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Gas Exchange

John G. Younger, MD
Associate Professor
Department of Emergency Medicine

Fall 2008

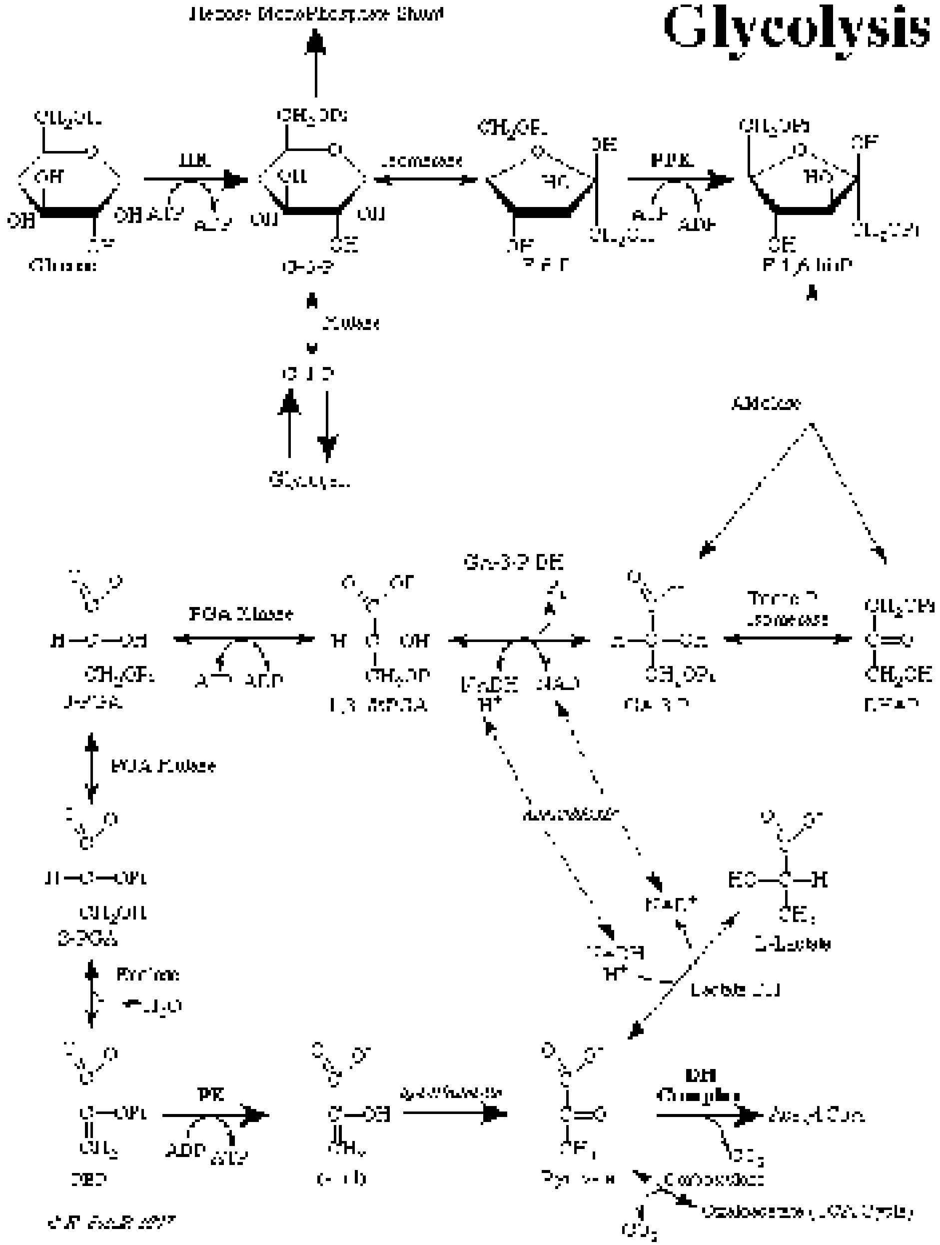
A Tour of the Lecture

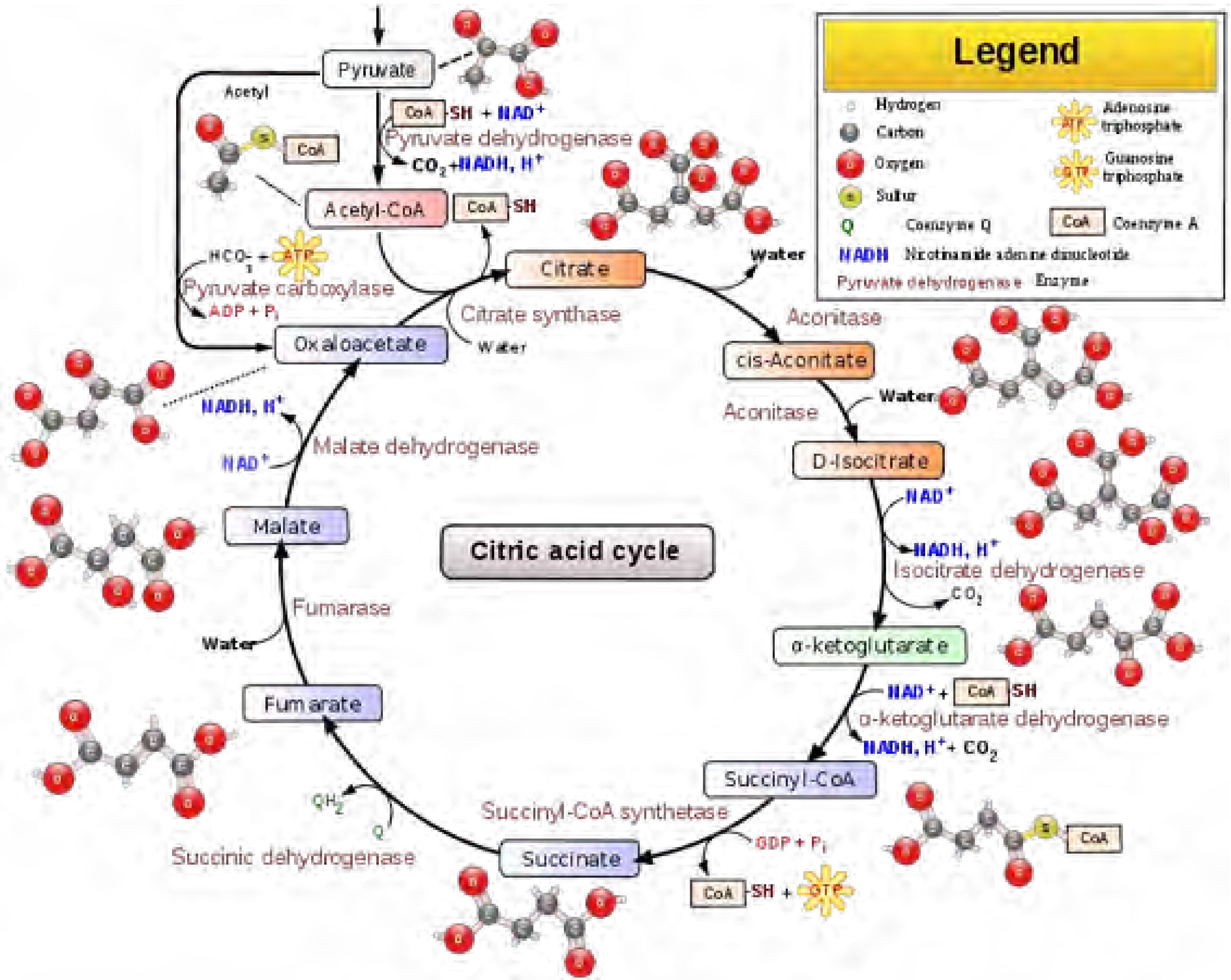
- Some perspective

- Some physics and biochemistry
  - Convection and Diffusion
  - Hemoglobin
  - Pressure, Content, and Transport

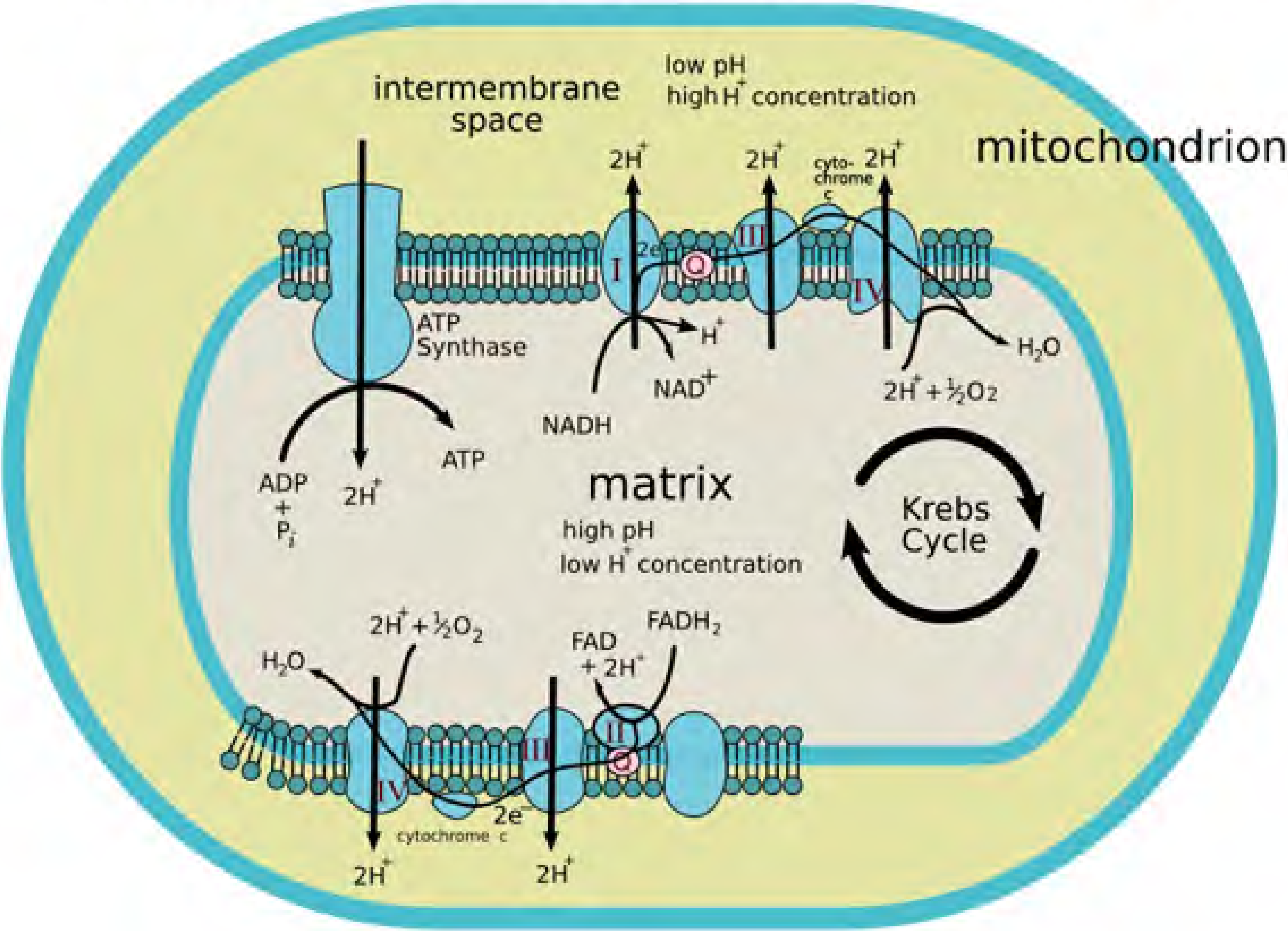
- The lung as a gas exchanger
  - Carbon dioxide handling and dead space
  - Oxygen handling
    - The four causes of hypoxia
  - Quantifying gas exchange

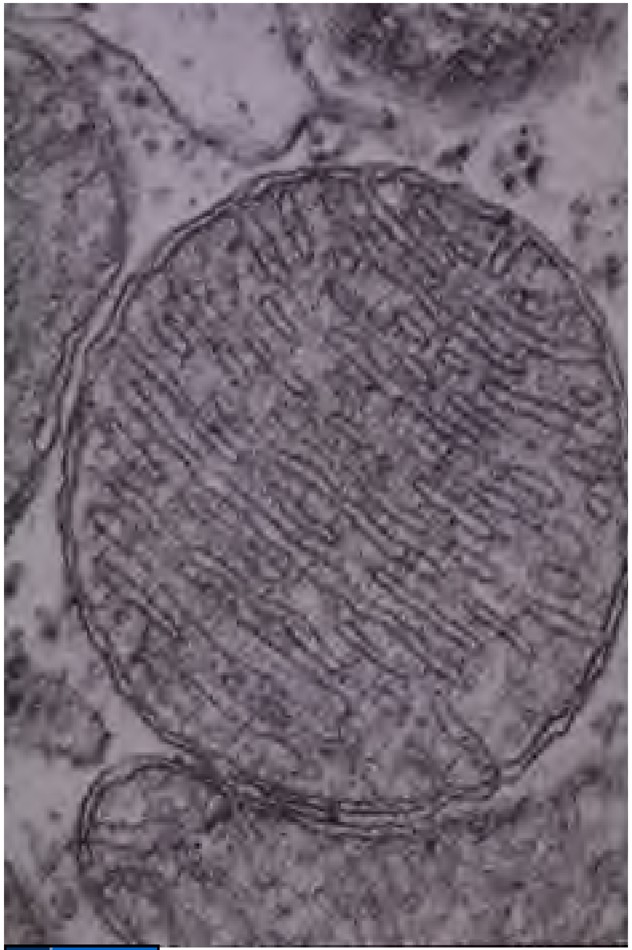
Glycolysis


Hexose MonoPhosphate Shunt
HK
PFK
Isomerase
Aldolase
GA-3-P DH
PGA Kinase
Enolase
PK
PDH Complex
Acetyl CoA
L-Lactate
Glycogen


Legend
Hydrogen
Carbon
Oxygen
Sulfur
Q Coenzyme Q
NADH Nicotinamide adenine dinucleotide
Pyruvate dehydrogenase Enzyme
Adenosine triphosphate
Guanosine triphosphate
CoA Coenzyme A
Citric acid cycle
Pyruvate
Acetyl
CoA-SH + NAD+
Pyruvate dehydrogenase
CO2 + NADH, H+
Acetyl-CoA
CoA-SH
HCO3- + ATP
Pyruvate carboxylase
ADP + Pi
Citrate
Citrate synthase
Water
Aconitase
cis-Aconitate
Water
Aconitase
D-Isocitrate
NAD+
NADH, H+
Isocitrate dehydrogenase
CO2
α-ketoglutarate
NAD+ + CoA-SH
α-ketoglutarate dehydrogenase
NADH, H+ + CO2
Succinyl-CoA
Succinyl-CoA synthetase
GDP + Pi
CoA-SH + GTP
Succinate
Succinic dehydrogenase
Q
QH2
Fumarate
Fumarase
Water
Malate
NAD+
Malate dehydrogenase
NADH, H+
Oxaloacetate

Mitochondrial Electron Transport Chain





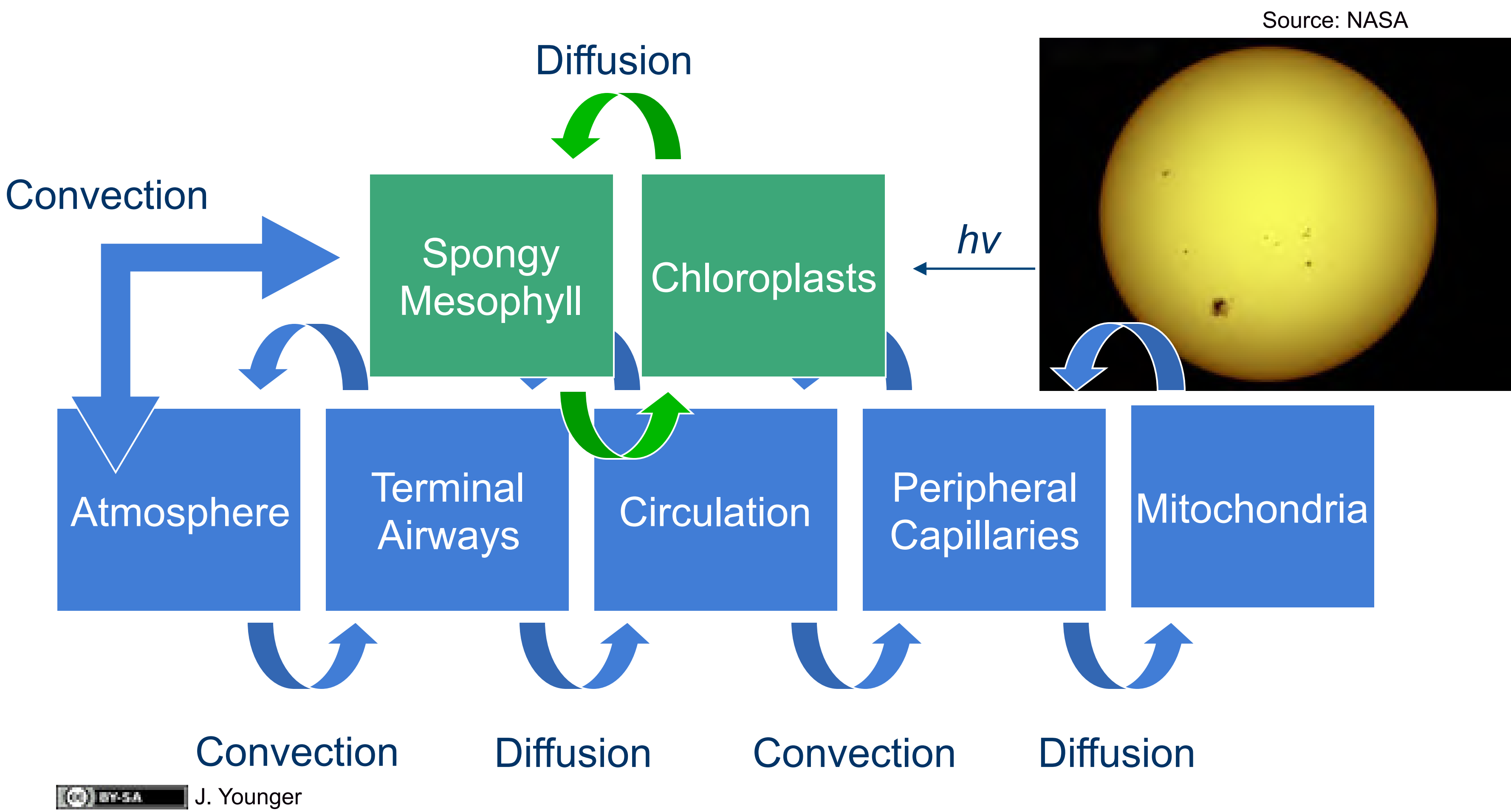
PD-INCL Source Undetermined

Mitochondria are where respiration occurs. The 'respiratory system' is really a bulk transport system for an incoming oxidizer (O_2) and outgoing gas (CO_2) and heat.

Bulk Transport:
Getting Molecules from One Point to Another

- Convection
  - Bulk movement of gas due to pressure gradients
  - Requires mechanical power input
  - Transport from the environment to the terminal bronchioles
  - Transport of erythrocytes between pulmonary capillaries and peripheral capillaries

- Diffusion
  - Transport based on random motion of thermally energetic particles situated in a concentration gradient
  - Requires thermal input
  - Transport from terminal bronchioles to erythrocytes
  - Transport between erythrocytes and peripheral mitochondria


Source: NASA
Diffusion
Convection
Spongy Mesophyll
Chloroplasts
hv
Atmosphere
Terminal Airways
Circulation
Peripheral Capillaries
Mitochondria
Convection
Diffusion
Convection
Diffusion
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J. Younger

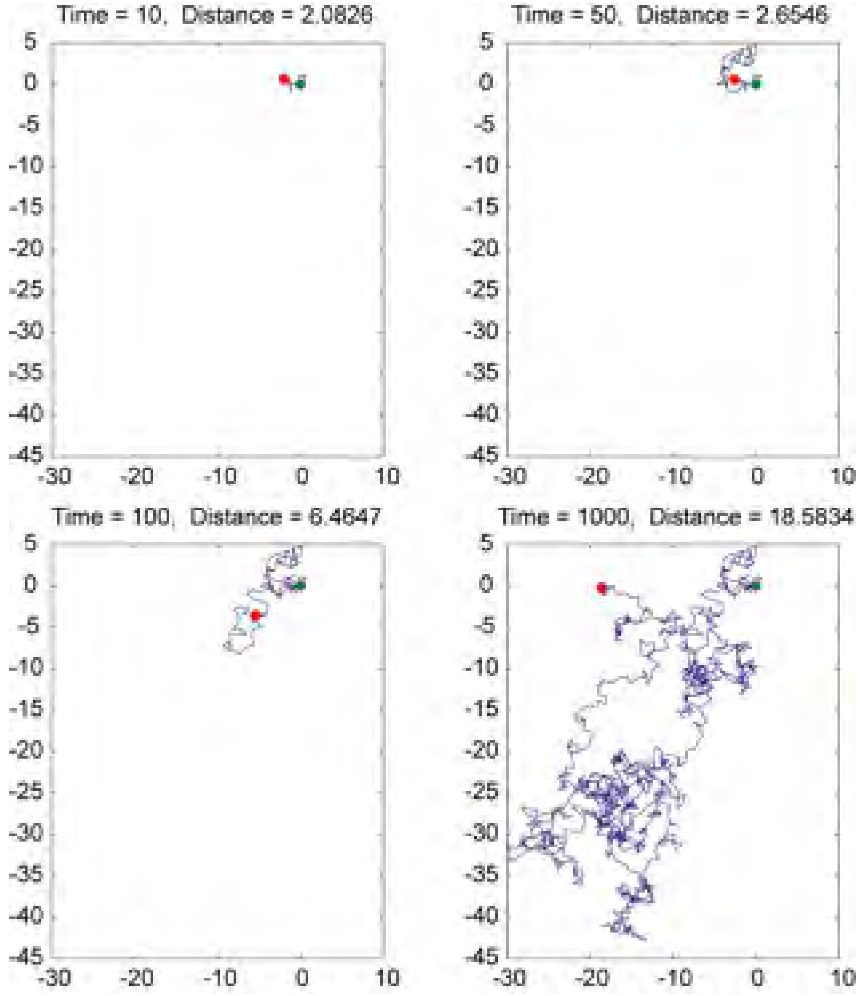
Transport by Convection

- The movement of particles by convection is driven by:
  - The pressure gradient between the atmosphere and terminal bronchioles
  - Thus, this is in the realm of what's typically referred to as pulmonary mechanics
- The mechanical work required to get this job done is a function of:
  - Resistance of the transport path to air flow
    - Itself a function of the effective cross-sectional area of the airways
  - The viscosity and density of the air being moved
  - The compliance of the lung and chest wall

Transport by Diffusion

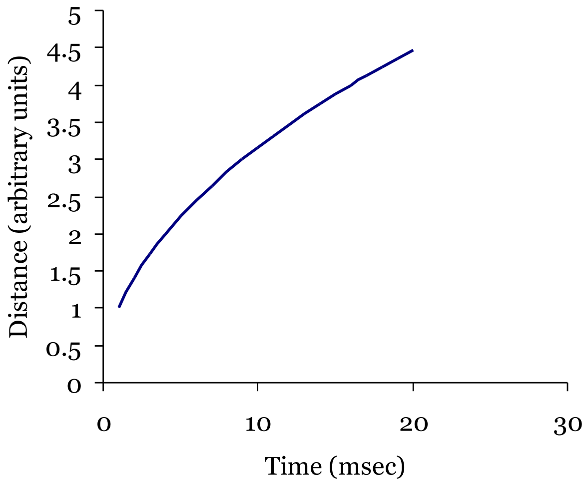
- The movement of particles by diffusion is driven by:
  - Concentration gradient
    - For physiological purposes, usually reported as differences in partial pressure
    - Gradient may exist in either gas phase (e.g., bronchiole->alveolus) or liquid phase (e.g., plasma->RBC membrane)
    - Note: Although concentrations are often reported in partial pressures, at it's heart this is a *Brownian Motion* based phenomenon!
  - Diffusivity
    - A measure of the tendency of a molecule to avoid getting 'hung up' in the surrounding media
    - Specific for solute, solvent, and temperature
    - In part is a function of molecular mass
    - E.g., the diffusivity of oxygen in air is different than in plasma, and the diffusivity of oxygen in plasma is different than the diffusivity of carbon dioxide

Diffusion is A Random Walk in Space



Bulk Transport by Diffusion

- The Brownian movement of particles over a distance is proportional to the square root of time
- At scales more than 50 microns or so, diffusion is a uselessly slow process!
- The keys to diffusing large amounts of gas (e.g., hundreds of milliliters per minute) are:
  - a very large surface area for gas particles to randomly walk across.
  - A very short diffusion path



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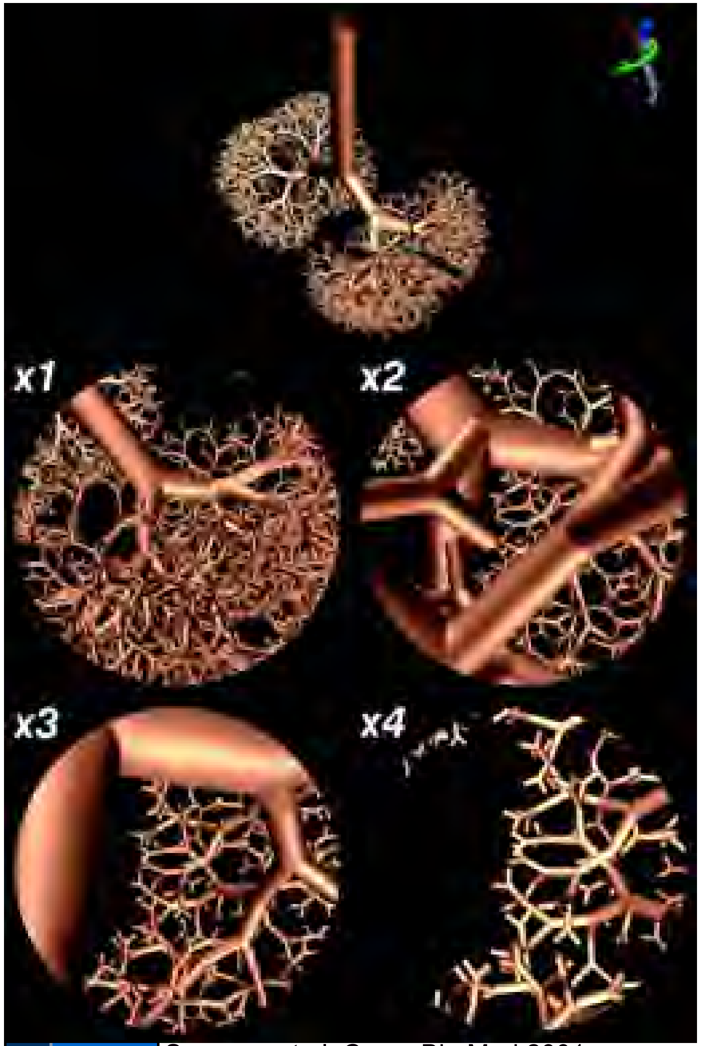
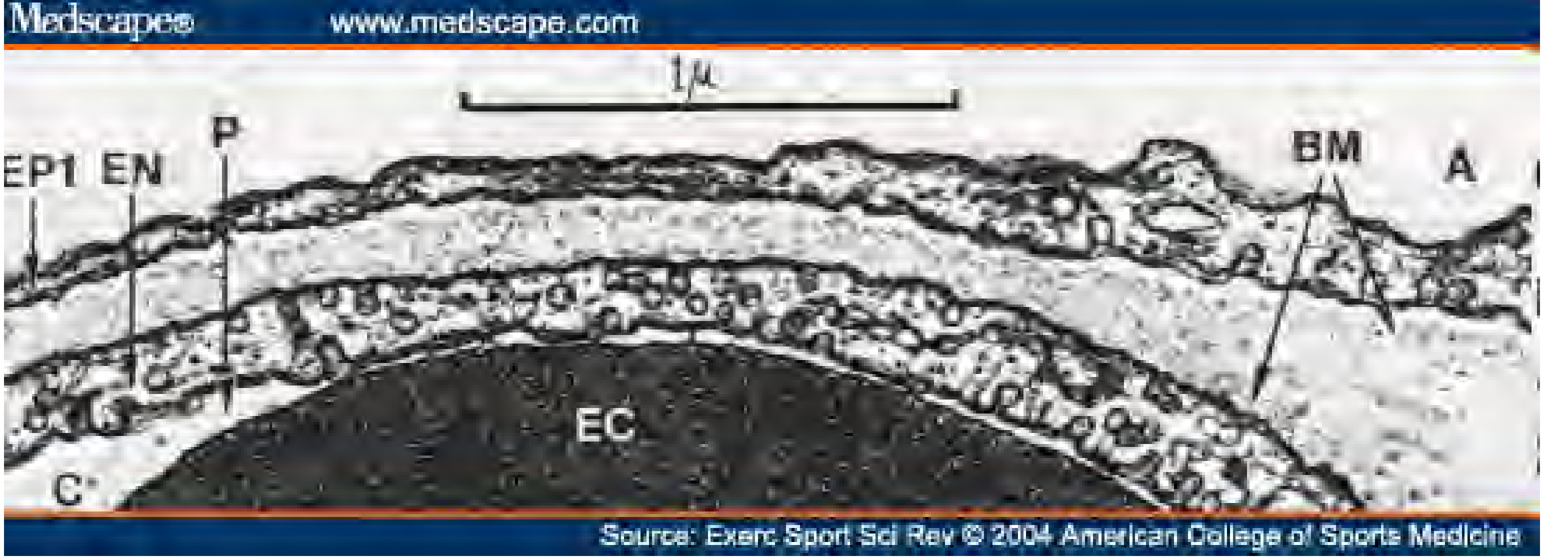


PD-INCL Spencer, et al. Comp Bio Med 2001

- In adult humans, ~23 generations of airway bifurcations
- 2.5 – 7.5 x 10^6 alveoli
- Total surface area of ~ 130 square meters
- Corresponding generations of both pulmonary arteries and pulmonary veins

- Arthur Ashe Stadium
  - Each player brings a respiratory surface area comparable to the area of the court
  - At capacity, the stadium has a respiratory surface area of $2.8x10^6$ m^2 and is diffusing more than 4,400 liters of O_2 per minute



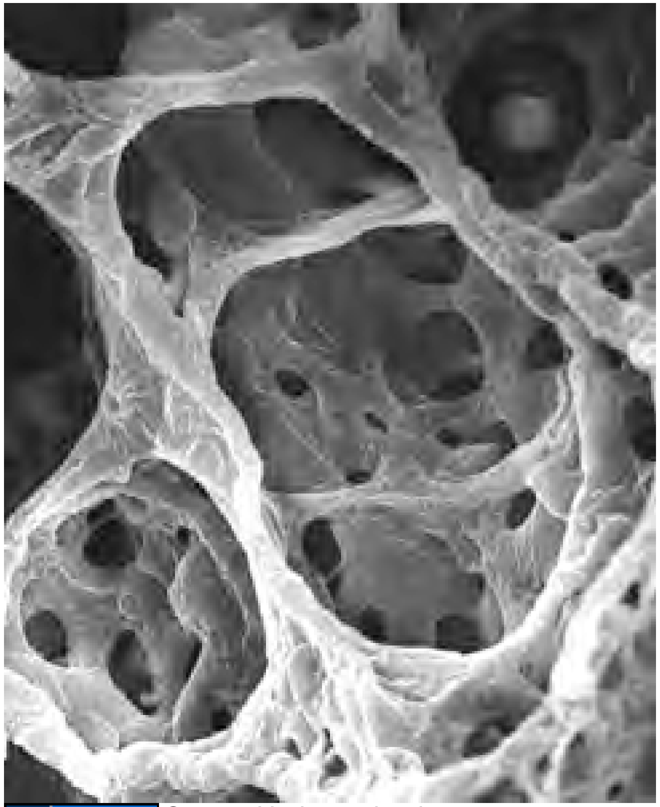
Exercise and Sport Science Review


Paolo Camera (Flickr)

Pulmonary Gas Diffusion in Health and Disease

- Factors Adversely Affected by Illness
  - Diminished concentration gradient between alveoli and pulmonary capillaries
    - Due to convective failure
  - Distance to be Traveled
    - Membrane thickness
    - Perivascular edema or fibrosis
  - Surface Area
    - Loss of alveoli, alveolar flooding

- At some level, many therapies for lung disease strive to reverse these physical issues and enhance diffusive transport



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Pressure, Content, and Transport

Pressure

Simple enough: Pressure is the force over an area applied perpendicular to that area's surface. Both gas diffusion and gas convection can exert pressure.

- Two useful laws for today's discussion – One applies to gas phase only, both apply to gases dissolved in liquid
  - Dalton's Law: The total pressure of a gas mixture is the sum of the partial pressures of its constituents:

$$P_{total} = \sum_i P_i$$

  - Henry's Law: The partial pressure of a gas in equilibrium with a volume of liquid is proportional to the amount of gas dissolved in the liquid:

$$P = kc$$

where *k* is a constant for a particular gas-solvent-temperature combination and *c* is the concentration of the gas.

Beware: This is also often written as $c = kP$, where the relationship is the same, but the value of *k* is the reciprocal of the one noted above.

Consequences and Caveats about Dalton's and Henry's Laws

- If total pressure is held constant (such as being held at atmospheric pressure), the partial pressure of one gas in a gas mixture or solution can only change if the partial pressures of one or more other gases change
- Both Dalton's and Henry's Laws assume that the gases under discussion (either as gases or dissolved in liquid) are inert – they don't interact with one another or chemically with the media which they're in.
  - Both of these are not true in the case of oxygen and carbon dioxide

Source Undetermined

John Dalton
1766-1844

Source Undetermined

William Henry
1775-1836

Content: Dissolved and Hemoglobin-Bound Oxygen

Implications and Limitations of Henry's Law

- Henry's Law relates partial pressure of oxygen to concentration of dissolved oxygen in plasma as follows:

$$[O_2] = 0.003 \times PO2$$

where $[O_2]$ is in ml/dl, PO_2 is in mmHg and *k* is in ml/dl/mmHg, and physiological temperature (37^{o}C) is assumed

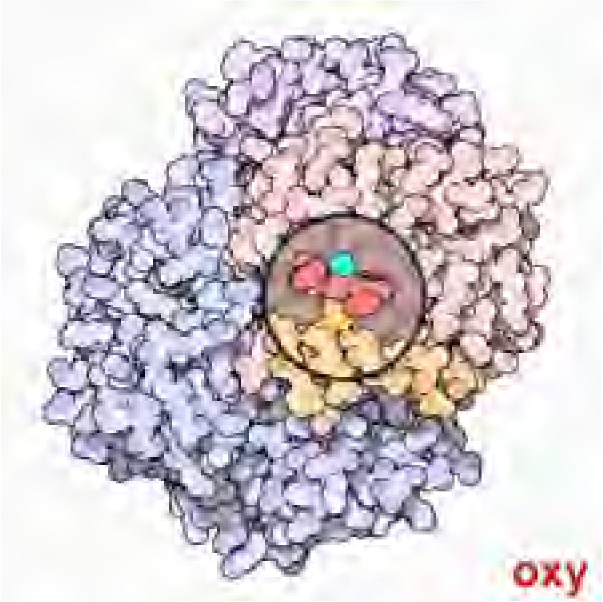
- For typical PO_2 values (~100 mmHg or so), this is a *very* modest amount of dissolved oxygen and would require a tremendously high cardiac output to deliver enough oxygen per minute to the periphery.

The Only Way to Make Gas Transport Work in Large Creatures is with a Dedicated Oxygen Carrier

- Some useful facts about hemoglobin*
  - Concentration in blood is very high (~15 g/dl), constituting about a third of the mass of an erythrocyte, and about 15% of the mass of blood
  - Each gram of hemoglobin can bind about 1.34 ml/g of O_2**
  - Always a tetramer, there are a variety of subunits that come to the fore at different points during development (including α, β, γ, δ, ε, and ζ). In large part, these provide different 'tunings' of the oxygen-hemoglobin dissociation curve
  - A number of physical features of the local environment also serve to tweak the loading and unloading of oxygen from hemoglobin
  - Hemoglobin is also an important carrier of carbon dioxide
    - carbaminohemoglobin

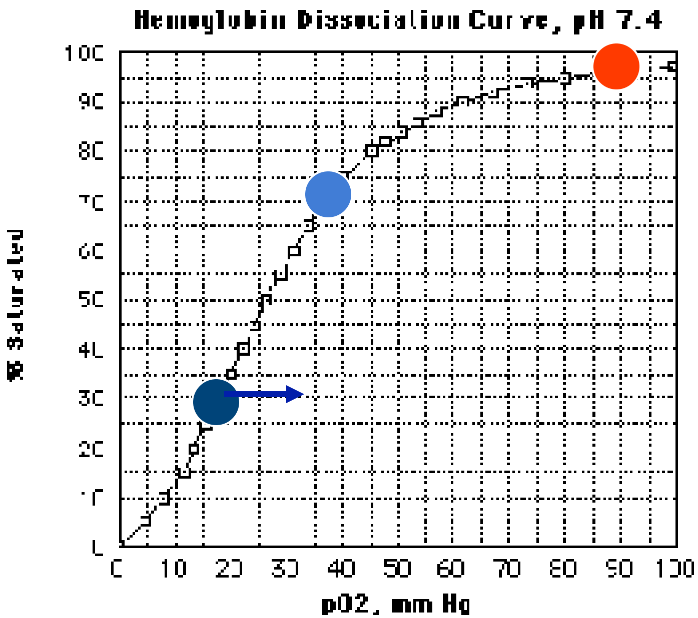
* By useful, I mean of course testable.
** Note: This number is convention – it's certainly an overestimate of the actual figure

Important Facts of O_2 Binding by Hemoglobin



- Binding is allosterically cooperative
  - O_2 binding to any heme group changes the structure of the entire molecule
  - Each O_2 bound promotes binding of the next O_2
  - The result is a very steep Hgb-O_2 dissociation curve in the physiologically useful range

Relationship Between Oxygen Tension and Hemoglobin Saturation



- Arterial blood
- Venous blood, at rest
- Venous blood, heavy exercise

PD-INEL Source Undetermined

- Under resting conditions, hemoglobin leaves about 25% of its oxygen in the periphery
- With exercise, greater and greater amounts of oxygen are extracted, with progressively deoxygenated hemoglobin returning to the lungs
- Acidosis and increased temperature* tend to move the curve to the right, facilitating better O_2 unloading

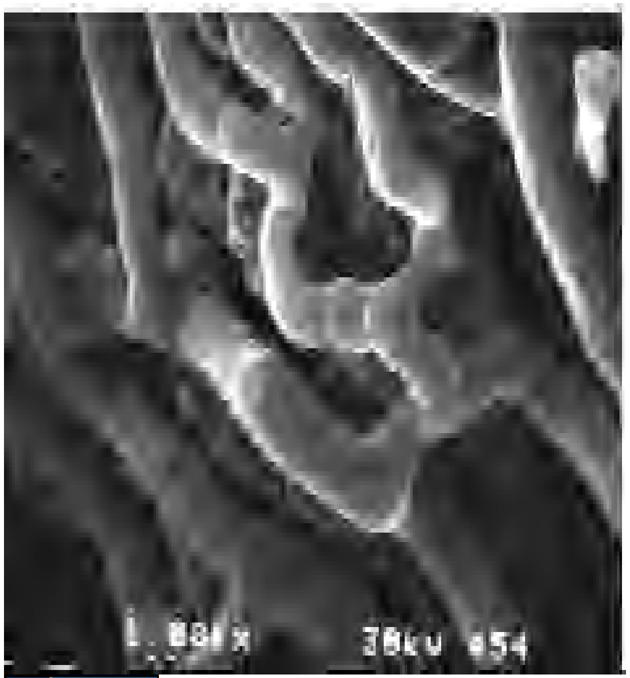
* At heavy exercise, peripheral venous pH and temperature may reach 7.25 and 40°C

Conditions Affecting Oxygen-Hemoglobin Dissociation Kinetics

- A shift to the right
  - For a given PO_2, hemoglobin will be less saturated
  - For a given drop from arterial PO_2, more oxygen will have been unloaded
  - Useful for unloading hemoglobin
- A shift to the left
  - For a given PO_2, hemoglobin will be more saturated
  - For a given drop from arterial PO_2, less oxygen will have been unloaded
  - Useful for loading hemoglobin
- Factors shifting to the right
  - High Temperature
  - High PCO_2
  - Low pH
  - 2,3 diphosphoglycerate
  - Adult (versus fetal) hemoglobin
- Factors shifting to the left
  - The inverse of those above, plus
  - Carbon monoxide
  - Methemoglobinemia

An Important Application of a Curve Shifted to the Left

- Maternal-fetal oxygen transfer
  - The affinity for oxygen of hemoglobin on the fetal side of the circulation must, at a given PO_2, be higher than the hemoglobin oxygen affinity on the maternal side



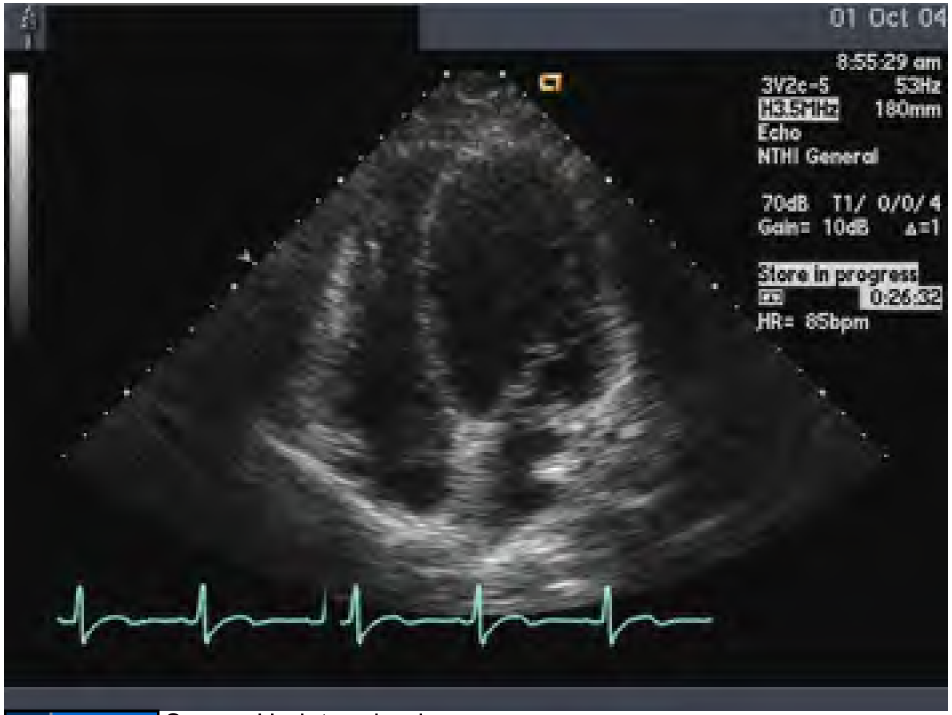
PD-INCL Source Undetermined

- Christian Bohr:
  - Acidosis decreases affinity of hemoglobin for O_2

Christian Bohr (1855-1911)

- J. S. Haldane:
  - Low PO_2 increases the affinity of hemoglobin for CO_2

John S. Haldane (1860-1936)



PD-INEL Source Undetermined

Content and Transport: The link between the cardiovascular and respiratory systems

Oxygen Content and Transport

- Oxygen content is the total amount of oxygen within a volume of blood
  - Determined by concentration of hemoglobin, its extent of saturation, and the partial pressure of oxygen
  - Typically abbreviated as C_xO_2 (Arterial: C_AO_2 Venous: C_VO_2)
  - Expressed in volume/volume (usually, clunkily, in ml/dl)

Hemoglobin-Bound Oxygen

Dissolved Oxygen

$$C = ([Hb] \times \text{Saturation} \times 1.34) + (0.003 \times PO_2)$$

g/dl

%/100

ml/g

ml/dl/mmHg

Oxygen Content and Transport

- Oxygen transport is the *rate* at which oxygen is being moved by the circulatory system from the lungs to the periphery
  - Determined by oxygen content and cardiac output
  - Typically referred to as oxygen delivery, DO_2
  - Expressed in volume/minute or volume/minute/surface area

$$DO_2 = \text{Cardiac Output} \times C_AO_2$$

l/min or l/min/m^2 (Cardiac Output)

ml/dl (C_AO_2)

Oxygen Consumption

- Oxygen consumption is the rate at which oxygen is utilized by the periphery
  - Defined as the difference between the oxygen content in arterial blood and in mixed venous blood in the pulmonary artery.
  - Expressed in volume/minute or volume/minute/surface area

$$VO_2 = \textit{Cardiac Output} \times (C_AO_2 - C_VO_2)$$

l/min
or
l/min/m²

ml/dl

Pressure, Content, and Transport

- Ultimately, respiratory failure is an issue of reduced oxygen transport.
- Clinical assessment of transport adequacy typically concentrates on pressure and content. Measuring blood flow requires more invasive methods than measuring hemoglobin saturation or the partial pressure of oxygen
- Physiological compensation and medical therapy are directed against each element of the content and transport equations
  - Increased PO_2
  - Increased hemoglobin concentration
  - Increased cardiac output

‘Nonrespiratory’ Situations May Have Large Impact on Oxygen and CO_2 Transport

- Anemia
  - Decreased oxygen content regardless of the extent of saturation
- Congestive heart failure
  - Decreased blood flow regardless of content
- Living at altitude or in artificial atmospheres
  - Low ambient oxygen tension

The Lung as a Gas Exchanger

The Human Lung as Gas Exchanger: System Requirements

- Oxygen uptake
  - Measured as volume of oxygen consumed per minute (VO_2)
  - At rest, VO_2 ~ 200 ml/min
  - At exercise, VO_2 ~ 3 l/min for 8 minute mile

- Carbon dioxide clearance
  - Commensurate with amount of oxygen consumed

- Extensive reserve
  - In health, for exercise
  - In illness, for 'wiggle room'

The Human Lung as Gas Exchanger: System Requirements

- The basic idea
  - Bring deoxygenated blood and well-ventilated alveoli as close to one another as you can. This is called ventilation:perfusion matching
  - Ventilation is controlled 'globally' by CNS respiratory regulation in conjunction with the chest wall and diaphragm
  - Perfusion is controlled globally by regulation of cardiac output, and locally by hypoxic pulmonary vasoconstriction
- How efficiency is lost
  - Malfunctioning alveoli are not appropriately ventilated
  - Local blood flow regulation fails to re-route blood around hypoxic alveoli
  - Diffusion distance is increased
  - Diffusion surface area is reduced

Highest VO_2 Measured in Human:

VO_2: 6.61 l/min

Respiratory Rate: 62

Tidal Volume: 3.29 l

PD-SELF John Slade (Wikipedia)

CO_2 Handling in the Lung

Carbon Dioxide Handling in the Lung

- CO_2 is ~ 20x more soluble than O_2 in plasma
- CO_2 transfer is therefore much less susceptible than oxygen transfer to changes in disease-related loss of diffusion ability
- For the sake of discussion, if CO_2 rich venous blood gets to an alveolus, the PCO_2 in blood and gas will quickly equilibrate

Changes in arterial PCO_2 are, practically speaking, a result of changes in CO_2 production by tissues or changes in alveolar ventilation

Functional Compartments in the Lung: Anatomic Dead Space

- Only a portion of the respiratory system participates in gas exchange (i.e., diffusion)
  - Respiratory Bronchioles -> Alveoli
- A portion of the system is only needed to move tidal breaths (i.e., convection)
  - Pharynx -> Bronchioles are ‘conducting airways’
  - ‘Anatomic dead space’

Functional Compartments in the Lung: Physiologic Dead Space

- Anatomic dead space, plus…
- Ventilated areas receiving no blood flow

Ventilation

- Ventilation is the movement of fresh gas from the environment down to the alveoli and, conversely, the movement of hypoxic, hypercarbic gas from the alveoli back to the environment

- Typically categorized into 3 component rates, each described as volume per time, derived from 3 anatomic compartments in the lung:
  - Minute ventilation: Tidal volume x Breaths per minute
  - Dead space ventilation: Dead space x Breaths per minute
  - Alveolar ventilation: (Tidal volume – Dead space) x Breaths per minute

Why Dead Space is Important

- To move air requires power
  - (i.e., work over time)
- To meet oxygen delivery and CO_2 removal demands, a certain amount of fresh gas *must* be moved per minute
- As dead space increases, more air has to be moved to maintain the same alveolar ventilation
- Therefore, increased dead space means decreased efficiency and increased work of breathing

Conditions Associated with Increased Dead space

- Chronic obstructive disease
  - Obliteration of capillaries

- Pulmonary embolism
  - Occlusion of vessels to ventilated alveoli

- Endotracheal incubation
  - Length of tube beyond the lips represents additional ‘anatomic’ dead space

Conditions Associated with Changes in Minute Ventilation

- Hyperventilation
  - Compensation for hypoxia
  - Compensation for metabolic acidosis
  - Anxiety
  - Intoxication (e.g., salicylates, pretty uncommon)

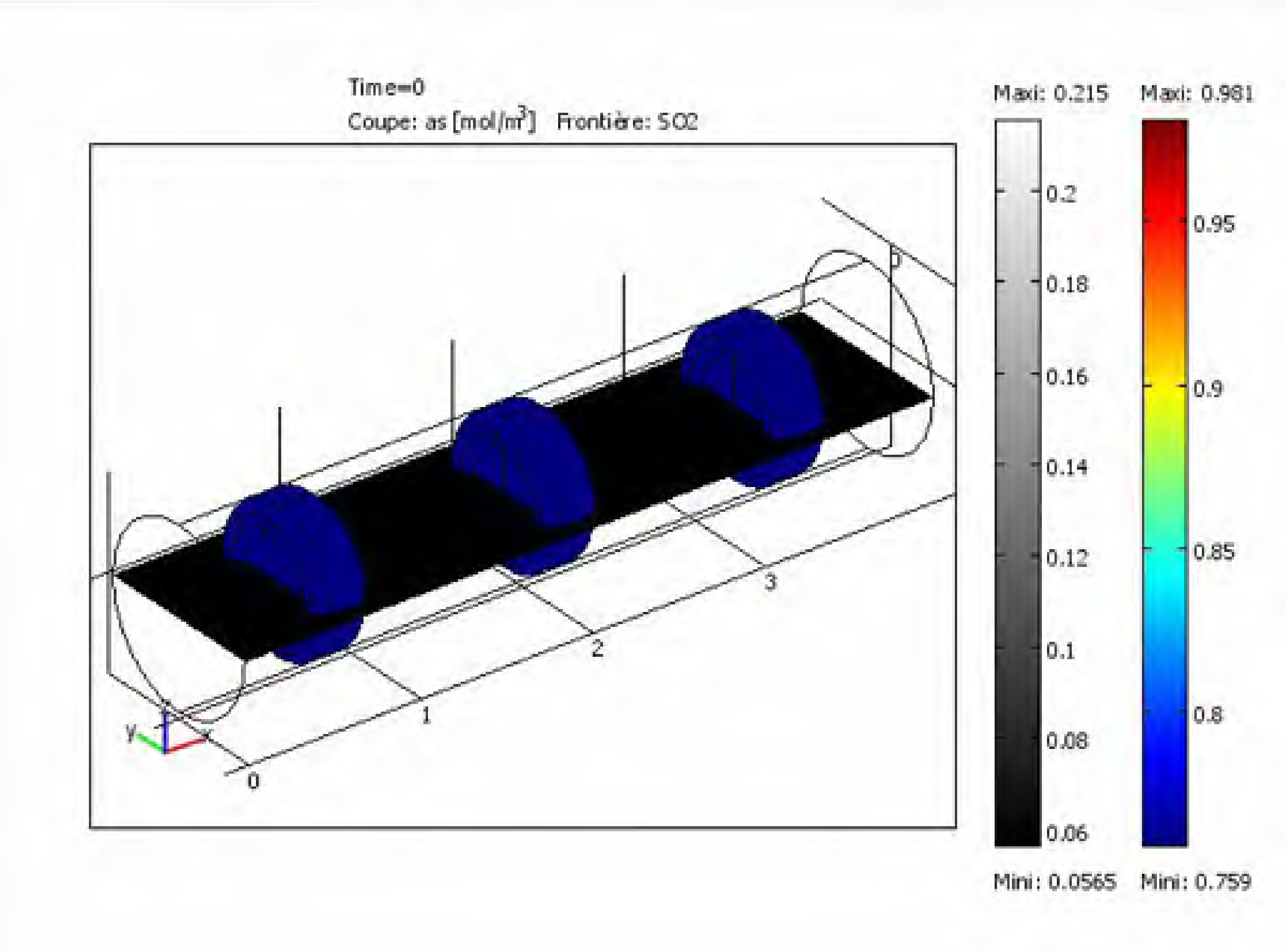
- Hypoventilation
  - Obstructive Sleep Apnea
  - CNS and Peripheral Neuromuscular Disease
  - Intoxication
  - Airway Obstruction
  - COPD

Oxygen Handling

The Problem with Oxygen

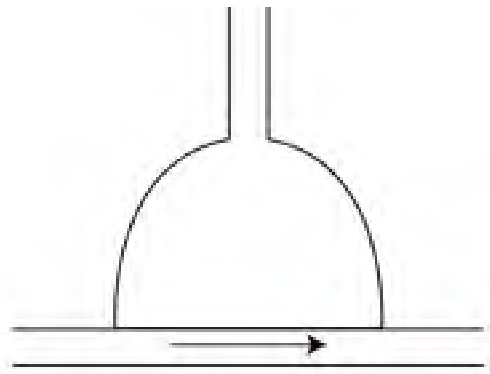
- Transfer into the plasma from the alveoli by diffusion is less rapid
  - Oxygen is less soluble
  - Diffusion is more strongly impacted by distances and surface area
- A lot of oxygen must be transferred, so the time required to ‘load up’ becomes important

Significant Time is Needed to Fully Oxygenate Blood Entering the Lung

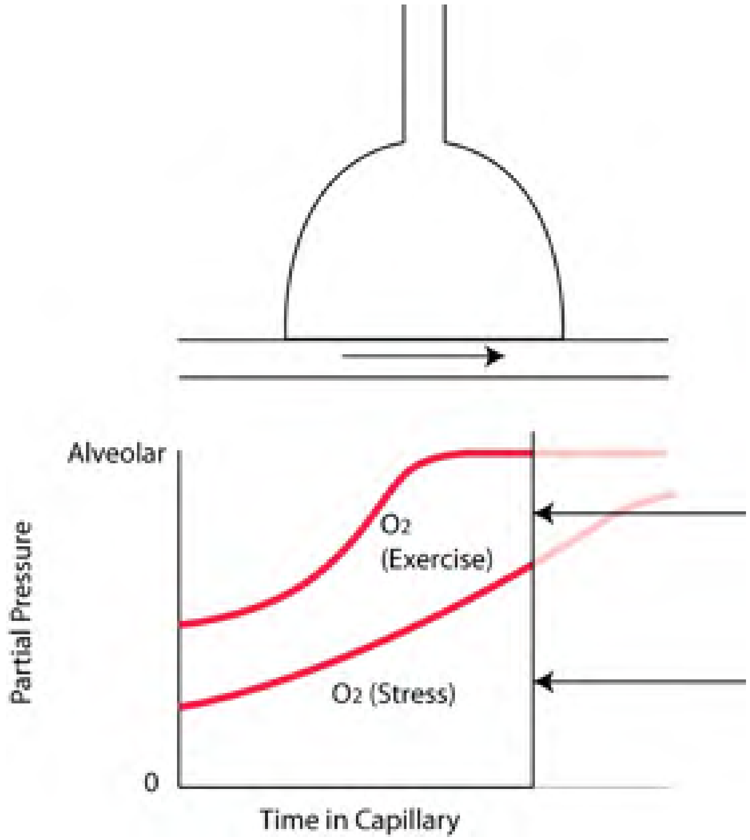


Source Undetermined

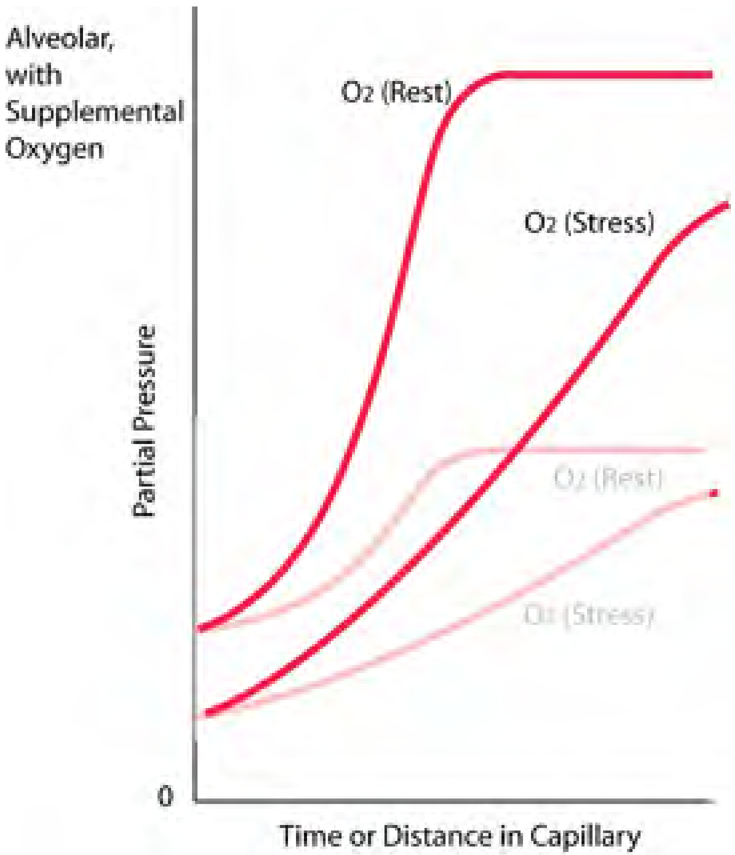
Diffusion of Gas from an Alveolus into Capillary Blood



Diffusion into capillaries: Impact of Short Transit Time



Impact of Supplemental Oxygen



Source Undetermined

- Supplemental oxygen increases the oxygen gradient from alveoli to capillaries
- Flux into capillary blood increases
  - Plasma and hemoglobin load more quickly
  - Blood can become fully oxygenated despite diffusion limitation

The Four Riders of the Apocalypse: The Causes of Hypoxia

- Hypoventilation
- Diffusion Block
- Shunt
- V/Q Mismatch

A Quick Diversion: Normal Partial Pressures of Various Gases in the Lung and Blood

- Alveolar Values
  - PH_2O ~47 mmHg
  - PO_2 ~150 mmHg
  - PCO_2 ~35-45 mmHg

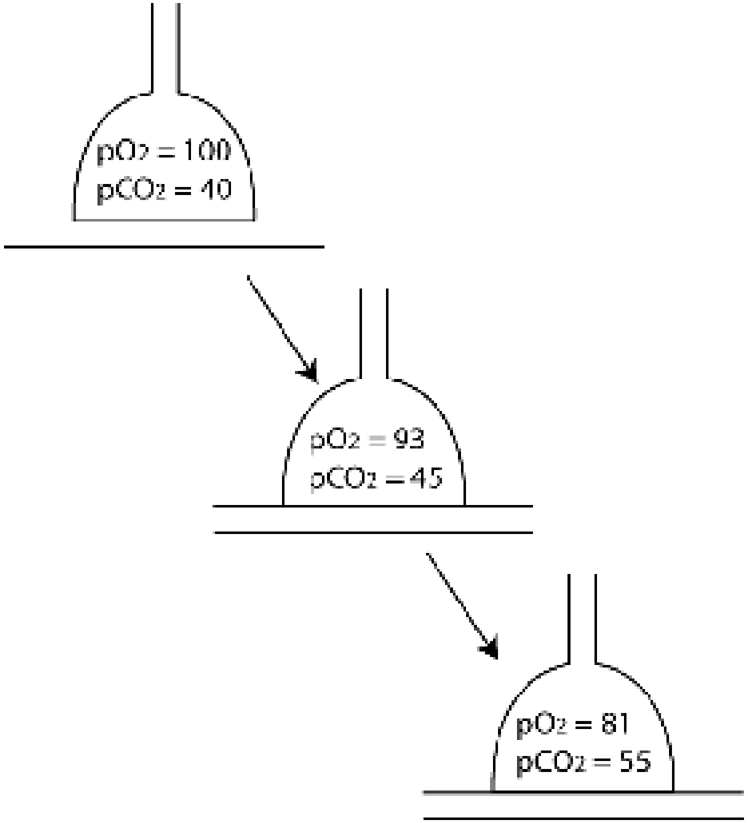
- Arterial Values (at Rest)
  - PO_2 ~90-100 mmHg
  - PCO_2 ~35-45

- Mixed Venous Values (At Rest)
  - PO_2 ~40 mmHg
  - PCO_2 ~45 mmHg

I. Hypoventilation

- Failure to bring fresh gas into the lung will decrease the arterial pO_2.

- Hypoventilation causes hypoxia by displacing alveolar O_2 with CO_2 -- the alveolar-capillary partial pressure gradient goes down, so diffusion is reduced

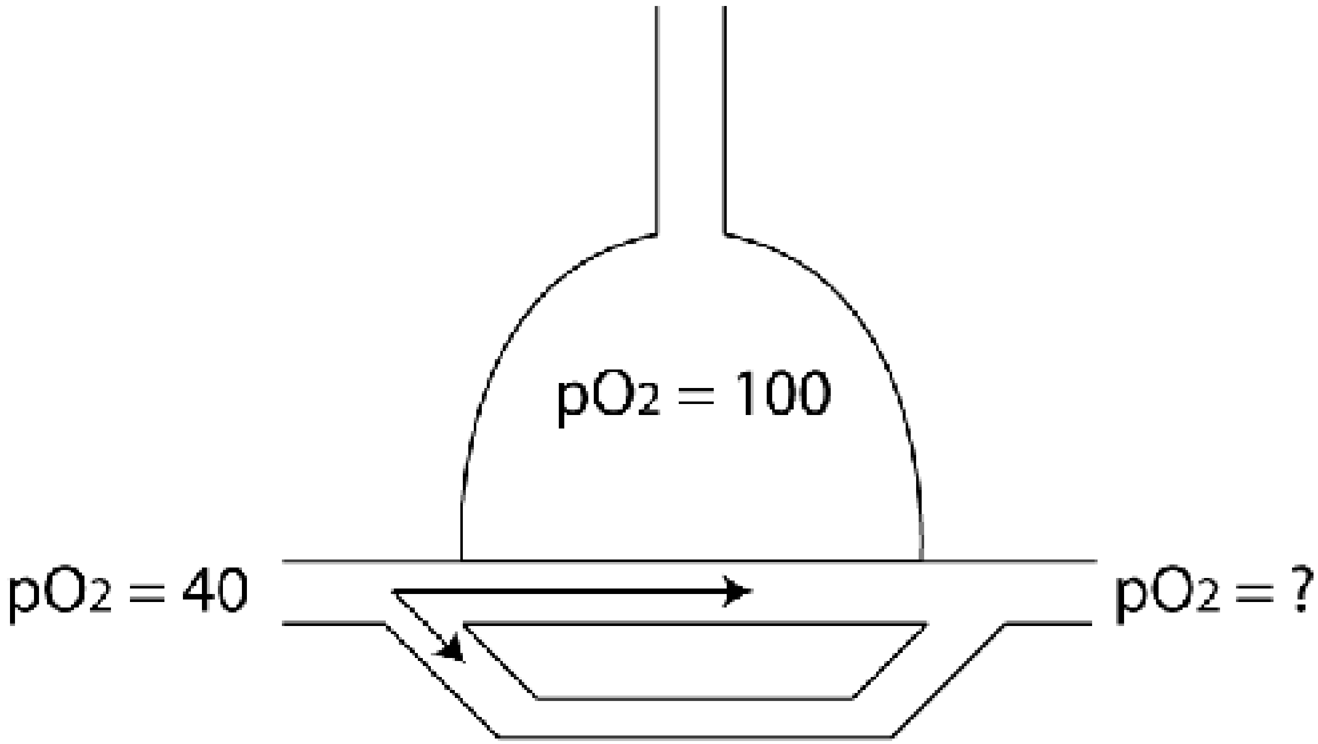


PD-INEL Source Undetermined

II. Diffusion Block

- Direct impairment of gas transfer across the alveolar membrane
- Seen in any disease that lengthens the gas diffusion path
  - Fibrotic disease
  - Lung edema
- Or that significantly reduces surface area
  - COPD

III. Venous Admixture (Shunt)



Venous Admixture and Arterial Oxygen Tension

- Key fact #1: The higher the proportion of flow through the shunt to the total flow in the lung, the lower the PaO_{2}.

Venous Admixture and Arterial Oxygen Tension

- Key Fact #2: Hypoxia caused by shunt cannot be overcome with supplemental oxygen. A portion of blood passing through the lung *never* encounters a ventilated alveolus.

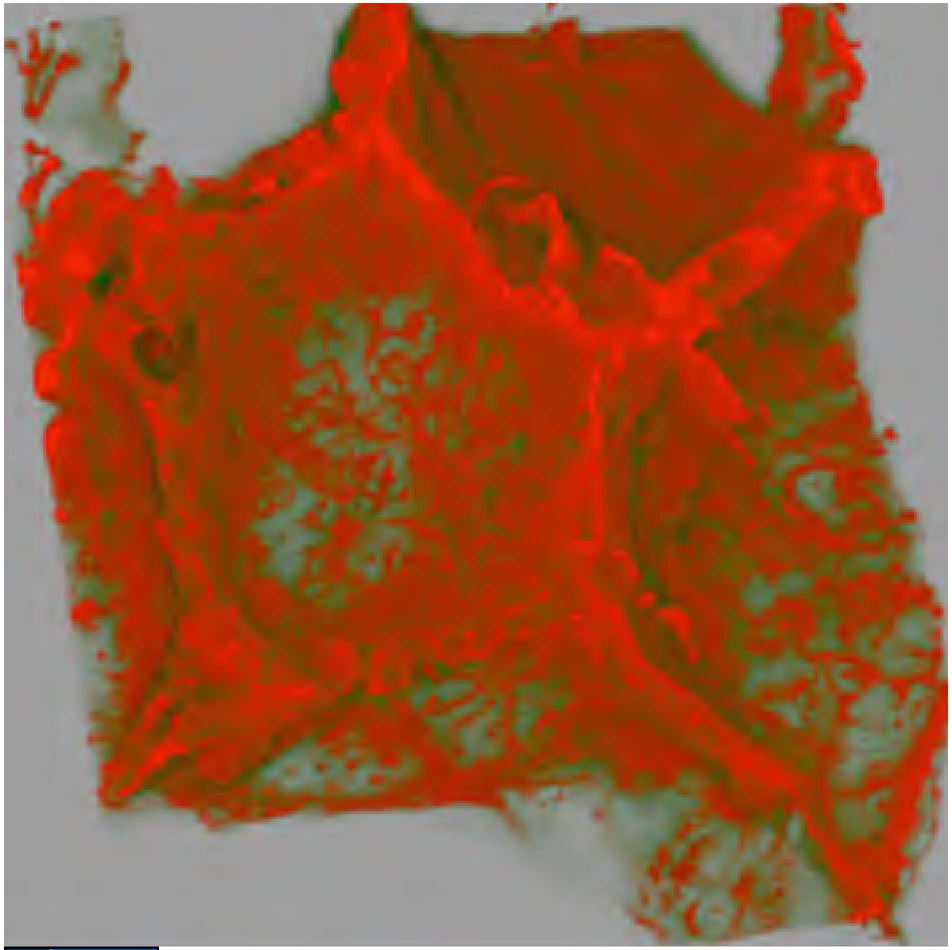
More on Venous Admixture

- Physiologic
  - Bronchial veins -> drain to pulmonary vein
  - Thebesian veins -> drain to left ventricle
- Pathologic
  - Intracardiac, R->L shunts
  - Intrapulmonary AV malformations
  - Totally unventilated alveoli
    - e.g., Collapsed lobe due to obstructing endobronchial cancer

IV. Ventilation-Perfusion Inequality

- Pure dead space and pure shunt are not commonly seen clinical
- Some 'blend' of these phenomena is the most common cause of hypoxia
- A mix of dead space and shunt physiology
- Requires thinking in a 'multi-alveolar' way

Multiple Alveolus Model



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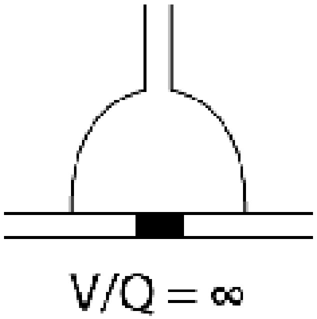
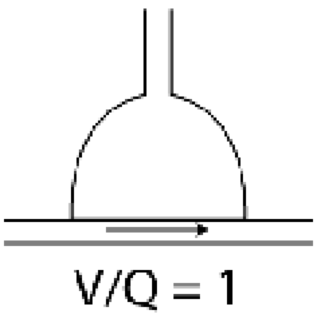
Character of Pulmonary Venous Blood



The Dead Space Alveolus. In theory, no blood leaves this unit. As V/Q approaches ∞, in pulmonary venous blood:

$PaO_2 \rightarrow (P_{atm} - P_{H2O}) \times FiO_2$

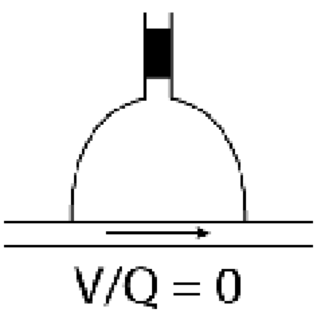
$PaCO_2 \rightarrow 0$ mmHg



The Ideal Alveolus. V/Q ~ 1. In pulmonary venous blood:

$PaO_2 \rightarrow [(Patm - P_{H2O}) \times FiO_2] - (PCO_2/RQ)$

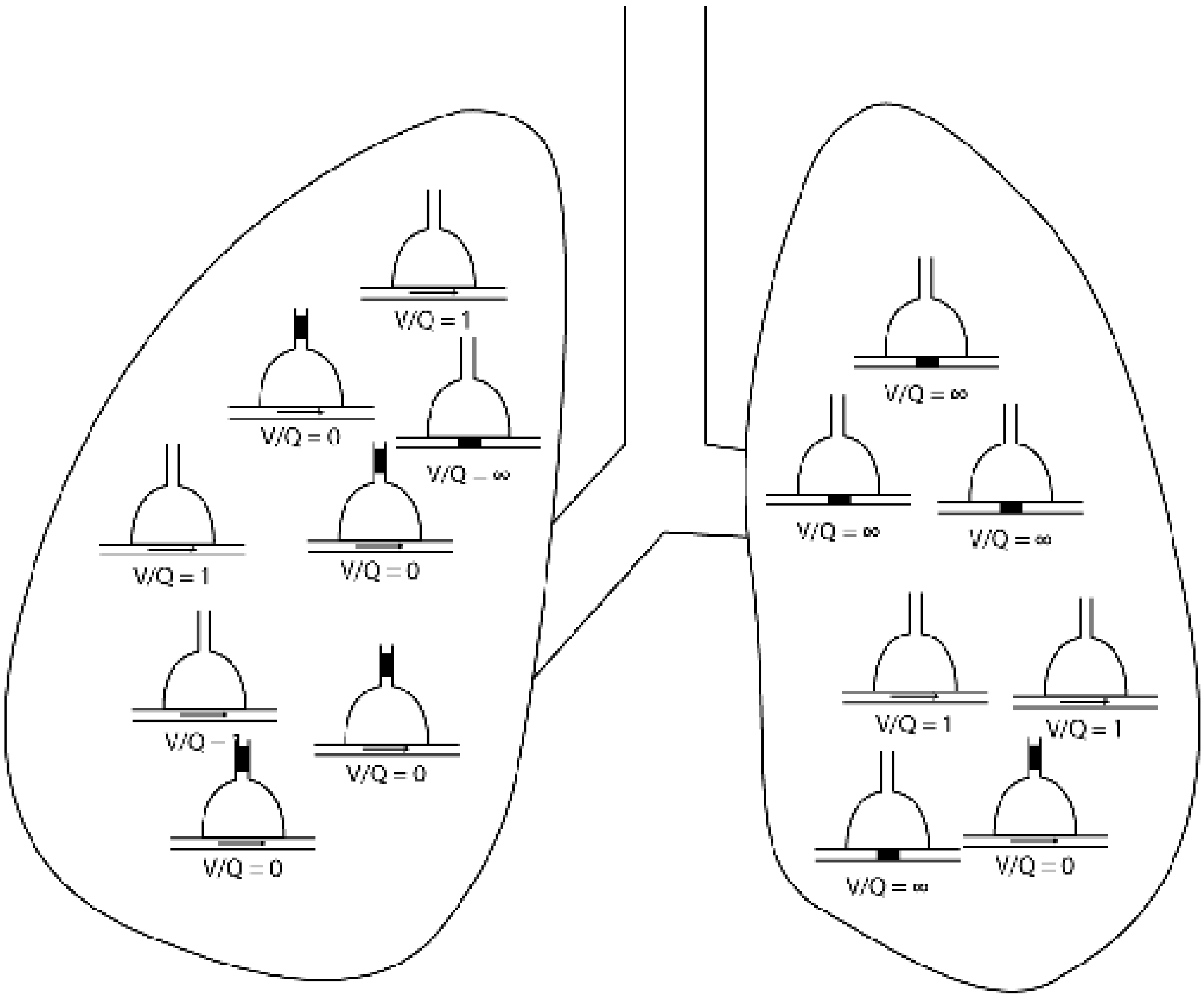
$PaCO_2 = 40$ mmHg



The Shunt Alveolus. No fresh gas is delivered to blood. As V/Q approaches 0, in pulmonary venous blood:

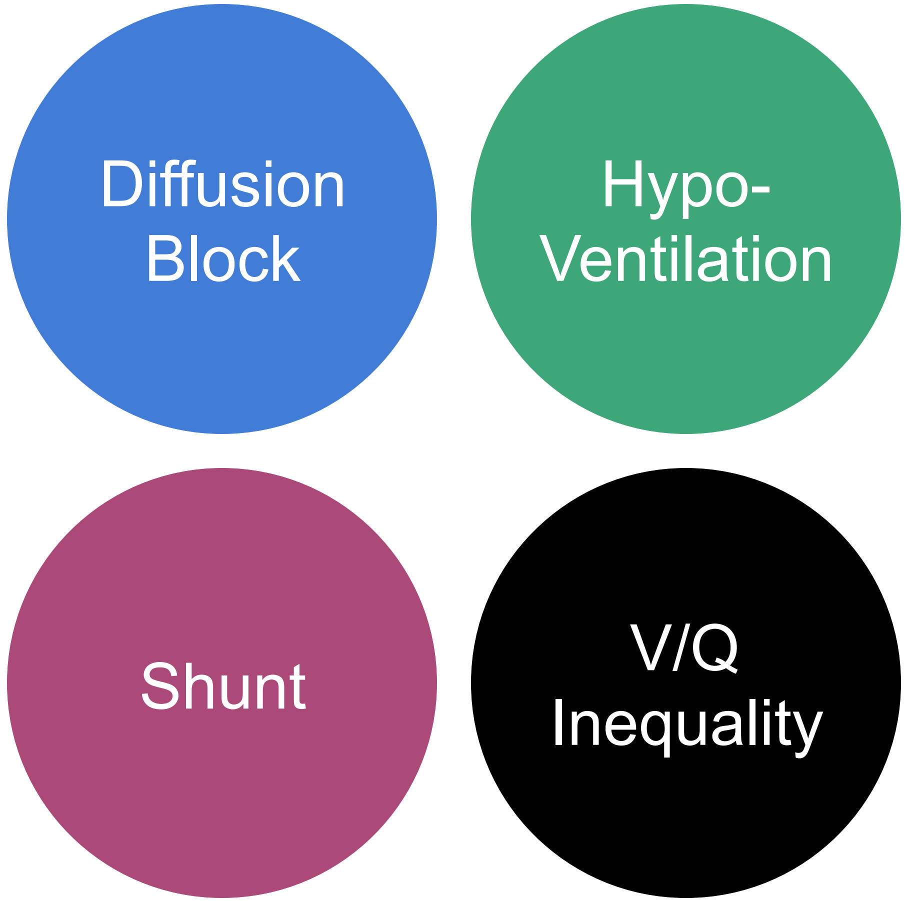
$PaO_2 \rightarrow PvO_2$

$PaCO_2 \rightarrow PvCO_2$

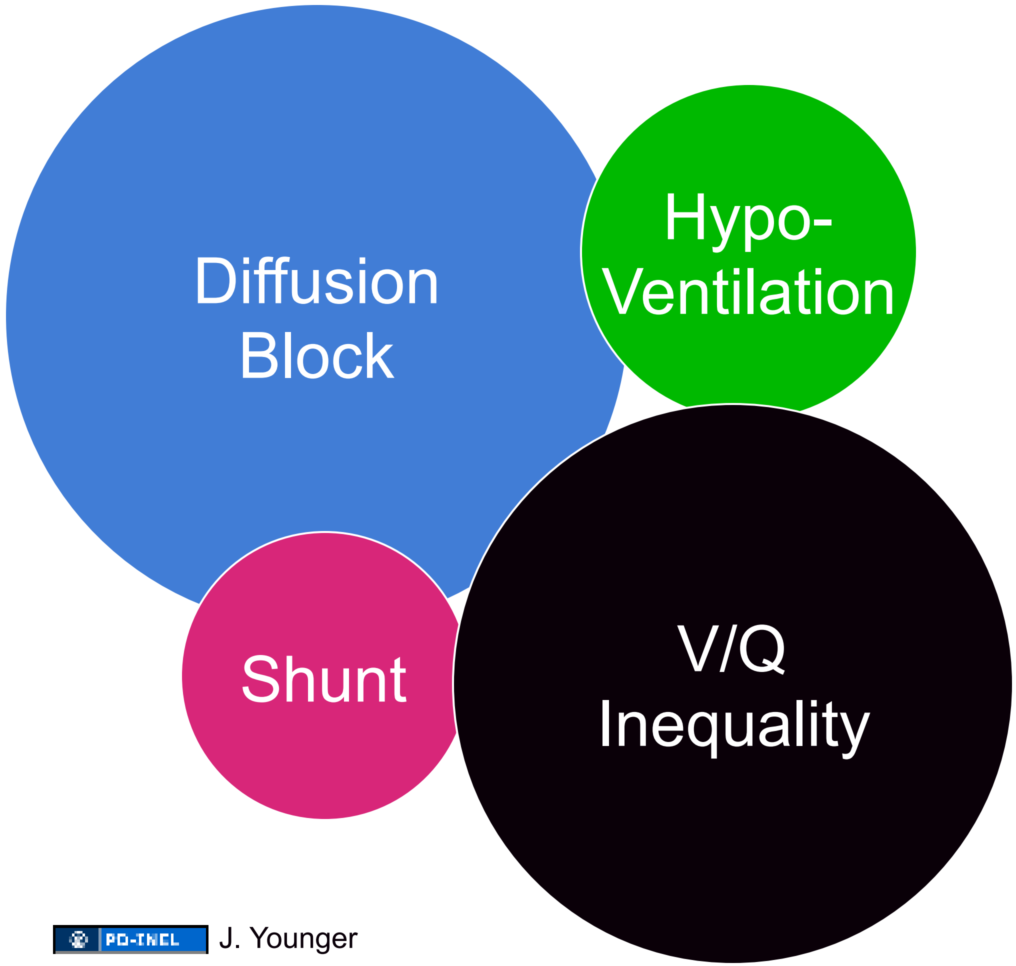

V/Q = 1
V/Q = 0
V/Q = ∞
V/Q = 1
V/Q = 0
V/Q = 1
V/Q = 0
V/Q = 0
V/Q = ∞
V/Q = ∞
V/Q = ∞
V/Q = 1
V/Q = 1
V/Q = ∞
V/Q = 0

Diseases Associated with V/Q Inequality

- Pretty much *everything* except pure shunt or pure hypoventilation will produce V/Q inequality
  - Pneumonia
  - Obstructive disease
  - Fibrotic disease
  - Pulmonary embolism


Diffusion Block
Hypo-Ventilation
Shunt
V/Q Inequality

Fibrosis



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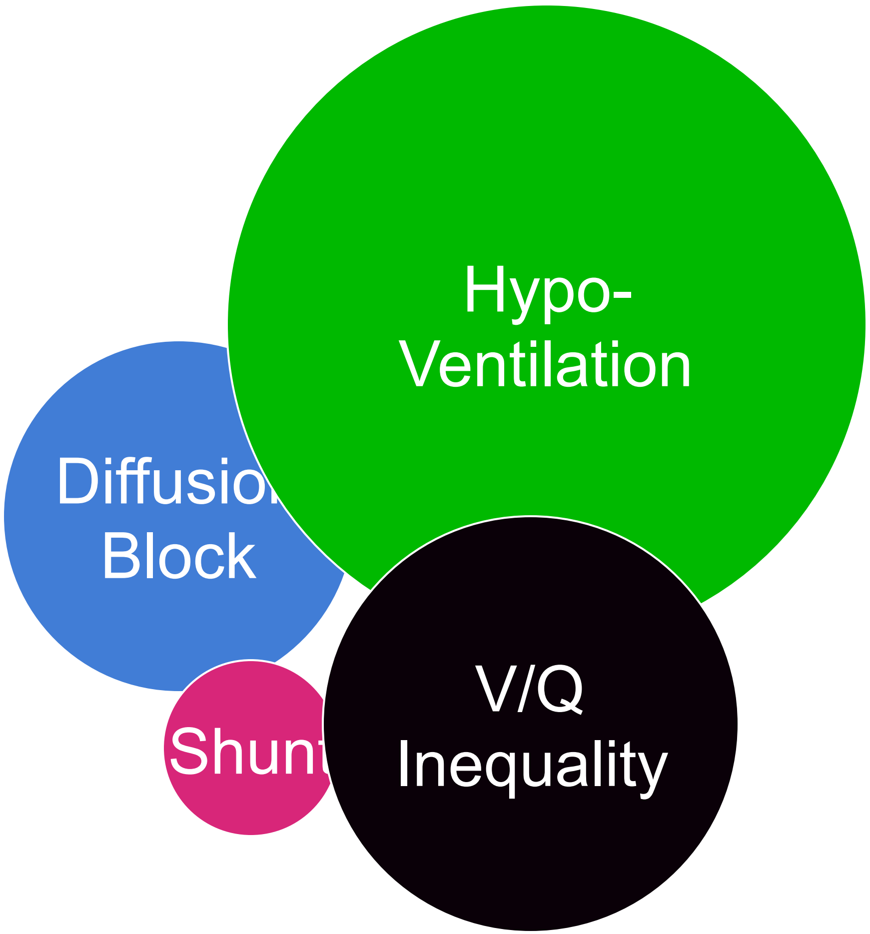

J. Younger

The 5th Cause: Low Inspired Oxygen Concentration

- Altitude
- Commercial air travel
  - Cabin pressurized to ~ 8,000 ft altitude
- Errors regarding supplemental oxygen

Thinking Clinically about Gas Exchange

- Clinically, quantifying gas exchange is used to evaluate the function of the lung
- If you know:
  - Gas partial pressures (tensions) in the alveoli
  - Gas tensions in the blood
- Then you can calculate the A-a gradient
  - This allows you to make some good guesses about:
    - Ventilation, perfusion, and diffusion phenomena across the alveolar membrane.
- In critical care and research settings, you can get fancier
  - PaO_2/FiO_2 ratio
  - Oxygenation Index
    - $(Paw \times FiO_2) / PaO_2$

The Alveolar Gas Equation

- The basis for calculating the alveolar-arterial O_2 difference (A-a gradient)
- The A-a gradient is a really useful way to ask the general question: How effectively is oxygen brought into the lung making it into the bloodstream?
- Simply pregnant with testing possibilities

To Evaluate the Performance of the Lung as a Gas Exchanger, Begin with the Gas Tensions in The Alveoli

- Measuring alveolar gas concentrations is not simple and is usually not done except in pulmonary function or research laboratories
- Guessing about alveolar gas concentrations usually suffices
- The ‘guess’ that is used is the alveolar gas equation

Source Undetermined

The Alveolar Gas Equation

Water Vapor: 47 mmHg

Everything else entering the lung : $(P_{atm} - P_{H2O})$

Oxygen entering the lung: $(P_{atm} – P_{H2O}) \times FiO_2$

Oxygen in the alveoli: $[(P_{atm} - P_{H2O}) \times FiO_2] - PaCO_2/RQ$

Carbon dioxide in the alveoli: Assumed equal to arterial PCO_2

The Respiratory Quotient

- The ratio of the amount of CO_2 produced to the amount of O_2 consumed
- Typical values range from 0.7 to 1.0
- Obviously dependent on relative consumption of carbohydrate, protein, and lipid substrates
- For many calculations, a value of 1.0 is reasonable
- Assumes metabolic equilibrium
  - Vigorous exercise is a great example of disequilibrium
  - During exercise beyond the anaerobic threshold, the value can take on values greater than 1.

The alveolar-arterial (A-a) oxygen gradient

- The difference between the oxygen partial pressure in alveoli and the pressure in blood
- Higher gradients mean worse performance

A-a Gradient and the 4 Causes of Hypoxia

- Hypoventilation
  - A-a Gradient should be normal
  - Hypoventilation simply increases the PCO_2 term in the alveolar gas equation
- A-a Gradient will not differentiate:
  - Diffusion block
  - V/Q inequality
  - Shunt

Figuring Out Which of the 4 Causes Affects a Given Patient

- History and Physical
  - i.e., the rest of the respiratory sequence
- Evaluate for obstructive physiology
- Test for diffusion abnormalities (DLCO)
- Intervene and see what happens
  - Supplemental oxygen
  - Augmented ventilation
    - Bronchodilators
    - Mechanical support

A Teaser for Next Week: Oxygen Delivery versus Mitochondrial Accessibility

- DO_2 is a global, 'gross' measure of a patient's ability to delivery oxygen to tissues
- Relying on DO_2 clinically assumes that downstream vascular 'plumbing' is working appropriately
  - Regional vascular autoregulation
- Shock states (e.g., sepsis, trauma) are associated with dysfunctional autoregulation at the tissue level, making DO_2 an imperfect parameter
- Sometime in our lifetime, practical tissue O_2 sensors will be available to monitor oxygen delivery at the tissue or cellular level

Important Things to Walk Away With

- Differences between convection and diffusion
- Meaning of tension, saturation, and content and associated calculations
- Impact of alveolar ventilation and dead space on carbon dioxide handling
- The 4 primary causes of low arterial PO_2 and the physiology of each
- The alveolar gas and A-a gradient equations

Question to Ponder Tonight:

Which would most adversely affect arterial oxygenation?

1. An acute pneumonia completely involving the left lower lobe such that no gas exchange could occur
2. Surgically removing a normal left lower lobe

Question to Ponder Tonight

At altitude, some degree of hypoxia is a common occurrence. If someone were hypoxic at a given altitude, how could you tell whether or not there lungs were exchanging gas properly?

Question to Ponder Tonight

For each measurement, which would take longer to reach equilibrium following a change?

- Arterial oxygen content, following a sudden decrease of atmospheric FiO_2 from 0.21 to 0.16
- Arterial carbon dioxide tension, following a sudden decrease in minute ventilation by 15%?
- Hint: At this moment, which gas are you carrying around more of, oxygen or carbon dioxide? Where do you store those gases?

Question to Ponder Tonight

Some seals, walruses, and whales can stay submerged for extended periods of time (approaching an hour). How is this possible?

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