



from Scheuring et. al., "Risk Assessment of Physiological Effects of Atmospheric Composition and Pressure in Constellation Vehicles" 16th Annual Humans in Space, Beijing, China, May 2007

# EVA Denitrogenation - 14.7 psi Cabin



# EVA Denitrogenation - 8.3 psi Cabin



# Constellation Spacecraft Atmospheres

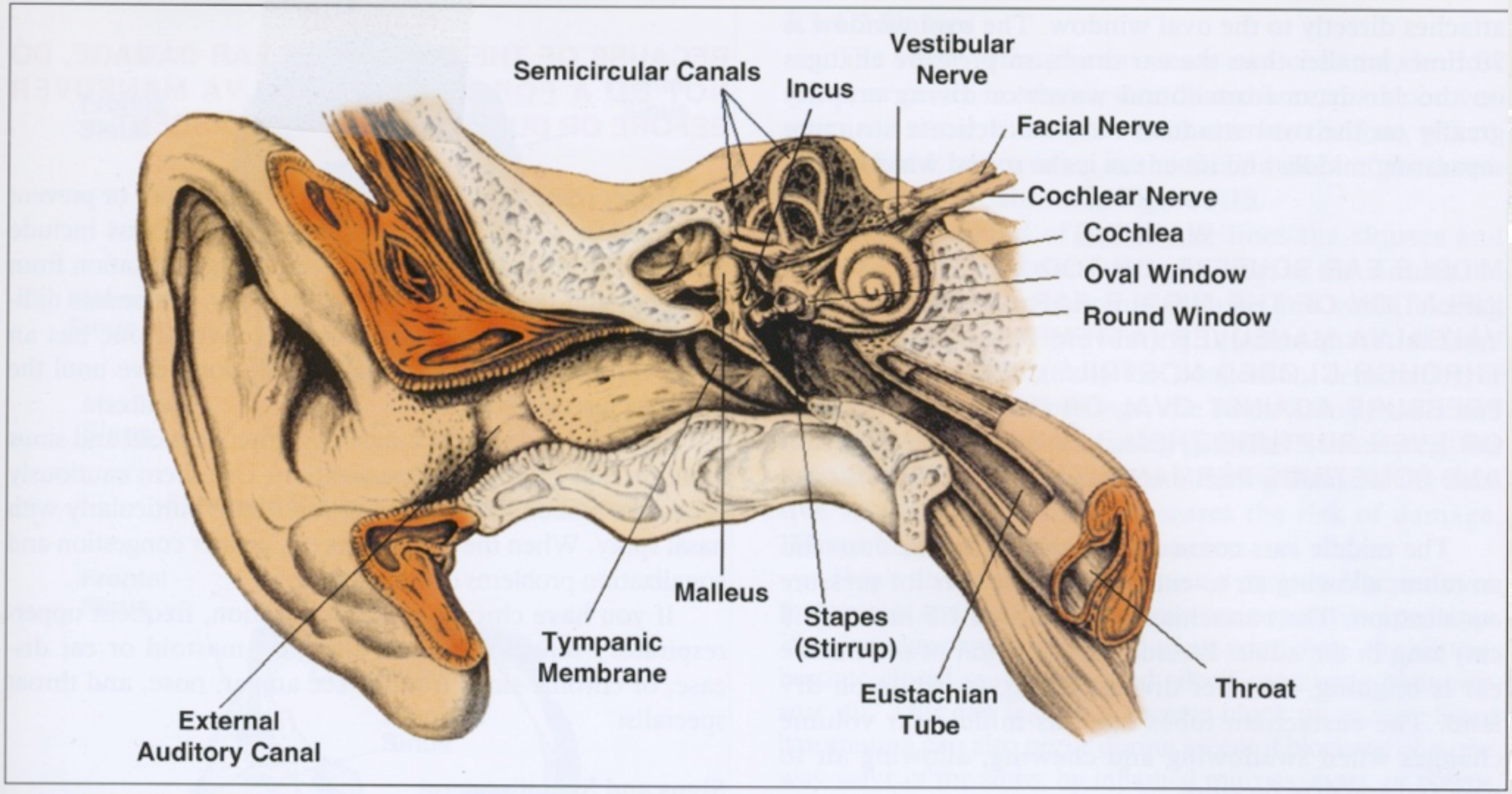
| Environment | $P_B$ psia | $P_B$ mmHg | $F_IO_2$ (%) | $P_IO_2$ mmHg | $P_AO_2$ mmHg | Actual Altitude m | Actual Altitude feet | Equivalent Air Altitude m | Equivalent Air Altitude feet |
|---|---|---|---|---|---|---|---|---|---|
| CEV + LSAM | | | | | | | | | |
| normal | 8.0 | 414 | 32.0 | 117 | 77 | 4,877 | 16,000 | 1,829 | 6,000 |
| **best case** | **8.2** | **424** | **34.0** | **128** | **86** | **4,816** | **15,800** | **1,158** | **3,800** |
| **worse case** | **7.8** | **403** | **30.0** | **107** | **68** | **5,029** | **16,500** | **2,438** | **8,000** |
| HABITAT | | | | | | | | | |
| normal | 7.6 | 393 | 32.0 | 111 | 71 | 5,182 | 17,000 | 2,286 | 7,500 |
| **best case** | **7.8** | **403** | **34.0** | **121** | **80** | **5,029** | **16,500** | **1,524** | **5,000** |
| **worse case** | **7.4** | **383** | **30.0** | **101** | **63** | **5,364** | **17,600** | **2,895** | **9,500** |

from Scheuring et. al., "Risk Assessment of Physiological Effects of Atmospheric Composition and Pressure in Constellation Vehicles" 16th Annual Humans in Space, Beijing, China, May 2007

# Categories of Sensing

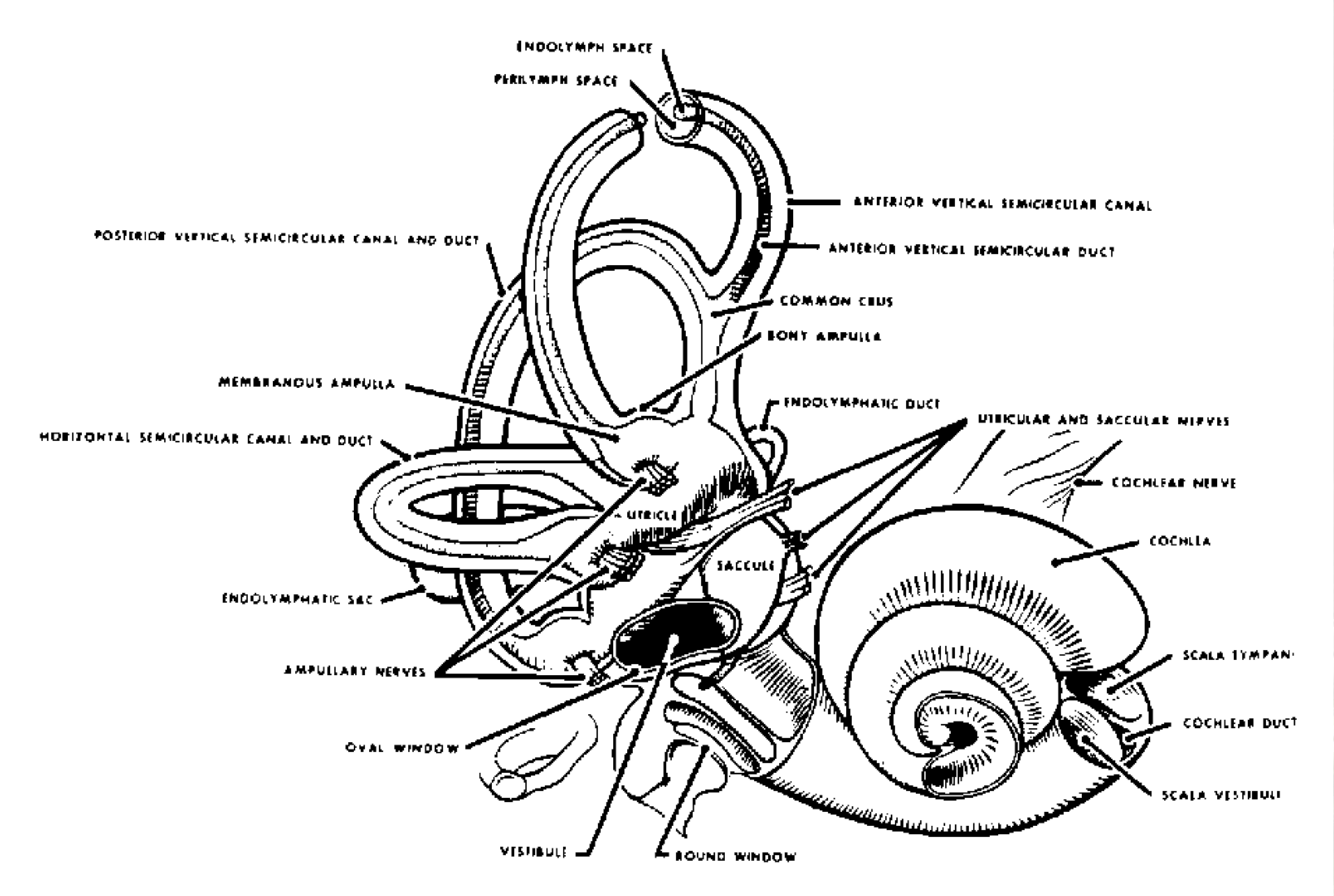
- Proprioception (internal to body)
  - "Self-Sensing"
  - Vestibular (inertial forces)
  - Muscle and tendon sensors (extension)
  - Joint sensors (angle)
- Exteroception (external to body)
  - Visual
  - Auditory
  - Cutaneous

# Anatomy of the Ear



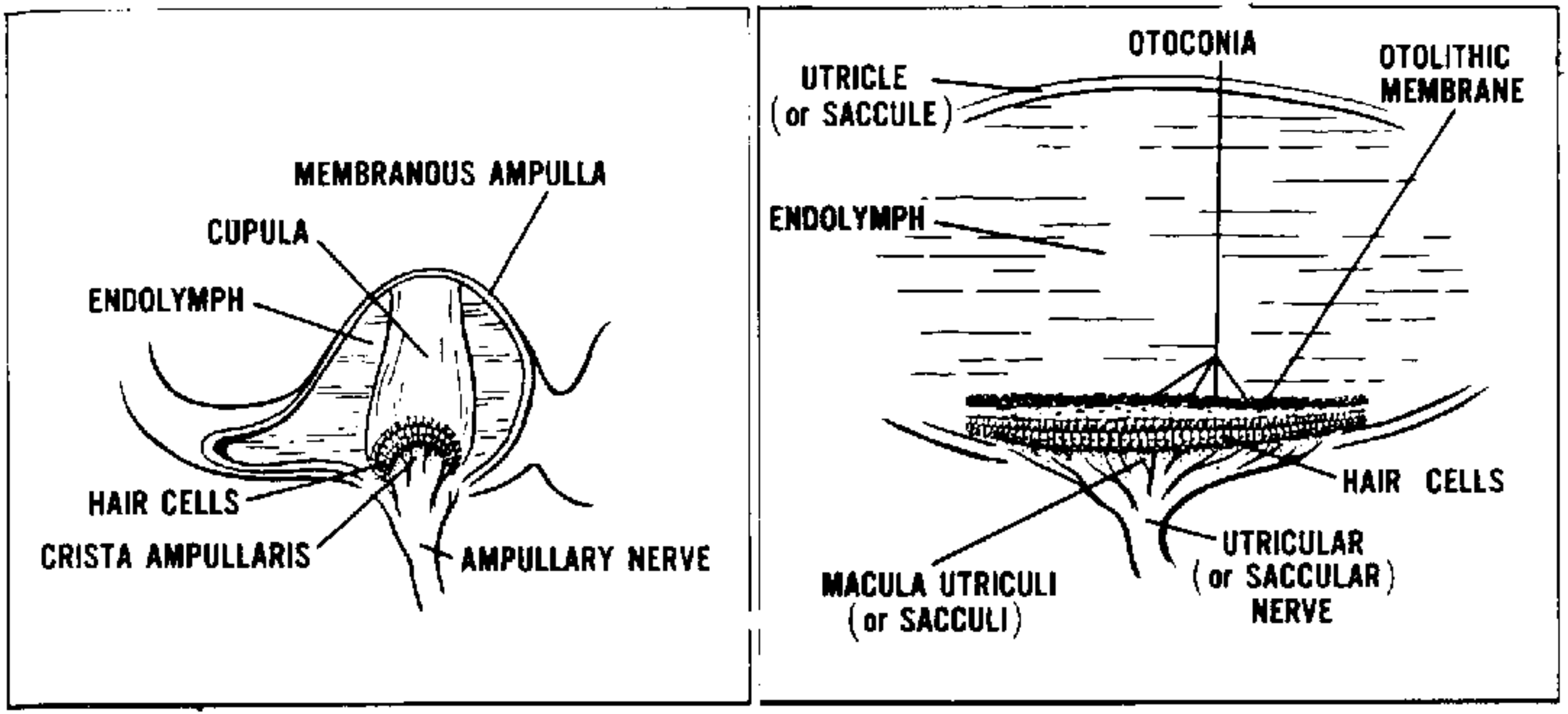

From James T. Joyner, ed., *NOAA Diving Manual*, Best Publishing, 2001

# Vestibular System




From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

# Vestibular Sense Organs

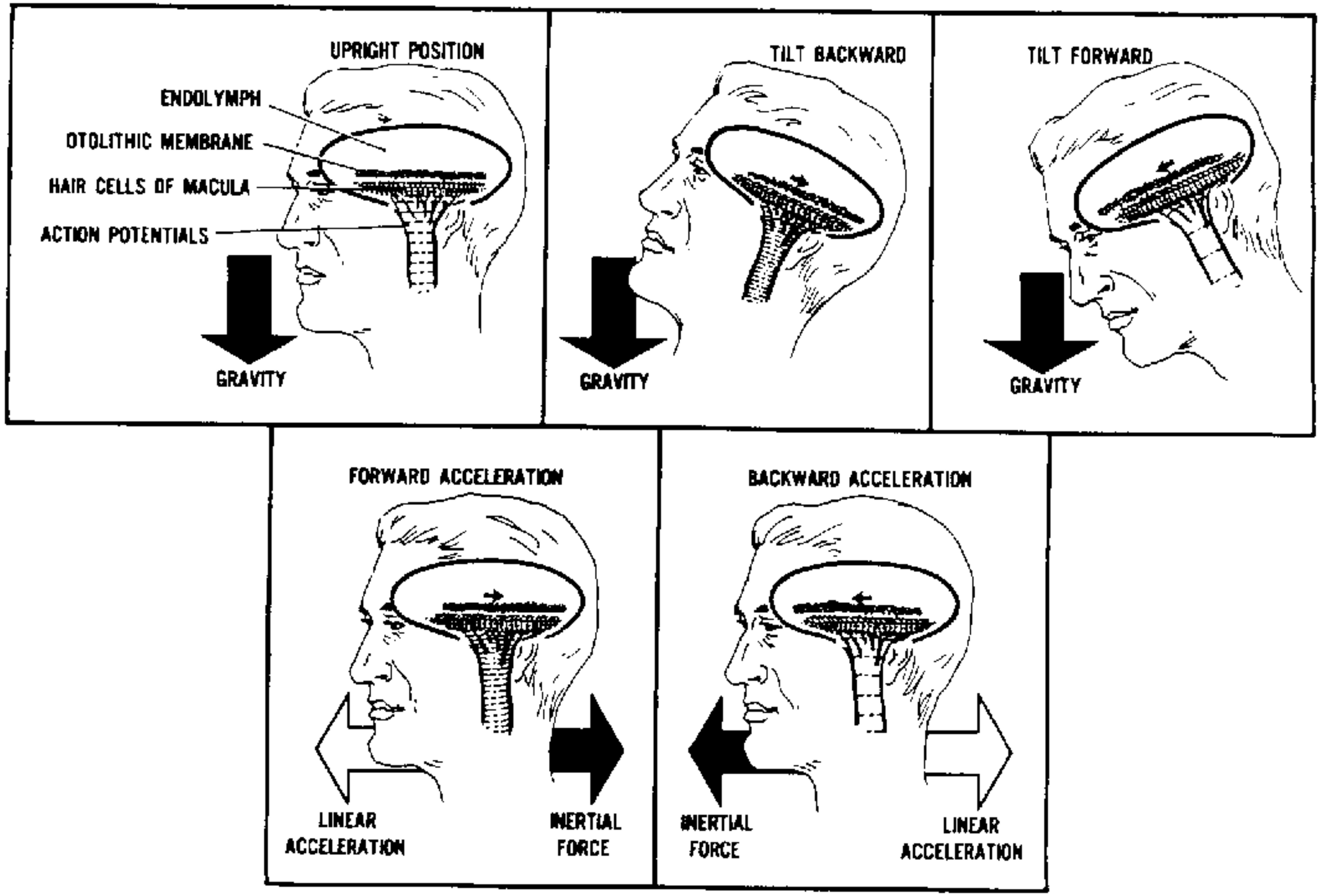



From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

# Thresholds of Rotational Perception

- Rotational accelerations
  - Yaw: 0.14 deg/sec$^2$
  - Roll and Pitch: 0.5 deg/sec$^2$
- Mulder's Constant
  - Acceleration x excitation time = 2 deg/sec
  - 5 deg/sec$^2$ x 0.5 sec -> sensed
  - 10 deg/sec$^2$ x 0.1 sec -> not sensed
- Rotational velocities - minimum perceived rotation rates 1-2 deg/sec (all axes)

# Otolith Responses




From Roy DeHart, *Fundamentals of Aerospace Medicine*, Lea & Febiger, 1985

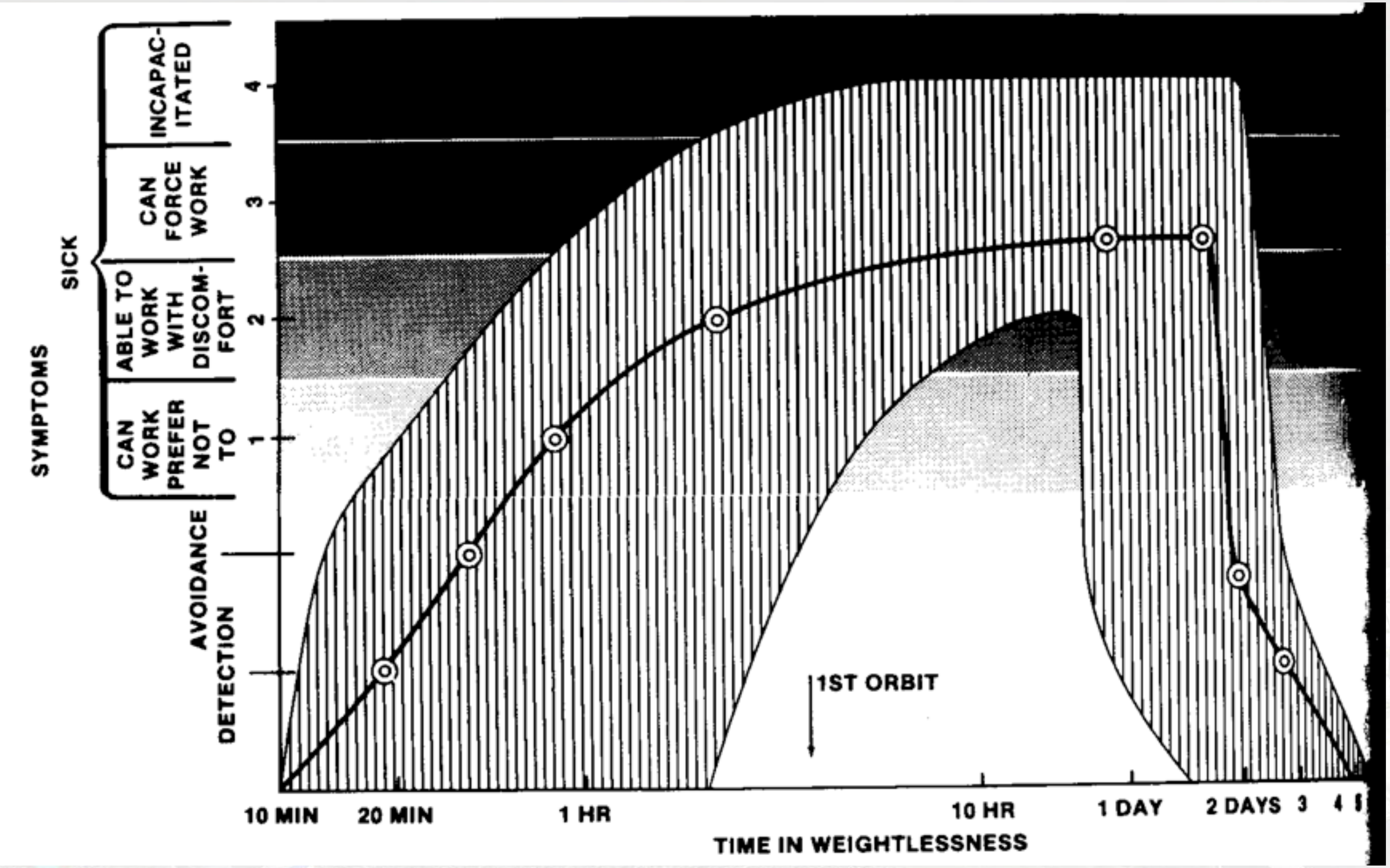
# Thresholds of Translational Perception

- $a_x$: 0.006 g
- $a_y$: 0.006 g
- $a_z$: 0.01 g
- Apparent change in direction of g vector = 1.5°

# Space Motion Sickness

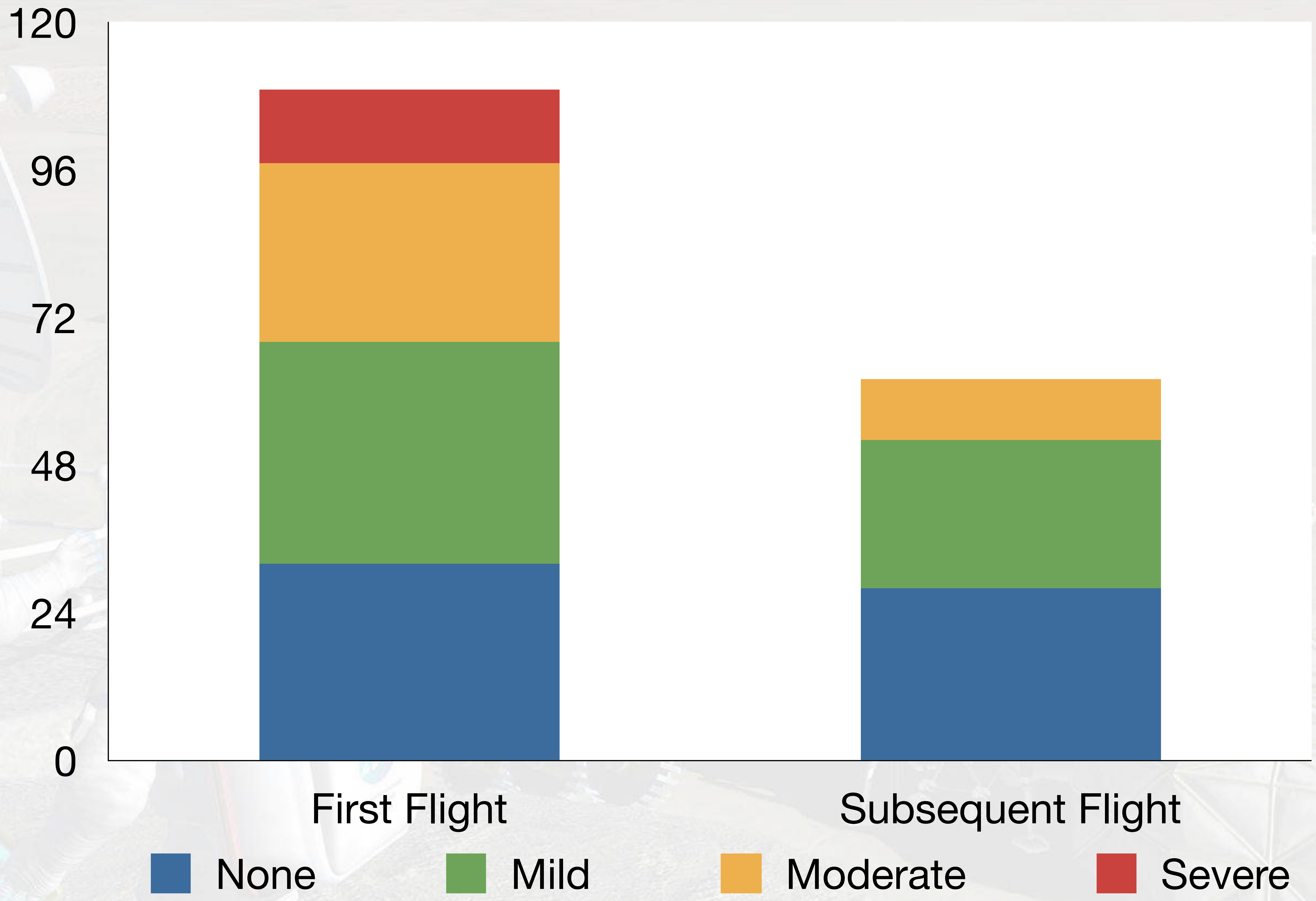
- "Space Adaptation Syndrome"
- 2/3 of astronauts report some effects
- Symptoms
  - Primary: stomach discomfort, nausea, vomiting
  - Secondary: pallor, cold sweats, salivation, depressed appetite, fatigue
- No correlation to susceptibility to motion sickness
- Primary hypothesis: sensory conflict (Treisman's Theory)

# Progression of Space Motion Sickness

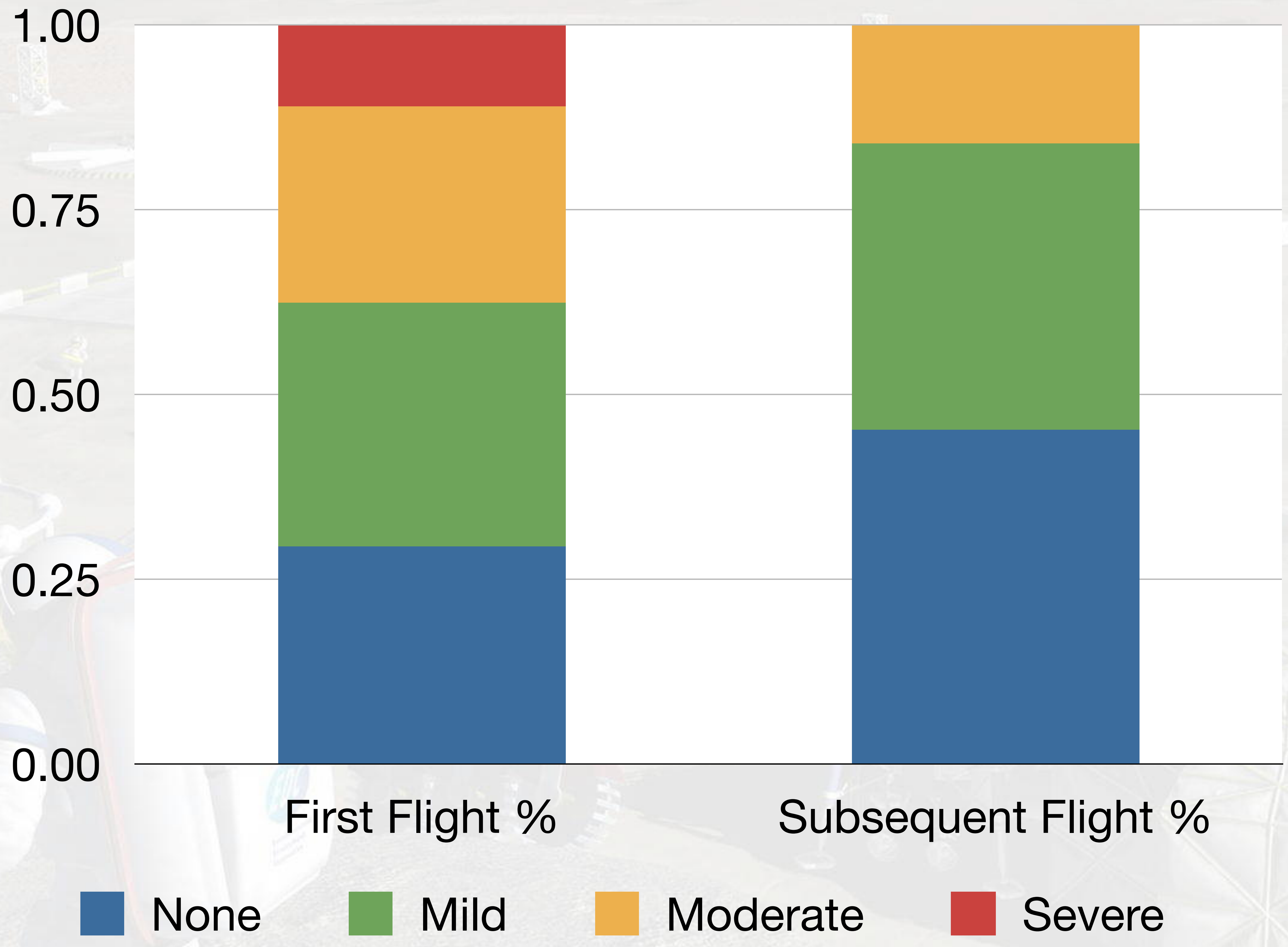



From Roy DeHart, *Fundamentals of Aerospace Medicine*, Williams and Wilkins, 1996

# SAS Experience of First 34 Shuttle Flights



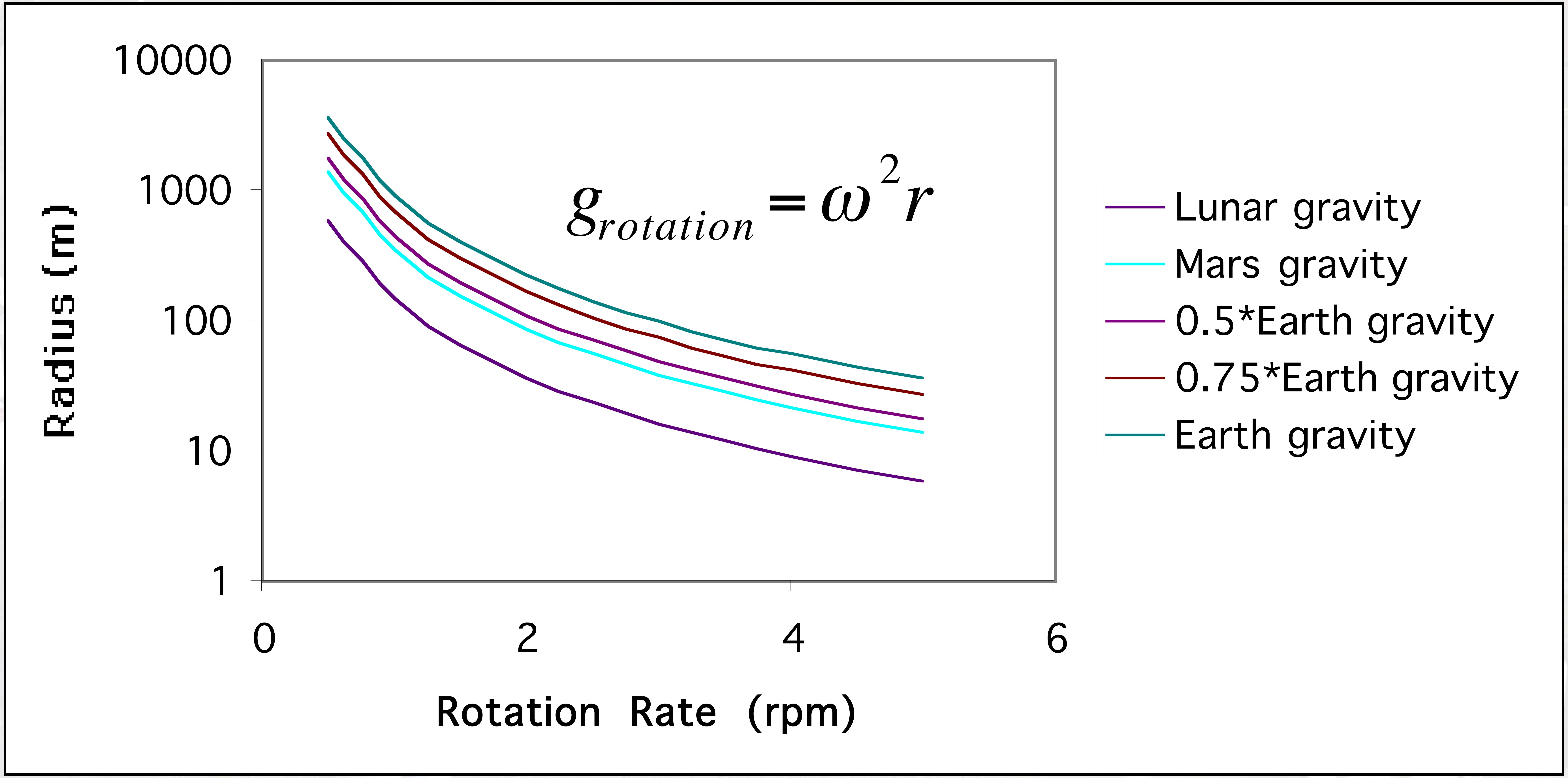
# SAS Experience of First 34 Shuttle Flights



# Space Motion Sickness Countermeasures

- Preflight training
  - Desensitization
  - Autogenic feedback training (AFT)
- Pharmaceuticals
  - Oral - scopolamine/dex-amphetamine (Scopdex)
  - Transdermal - scopolamine
  - Intramuscular - promethazine
- Mechanical systems
  - Pressurized insoles
  - Load suits
  - Neck restraints

# Artificial Gravity



# Allowable Rotation Rates

- Select groups (highly trained, physically fit) can become acclimated to 7 rpm
- 95% of population can tolerate 3 rpm
- Sensitive groups (elderly, young, pregnant women) may have tolerance levels as low as 1 rpm

# References


- R. L. DeHart, ed., Fundamentals of Aerospace Medicine, Second Edition Williams and Wilkins, 1996
- A. E. Nicogossian, C. L. Huntoon, and S. L. Pool, Space Physiology and Medicine, Third Edition Lea and Febiger, 1994
- A. E. Nicogossian, S. R. Mohler, O. G. Gazenko, and A. I. Grigoriev, eds., Space Biology and Medicine (Volume III, Book 1: Humans in Spaceflight) American Institute of Aeronautics and Astronautics, 1996
- J. T. Joiner, ed., NOAA Diving Manual: Diving for Science and Technology, Fourth Edition Best Publishing, 2001