Don’t Hold Your Breath

Mammalian Adaptations to High Altitudes & Deep Sea

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BSCI 279

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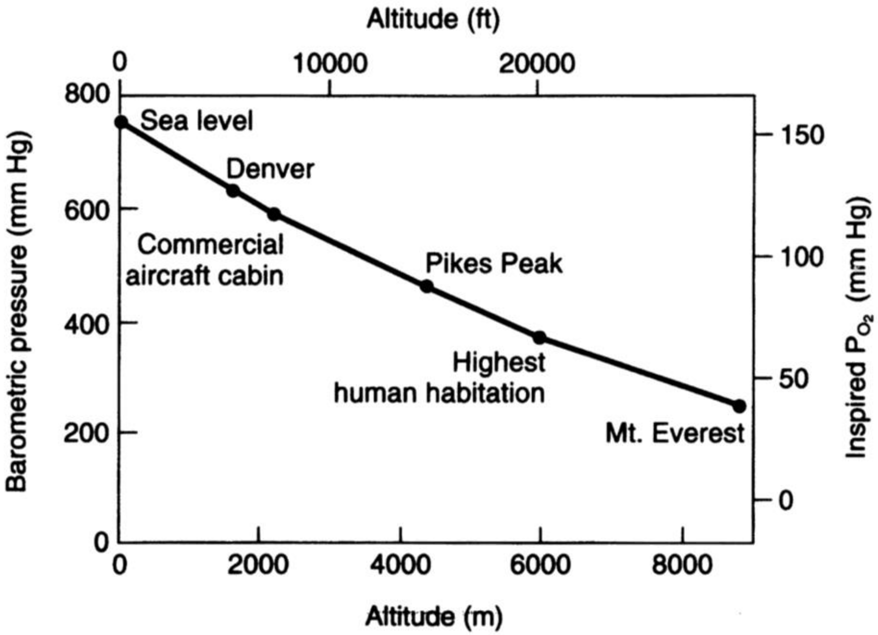
Outline

- High altitudes
  - What can go wrong: acute mountain sickness, HAPE, & HACE
  - Human adaptations: Tibetans & Andeans
  - Animal adaptations: yak & deer mouse
- Deep Sea
  - What can go wrong: decompression sickness & raptures of the deep
  - Human “adaptations”: Japanese pearl divers
  - Animal adaptations: Weddel seals & sea otters

High Altitude Humans

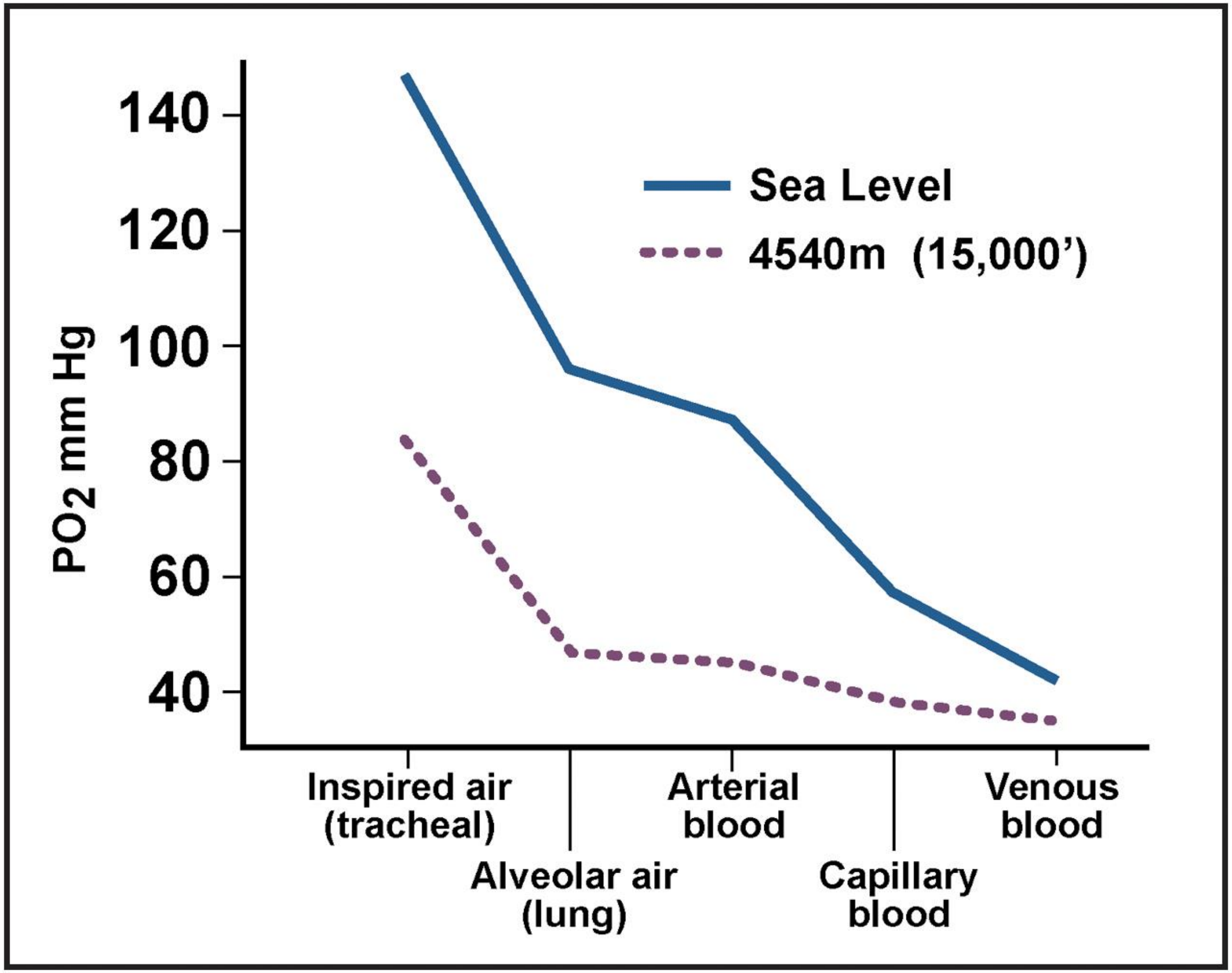
Atmospheric Gases



Dalton's Law: $P_t = P_{O2} + P_{N2} + P_x$

Altitude (feet)	Atmospheric Pressure (mm/Hg)	PAO_2 (mm/Hg)	PVO_2 (mm/Hg)	Pressure Differential (mm/Hg)	Blood Saturation (%)
Sea Level	760	100	40	60	98
10,000	523	60	31	29	87
18,000	380	38	26	12	72
22,000	321	30	22	8	60
25,000	282	7	4	3	9
35,000	179	0	0	0	0

Partial Pressure of Oxygen



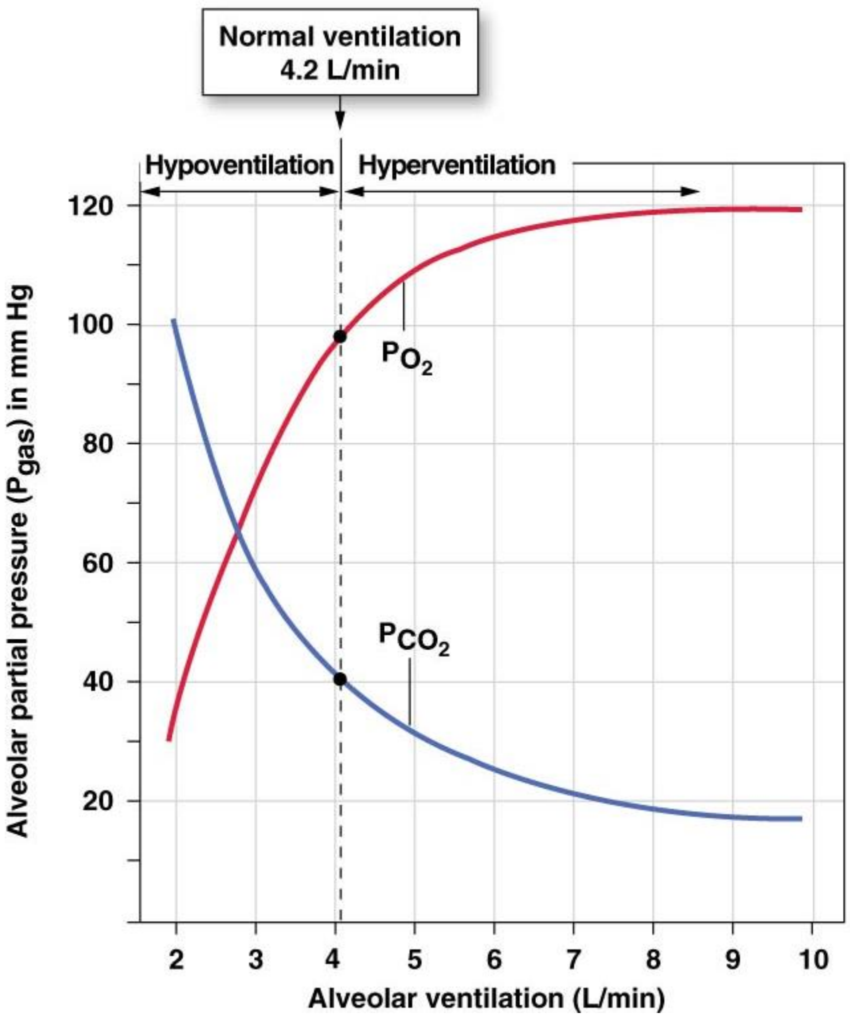
Acute Mountain Sickness

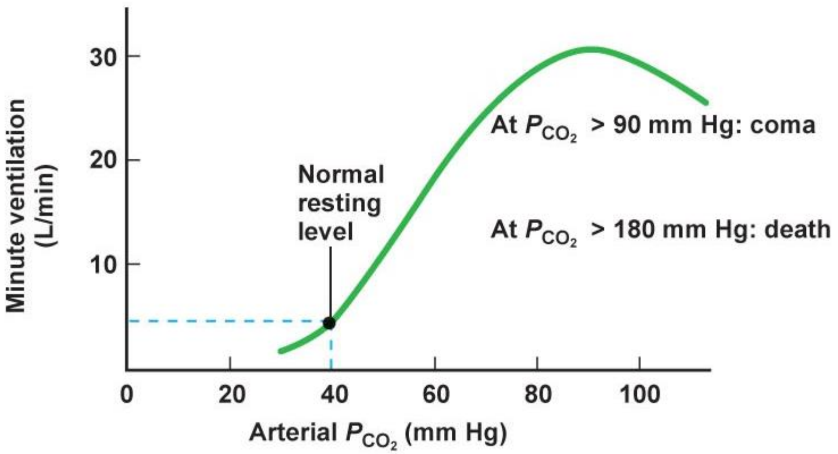
- Symptoms: fatigue, nausea, dizziness, headache, difficulty sleeping, loss of appetite, rapid pulse, shortness of breath

? Why?

- Hypoxemia, hypocapnia, & alkalosis

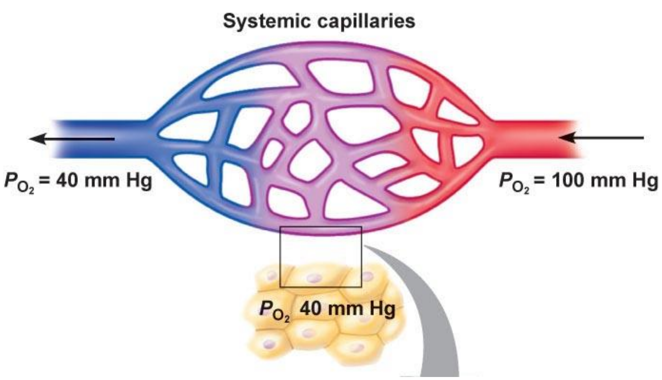
Perfusion & Peripheral Chemoreceptors

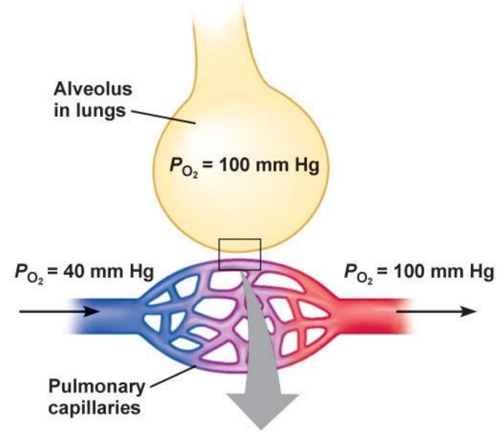


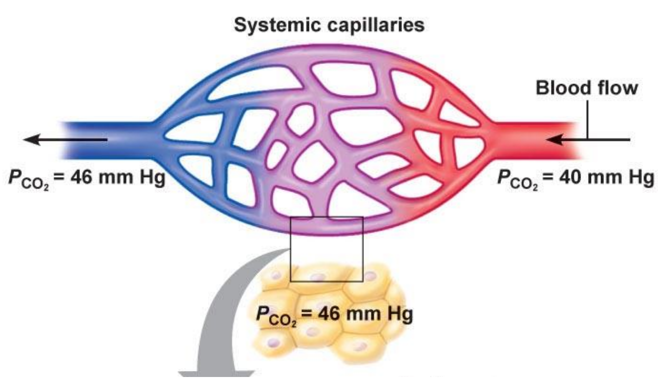


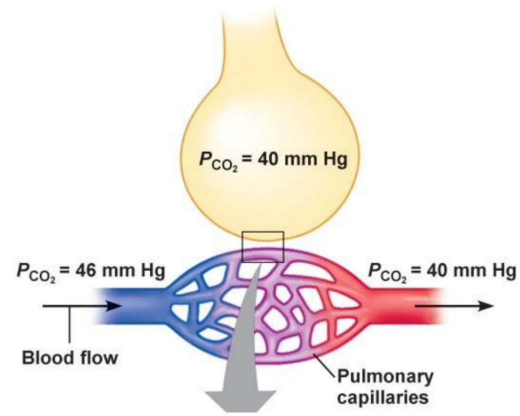
(b) Effects of arterial P_{CO_2} on ventilation

CO_2 & O_2 Pressure Differentials



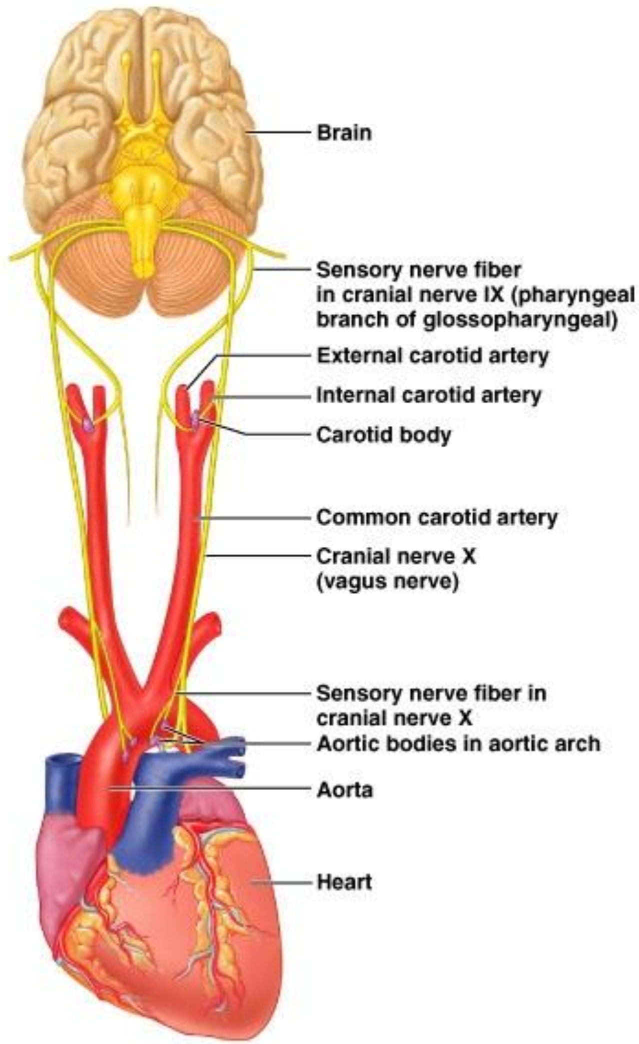


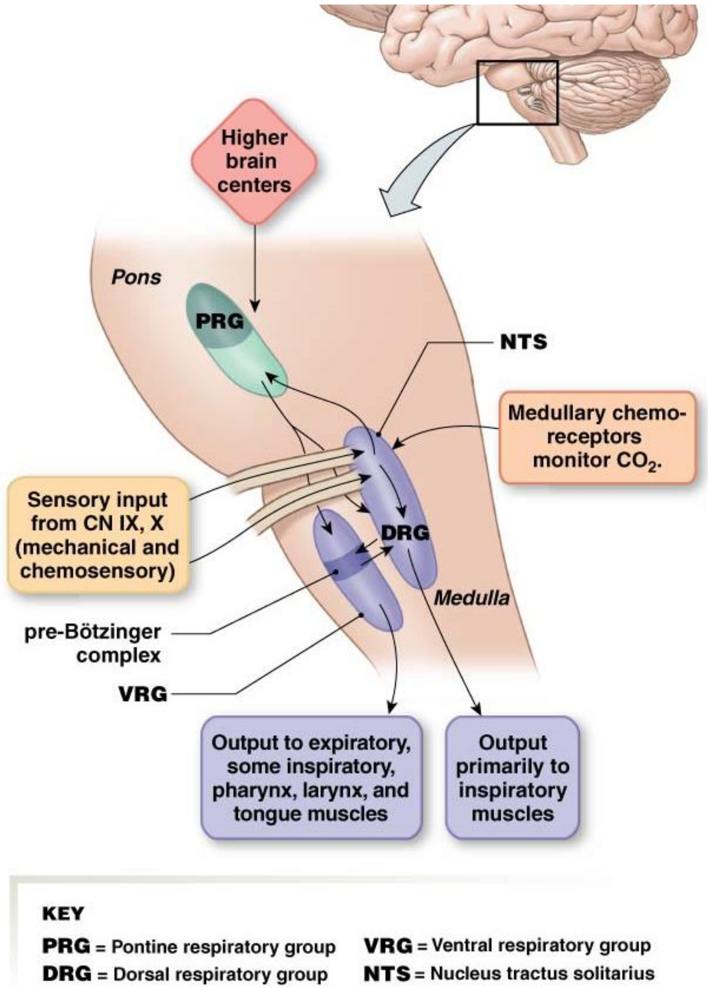




Fick's Law: $V_{gas}=A/T*D_k(P_1-P_2)$

Carotid Body and Medulla





Acute Mountain Sickness

- Symptoms: fatigue, nausea, dizziness, headache, difficulty sleeping, loss of appetite, rapid pulse, shortness of breath
- Hypoxemia, hypocapnia, & alkalosis
- Caused by decreased ventilation drive & erythrocytosis
  - people with AMS have lower minute ventilation, higher expired CO_2, & lower arterial O_2
  - Hb > 200 g/L, Hct > 65%, and arterial O_2 < 85%
- Maximum oxygen intake decreases 20-30%

Acclimatization

- ↑Erythropoietin → ↑hematocrit and hemoglobin
  - at high enough concentrations, can increase blood viscosity enough to compromise vasculature & decrease tissue oxygenation
- ↑2,3-DPG

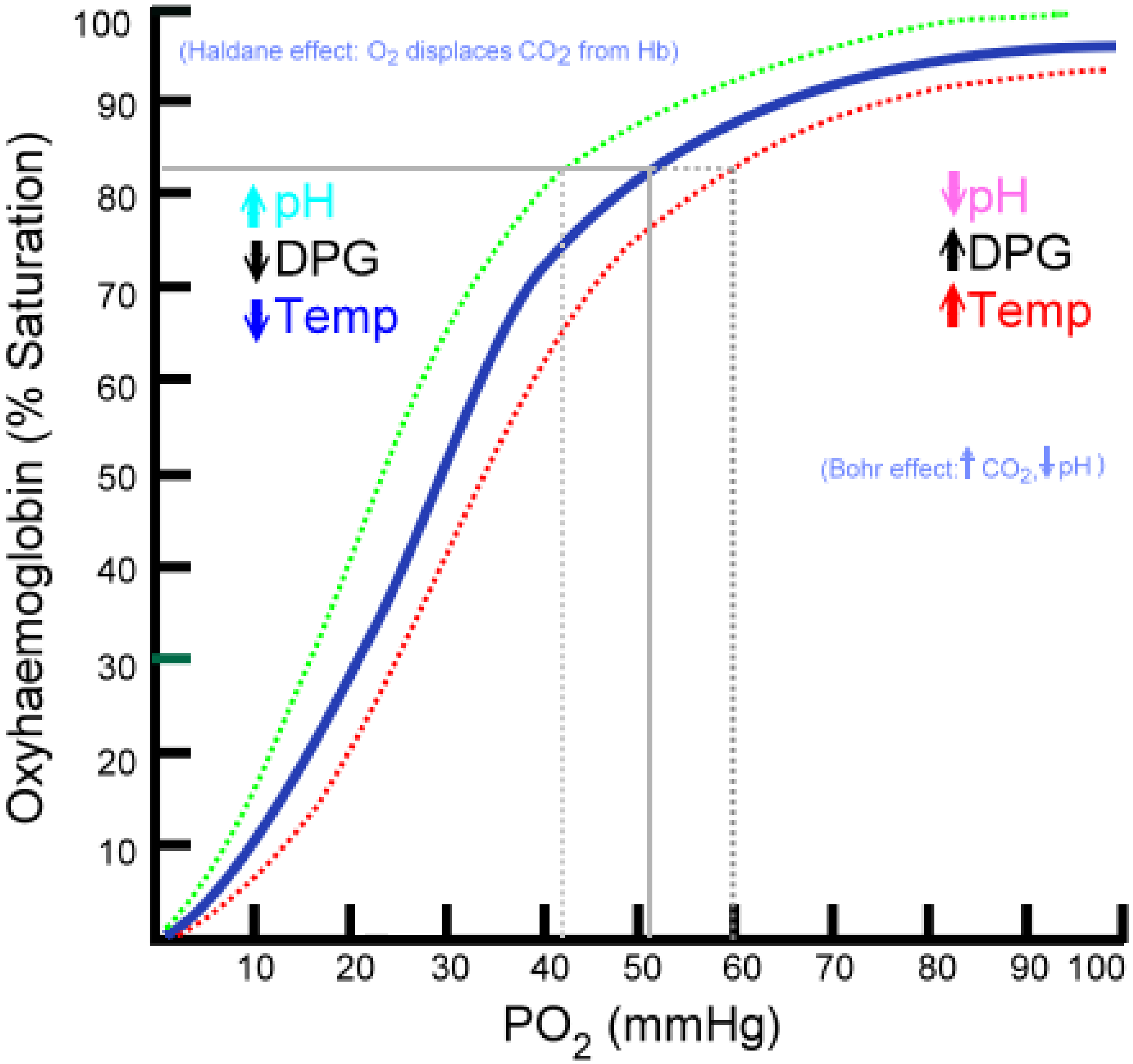
? Why would this help?

- ↑renal retention of bicarbonate

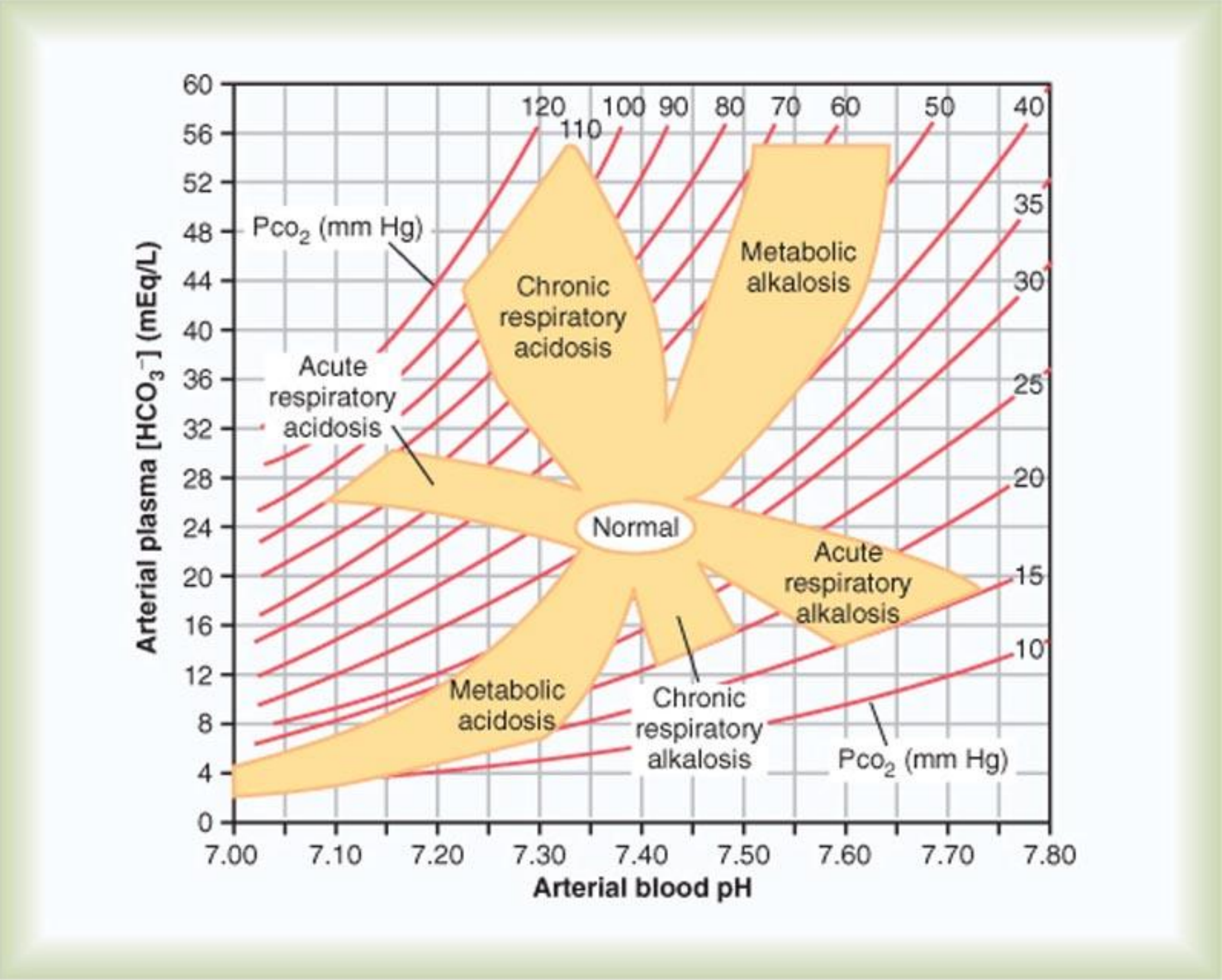
? Why would this help?

- Maximum oxygen intake increases to nearly normal levels over 1 year
- Proposed mechanism: ↑ carotid chemoreceptor activity

Hemoglobin



(Haldane effect: O_2 displaces CO_2 from Hb)
↑pH
↓DPG
↓Temp
↓pH
↑DPG
↑Temp
(Bohr effect: ↑ CO_2, ↓ pH)
Oxyhaemoglobin (% Saturation)
100
90
80
70
60
50
40
30
20
10
10 20 30 40 50 60 70 80 90 100
PO_2 (mmHg)



Arterial plasma [HCO_3^-] (mEq/L)
60
56
52
48
44
40
36
32
28
24
20
16
12
8
4
0
7.00
7.10
7.20
7.30
7.40
7.50
7.60
7.70
7.80
Arterial blood pH
120
110
100
90
80
70
60
50
40
35
30
25
20
15
10
P_{CO_2} (mm Hg)
Chronic respiratory acidosis
Metabolic alkalosis
Acute respiratory acidosis
Normal
Acute respiratory alkalosis
Metabolic acidosis
Chronic respiratory alkalosis
P_{CO_2} (mm Hg)

Treatment

- Stay 1 night for every 300m (1000ft) gained above 8000ft
- Acetazolamide: acidifies the blood

? Why would this help?

- Myo-Inositol Trispyrophosphate could release more oxygen from hemoglobin to improve symptoms
- Oxygen

High Altitude Cerebral & Pulmonary Edema (HACE/HAPE)

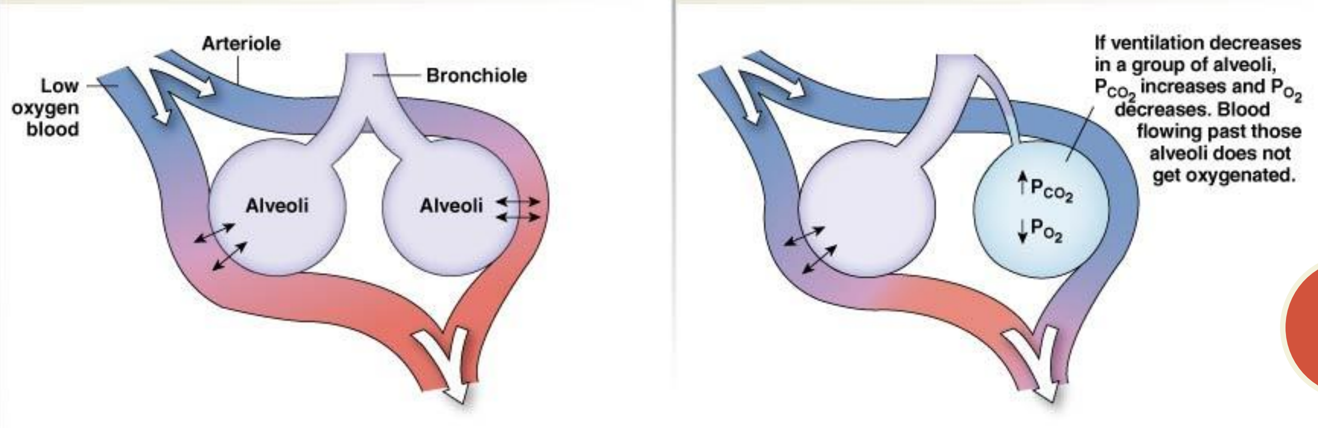
- Symptoms: confusion, decreased consciousness, grey complexion, coughing
- Pulmonary edema from vaso
- Cerebral edema from vaso
- Treat with anti-inflammatory (dexamethasone) & phosphodiesterase (reduces pulmonary artery pressure)

Pulmonary Vasoconstriction

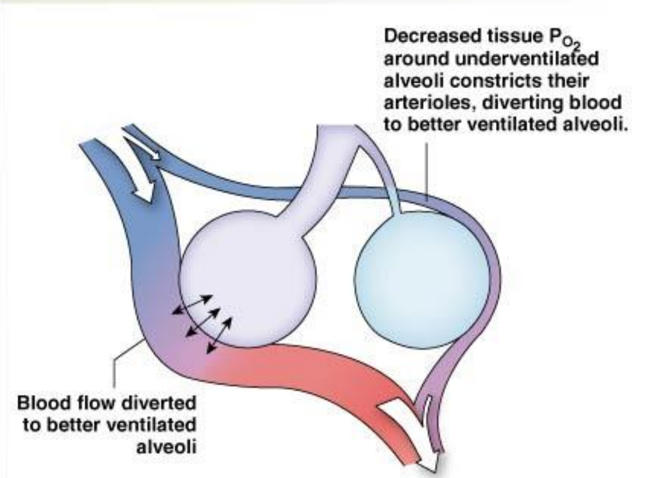
Local control mechanisms attempt to match ventilation and perfusion.

(a) Normally perfusion of blood past alveoli is matched to alveolar ventilation to maximize gas exchange.

(b) Ventilation-perfusion mismatch caused by under-ventilated alveoli.



(c) Local control mechanisms try to keep ventilation and perfusion matched.



(d) Bronchiole diameter is mediated primarily by CO_2 levels in exhaled air passing through them.

Local Control of Arterioles and Bronchioles by Oxygen and Carbon Dioxide

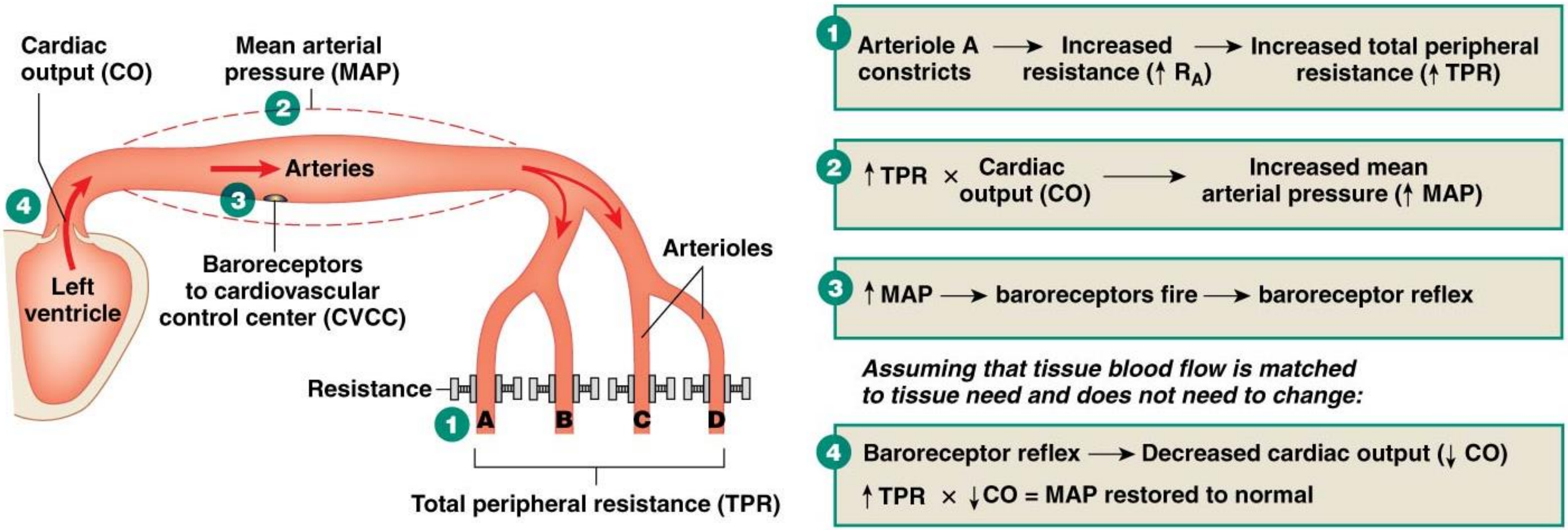
Gas composition	Bronchioles	Pulmonary arteries	Systemic arteries
P_{CO_2} increases	Dilate	(Constrict)*	Dilate
P_{CO_2} decreases	Constrict	(Dilate)	Constrict
P_{O_2} increases	(Constrict)	(Dilate)	Constrict
P_{O_2} decreases	(Dilate)	Constrict	Dilate

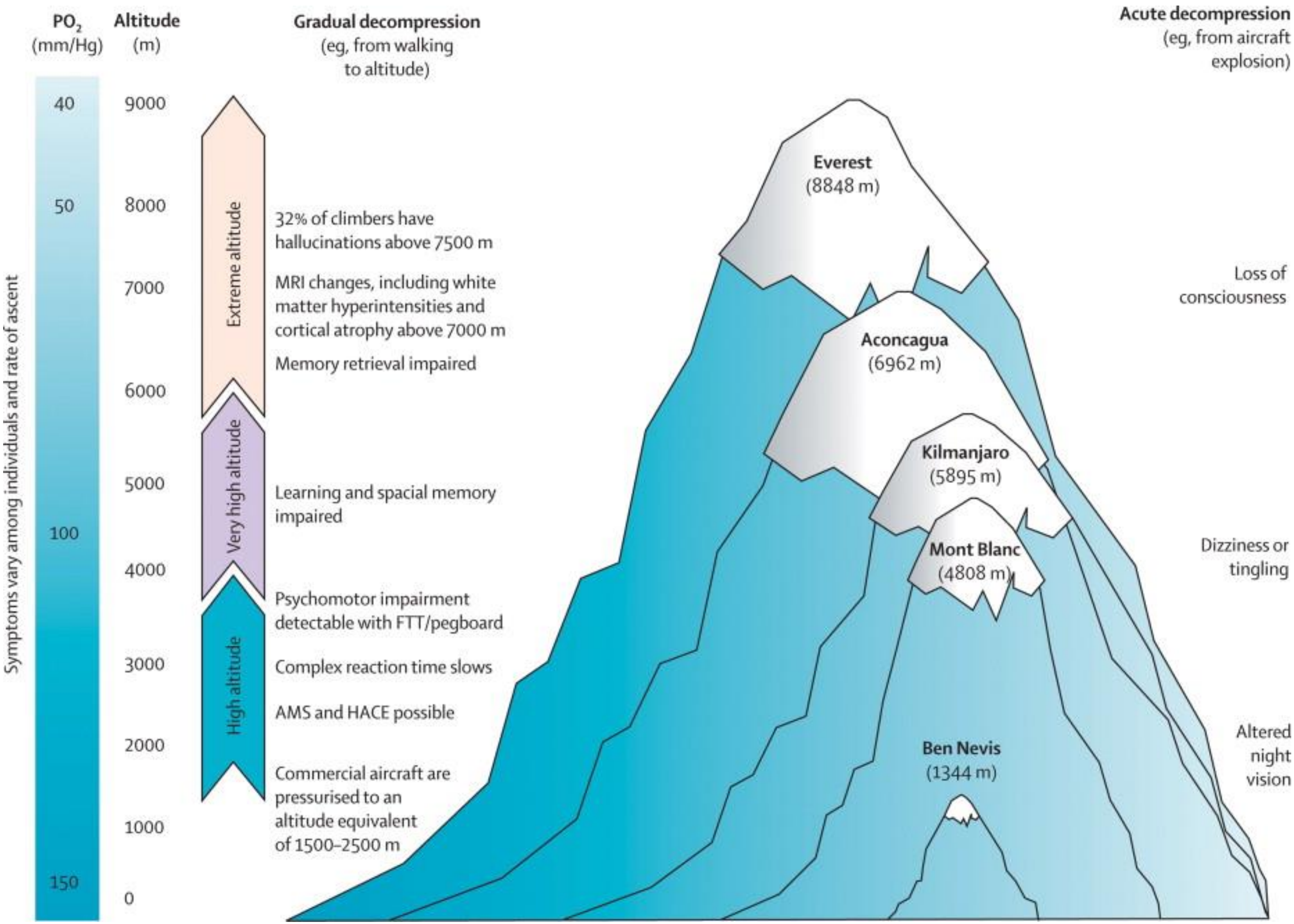
* Parentheses indicate weak responses.

? Why?

? Heart effects?

CO = MAP/TPR


Cardiac output (CO)
Mean arterial pressure (MAP)
Arteries
Left ventricle
Baroreceptors to cardiovascular control center (CVCC)
Arterioles
Resistance
A
B
C
D
Total peripheral resistance (TPR)
1 Arteriole A constricts → Increased resistance (↑ R_A) → Increased total peripheral resistance (↑ TPR)
2 ↑ TPR × Cardiac output (CO) → Increased mean arterial pressure (↑ MAP)
3 ↑ MAP → baroreceptors fire → baroreceptor reflex
Assuming that tissue blood flow is matched to tissue need and does not need to change:
4 Baroreceptor reflex → Decreased cardiac output (↓ CO)
↑ TPR × ↓CO = MAP restored to normal


PO2 (mm/Hg)
Altitude (m)
Gradual decompression (eg, from walking to altitude)
Acute decompression (eg, from aircraft explosion)
40
50
100
150
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Symptoms vary among individuals and rate of ascent
Extreme altitude
Very high altitude
High altitude
32% of climbers have hallucinations above 7500 m
MRI changes, including white matter hyperintensities and cortical atrophy above 7000 m
Memory retrieval impaired
Learning and spacial memory impaired
Psychomotor impairment detectable with FTT/pegboard
Complex reaction time slows
AMS and HACE possible
Commercial aircraft are pressurised to an altitude equivalent of 1500–2500 m
Everest (8848 m)
Aconcagua (6962 m)
Kilmanjaro (5895 m)
Mont Blanc (4808 m)
Ben Nevis (1344 m)
Loss of consciousness
Dizziness or tingling
Altered night vision

Andeans & Tibetans

Populated since 11,00 years ago
Average elevation: 4000m (13,000ft)

Populated since 25,000 years ago
Average elevation: 4900m (16,000ft)

Highlanders

- Denser capillary beds to reduce diffusion distance
- Higher 2,3-DPG
- Exercise capacity is better than lowlanders at high elevation, but not as good as lowlanders at sea level
- Limits: no human habitation above 6000m

Andeans & Tibetans

- Andeans have higher [Hb] than lowlanders at sea level
- Tibetans have a higher ventilation rate (15 L/min vs 10.5 L/min)
- Tibetans have increased NO

? Why would this help?

- Both have heavier babies than expected due to increased NO (Tibetans) and increased gestational ventilation (Andeans), but also have high rates of diseases associated with low fetal oxygen (schizophrenia & epilepsy)
- Overall, Andeans have higher arterial O_2

Hypoxia-Inducible Factor (HIF) Oxygen Signaling Pathway

- Tibetans have variants of: EPAS1 (the oxygen-sensing subunit), EGLN1 (HIF regulator), & PPARA (HIF transcriptional regulator)
  - only EGLN1 also mutated in Andeans
  - EPAS1 variants between Tibetans & Hans show the fastest allele frequency change in any human gene ever observed strongly correlated with low hemoglobin & RBC → regulation of hemoglobin rather than changing its subunits to change affinity
- Also show variants in FANCA & PKLR (RBC creation & maintenance)

High Altitude Animals

Other animals

- Various animals
- Hypobaric chamber
- Measured hypoxic response
- Smooth muscle plays a role

Hypoxic Response

- Pulmonary vasoconstriction
- Systemic vasodialation
- Carotid body and Medulla
- Cellular response
- Genetic response

Pulmonary Vasoconstriction

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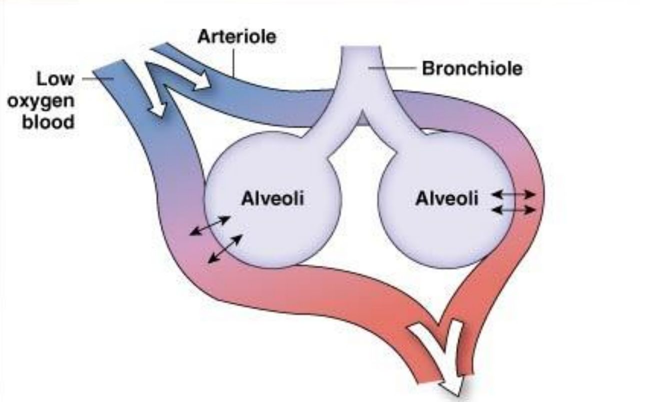

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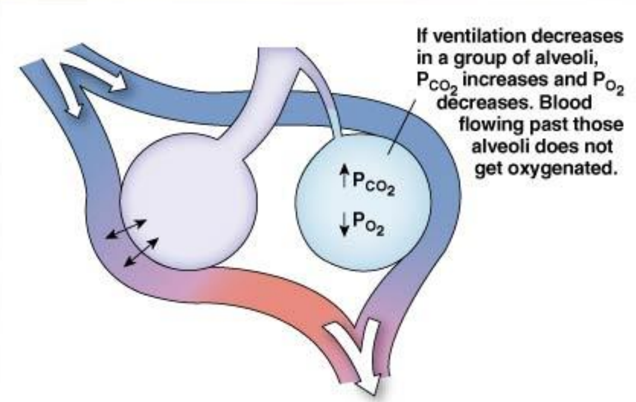

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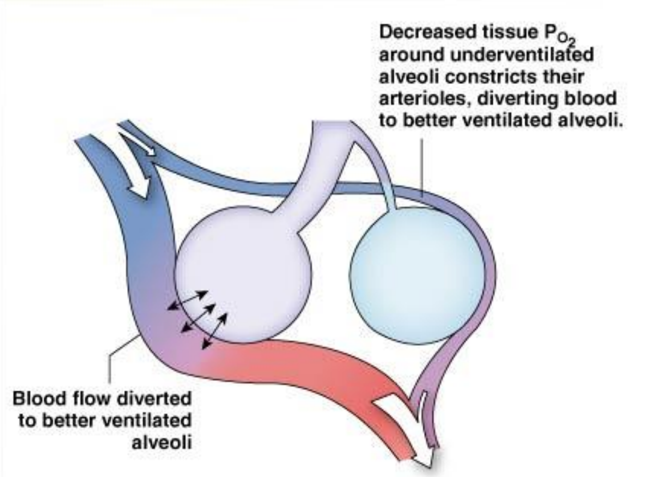

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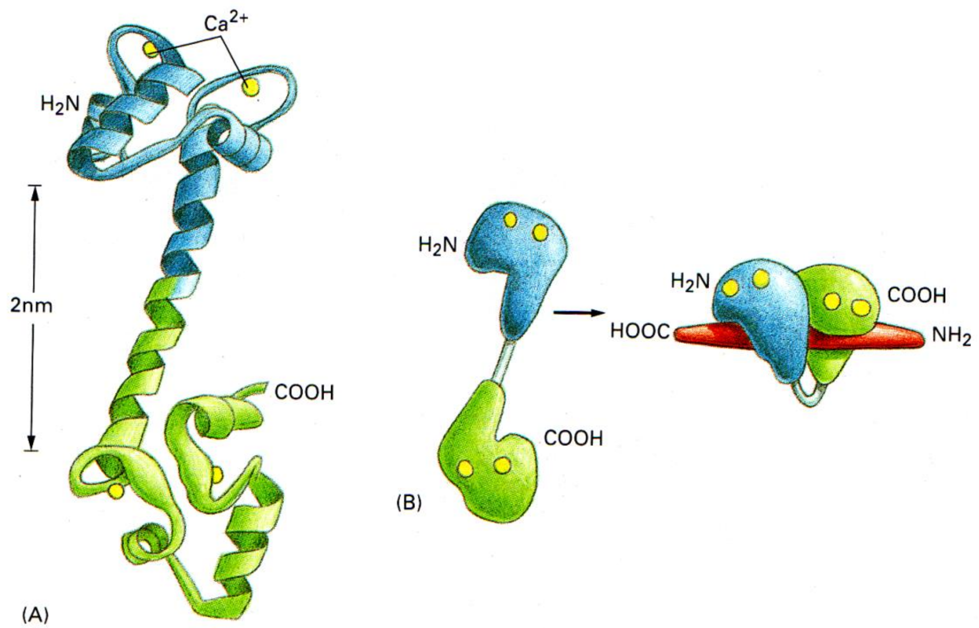
P_{O_2} decreases	(Dilate)	Constrict	Dilate

* Parentheses indicate weak responses.

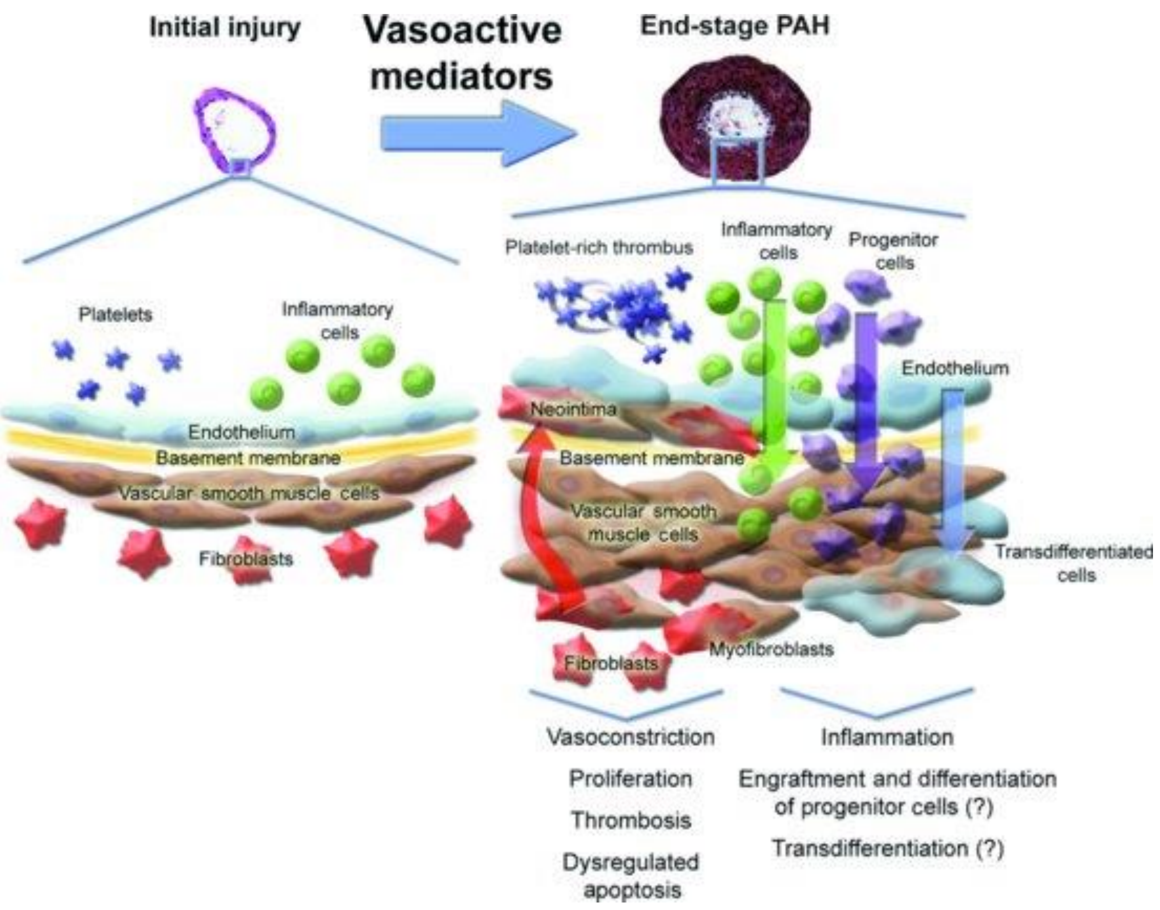
Smooth muscle contraction

- Membrane depolarizes
- Ca+2 influx
- Ca+2 and calmodulin complex
- MLCK
- Contraction

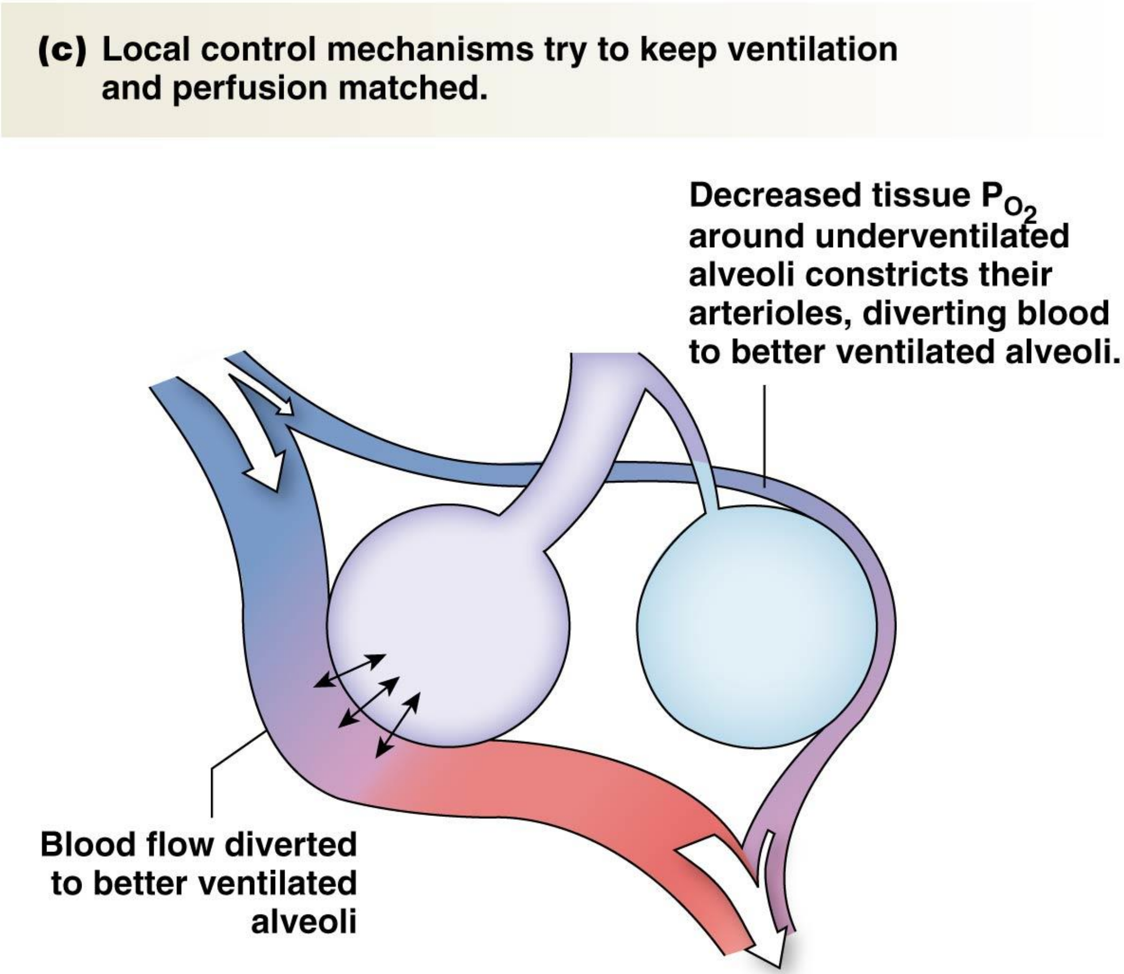
? Compare with skeletal



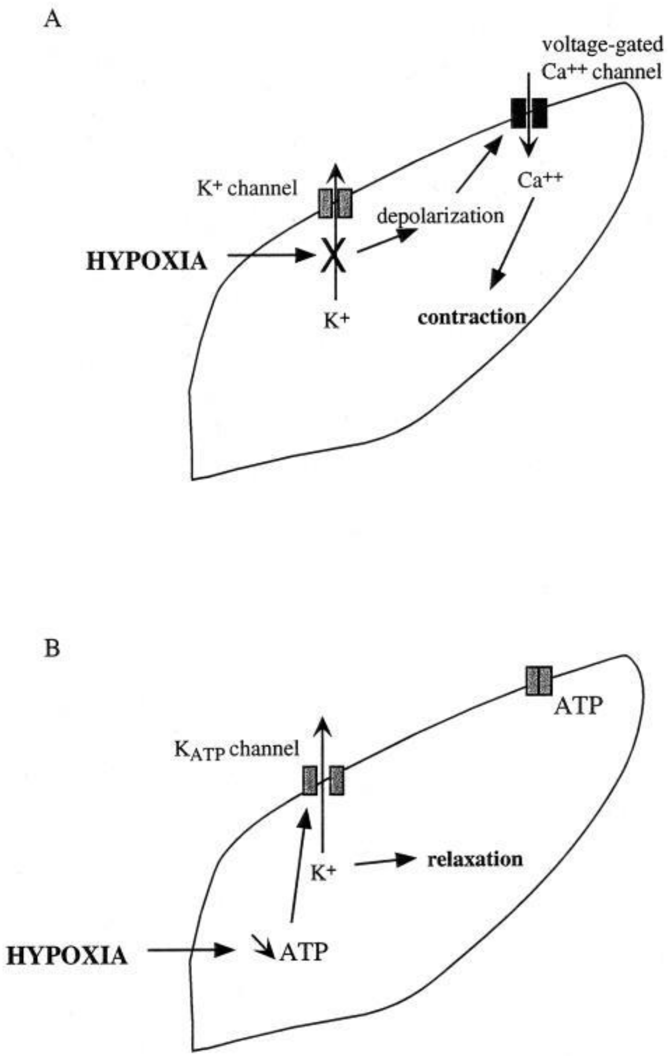
Pulmonary Hypertension



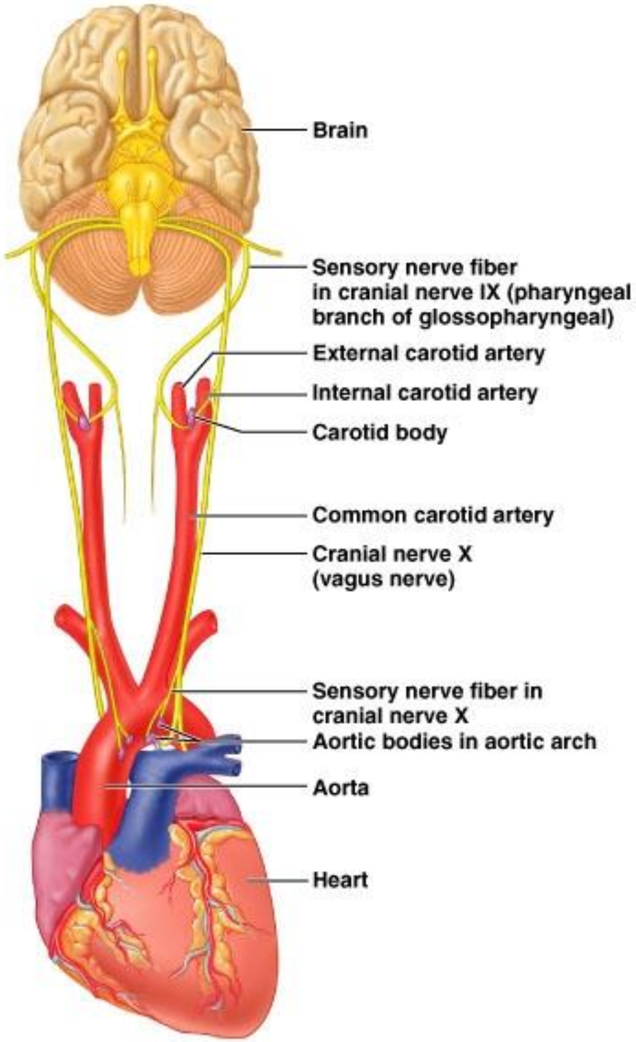
Systemic Vasodialalation

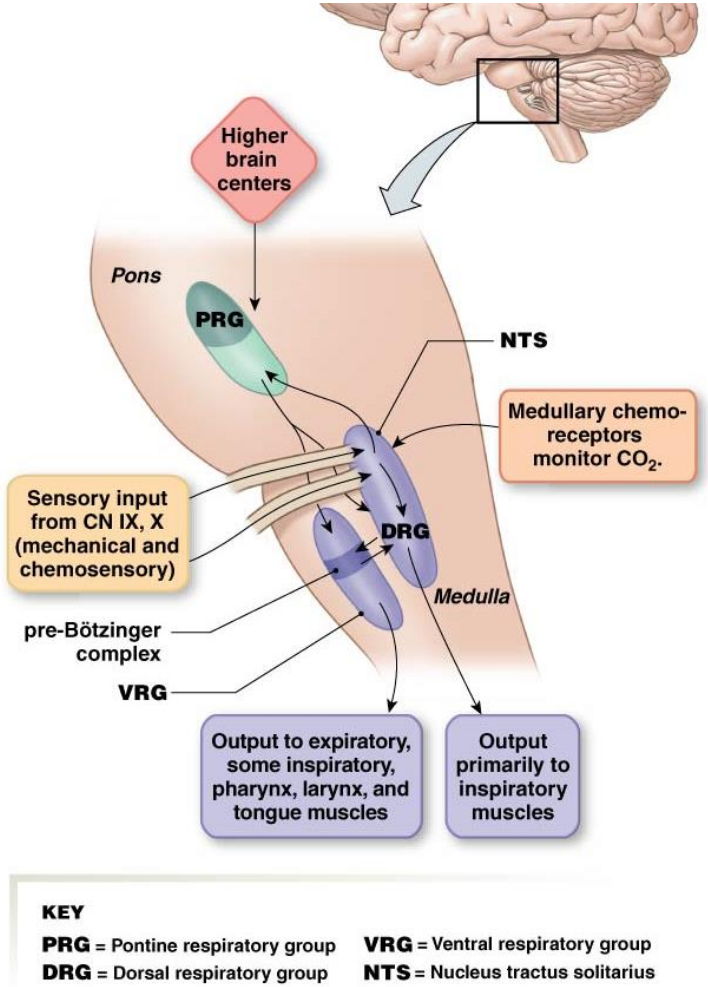


Difference between two



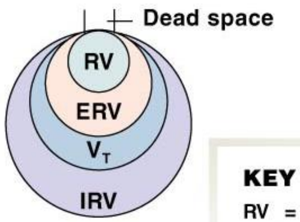
Carotid Body and Medulla





Respiration

The four lung volumes



KEY

RV = Residual volume
ERV = Expiratory reserve volume
V_T = Tidal volume
IRV = Inspiratory reserve volume

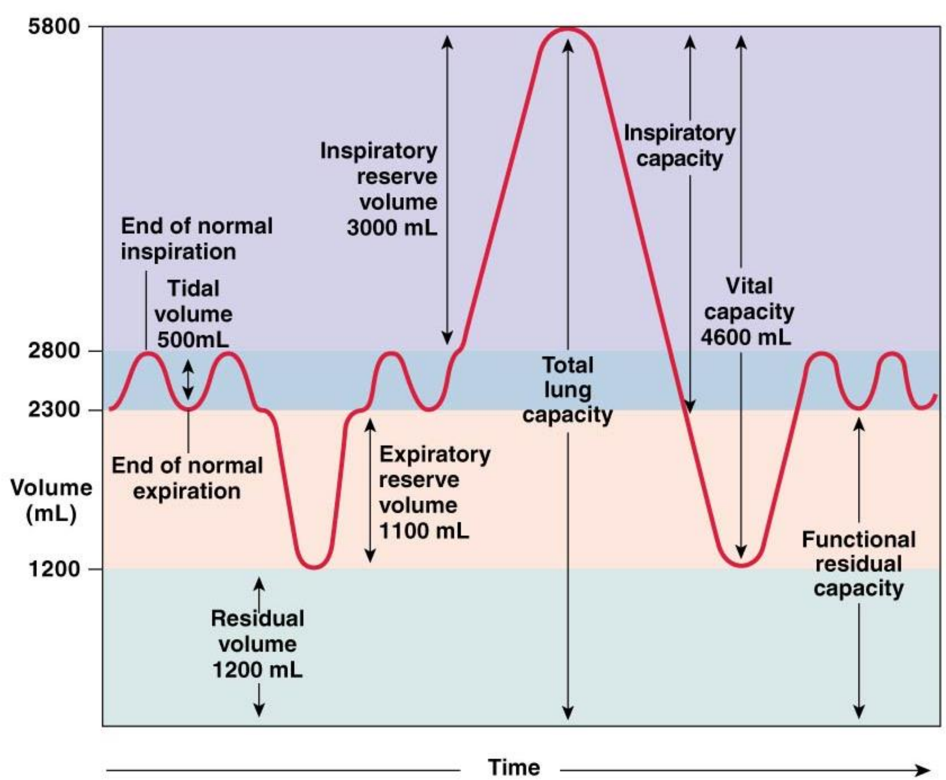
Capacities are sums of 2 or more volumes.

Inspiratory capacity = V_T + IRV
Vital capacity = V_T + IRV + ERV
Total lung capacity = V_T + IRV + ERV + RV
Functional residual capacity = ERV + RV

Pulmonary Volumes and Capacities*

		Males	Females
Vital capacity	IRV	3000	1900
	V_T	500	500
	ERV	1100	700
Residual volume		1200	1100
Total lung capacity		5800 mL	4200 mL

A spirometer tracing showing lung volumes and capacities.



*Pulmonary volumes are given for a normal 70-kg man or a 50-kg woman, 28 years old.

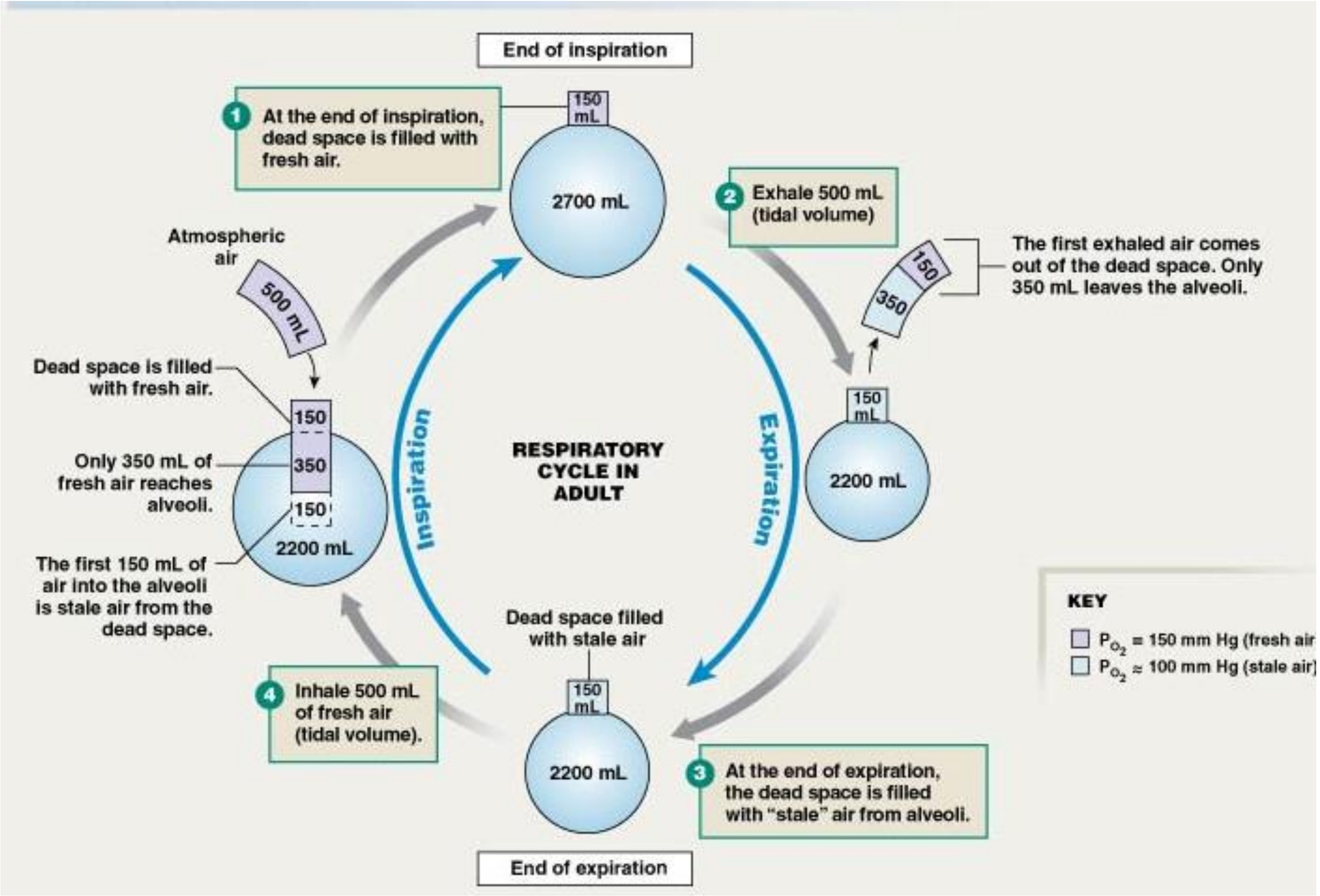
Respiration Rate

- Minute Ventilation = Tidal Volume X Respiratory Rate

? Which is better?

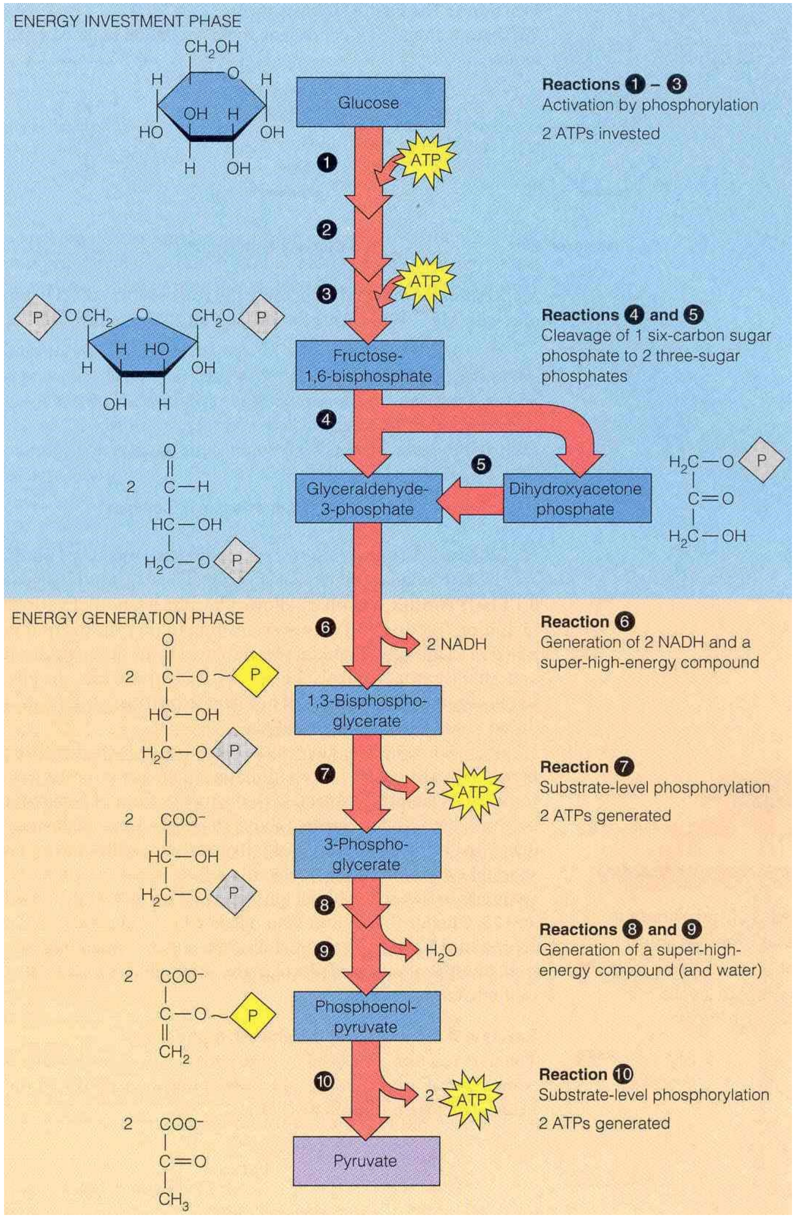
- Alveolar Ventillation
- VA = (VT X RR) – (DSV X RR)
- This gives a measure of how much gas exchange can occur
- It’s more efficient to increase VT than RR

DSV


End of inspiration
1 At the end of inspiration, dead space is filled with fresh air.
150 mL
2700 mL
2 Exhale 500 mL (tidal volume)
The first exhaled air comes out of the dead space. Only 350 mL leaves the alveoli.
150
350
150 mL
2200 mL
Atmospheric air
500 mL
Dead space is filled with fresh air.
Only 350 mL of fresh air reaches alveoli.
The first 150 mL of air into the alveoli is stale air from the dead space.
150
350
150
2200 mL
Inspiration
Expiration
RESPIRATORY CYCLE IN ADULT
Dead space filled with stale air
150 mL
2200 mL
4 Inhale 500 mL of fresh air (tidal volume).
3 At the end of expiration, the dead space is filled with "stale" air from alveoli.
End of expiration
KEY
P_{O_2} = 150 mm Hg (fresh air
P_{O_2} ≈ 100 mm Hg (stale air)

Cellular Response

- Glycolysis
- Shift processes
- Necrosis



Genetic response

- VEGF
- NO
- Erythropoietin

Yak vs. Cattle

Varying altitude

- Switch conditions
- Brisket Disease
  - Right side heart failure
  - Pulmonary hypertension

? What is different in Yaks?

Yaks

- Hypoxic response is reduced in yaks vs cattle

?

Why?

- Larger heart
- Large lungs
- Large chest

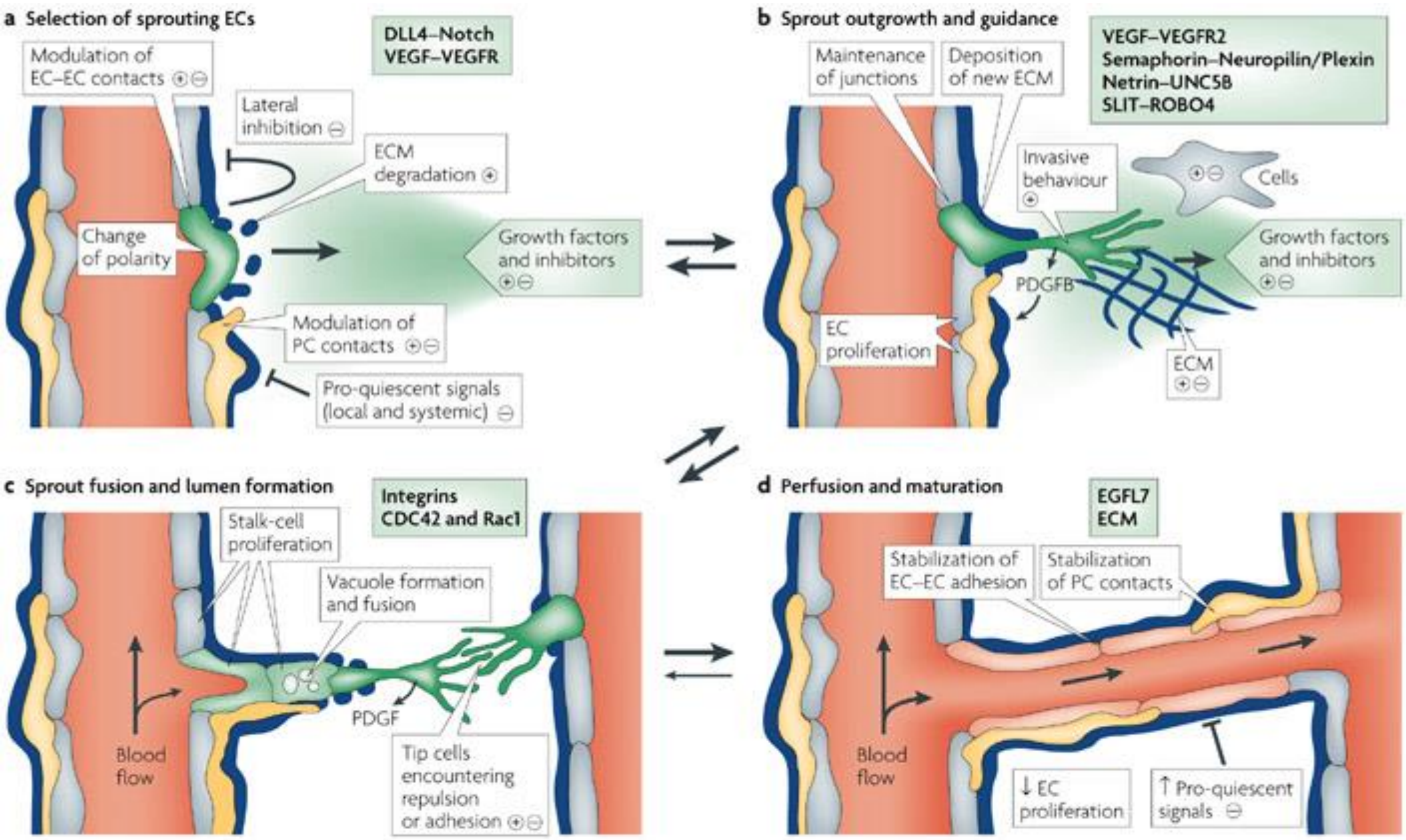
HIF-1

- Hypoxia-inducing factor 1
- Heterodimeric
- Produced in normoxia and hypoxia
- Normoxia: polyubiquitinylated
- Hydroxylase destroys HIF-α in presence of O2
- Stimulates:
  - VEGF
  - Erythropoietin

VEGF

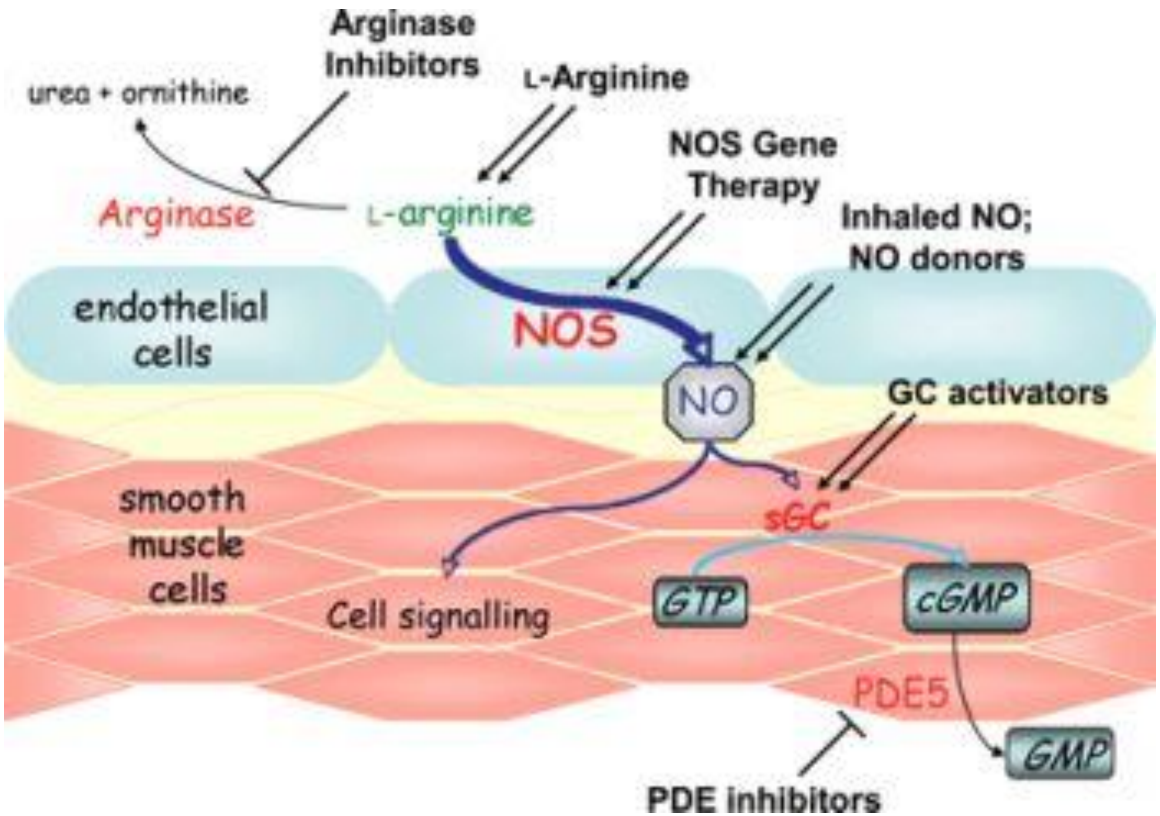
- Vascular Endothelial Growth Factor
- Angiogenesis
- NO synthesis

Angiogenesis



Nature Reviews | Molecular Cell Biology

NO



Arginase Inhibitors
urea + ornithine
L-Arginine
NOS Gene Therapy
Arginase
L-arginine
Inhaled NO; NO donors
endothelial cells
NOS
NO
GC activators
smooth muscle cells
sGC
Cell signalling
GTP
cGMP
PDE5
GMP
PDE inhibitors

? How?

Erythropoietin

- Released by kidney under hypoxic conditions
- Bone marrow
- Increases red blood cell count

LDH-1

- Lactate dehydrogenase
- Pyruvate → Lactate
- LDH-1 variant
- Higher Km value

? Why?

Deer mouse

High vs. Low

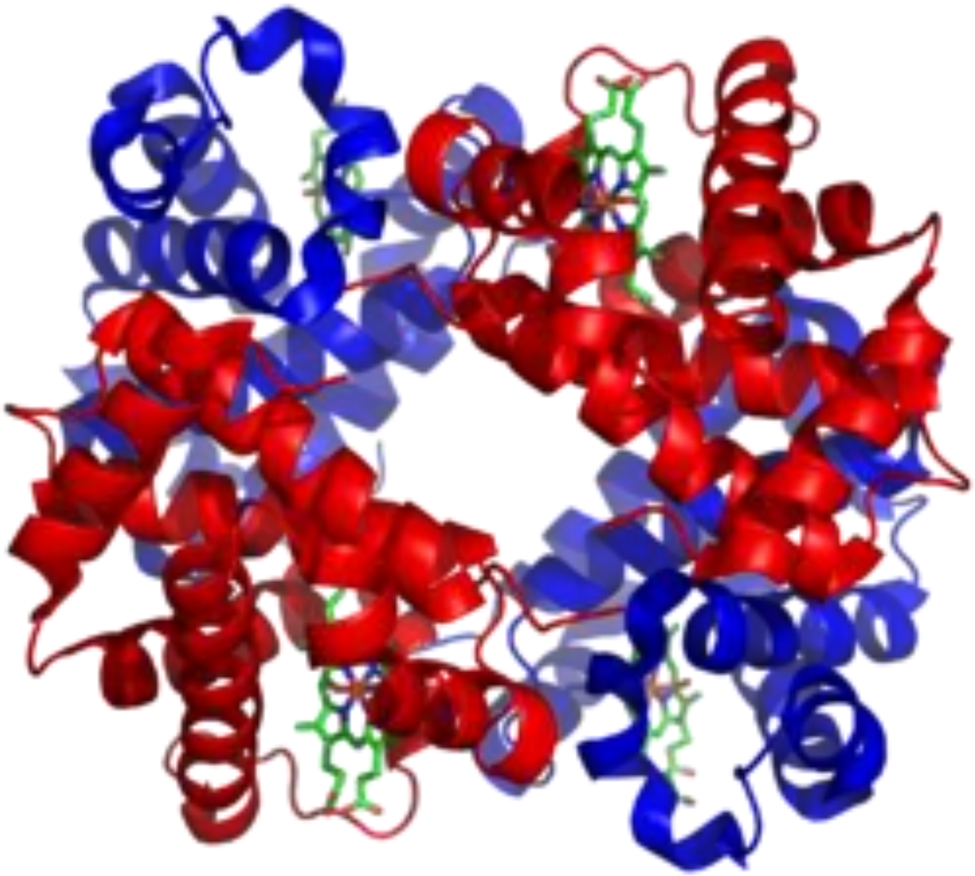
- Slight variation
- Organs
- Energy Demands

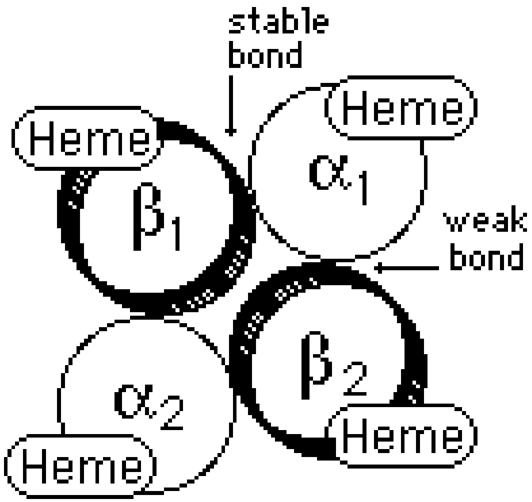
? Why?

Hemoglobin

- Heterotetrameric
- T and R state
- 2,3 DPG

Heterotetrameric





Conformations

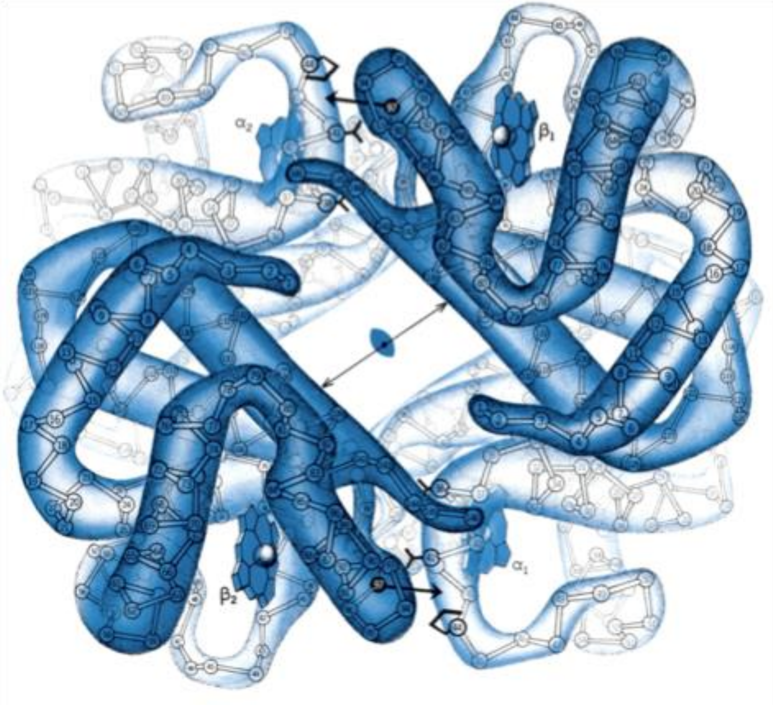


Figure 7-5a

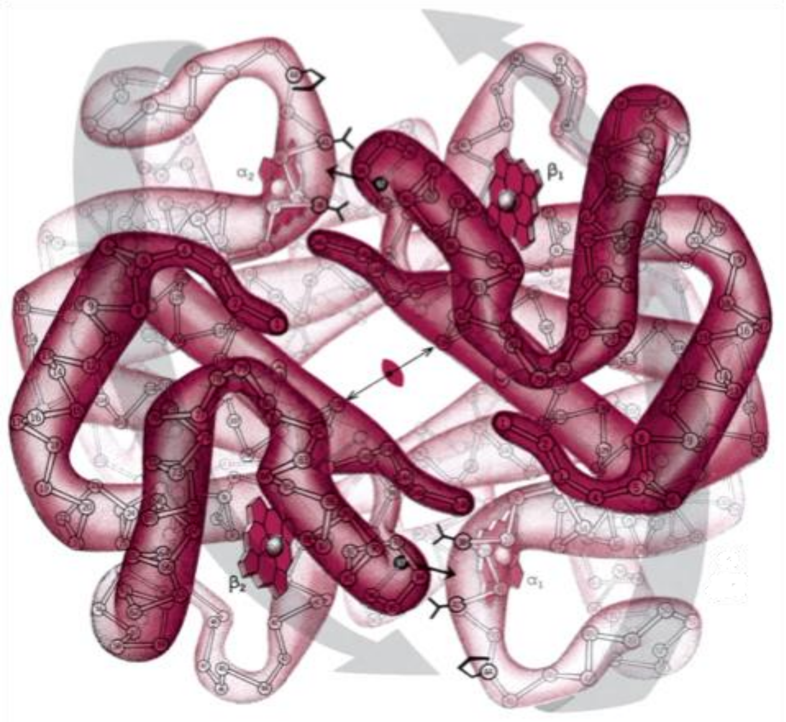


Figure 7-5b

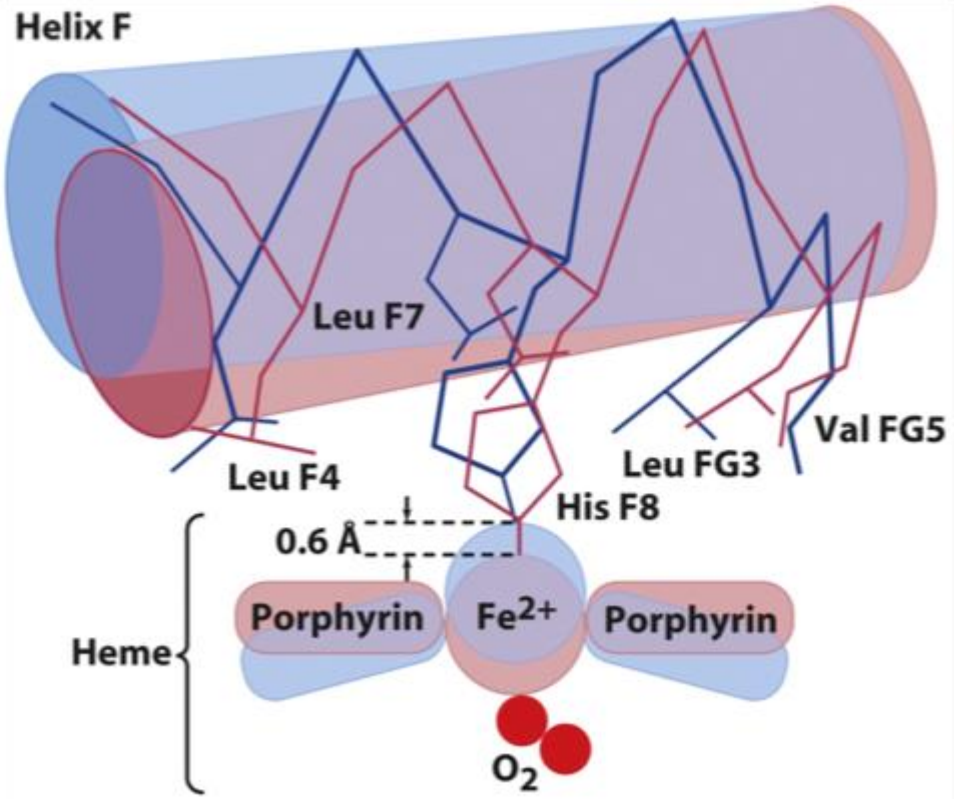

Helix F
Leu F7
Val FG5
Leu FG3
Leu F4
His F8
0.6 Å
Porphyrin
Fe^{2+}
Porphyrin
Heme
O_2

Figure 7-8

2,3 DPG

?

Why?

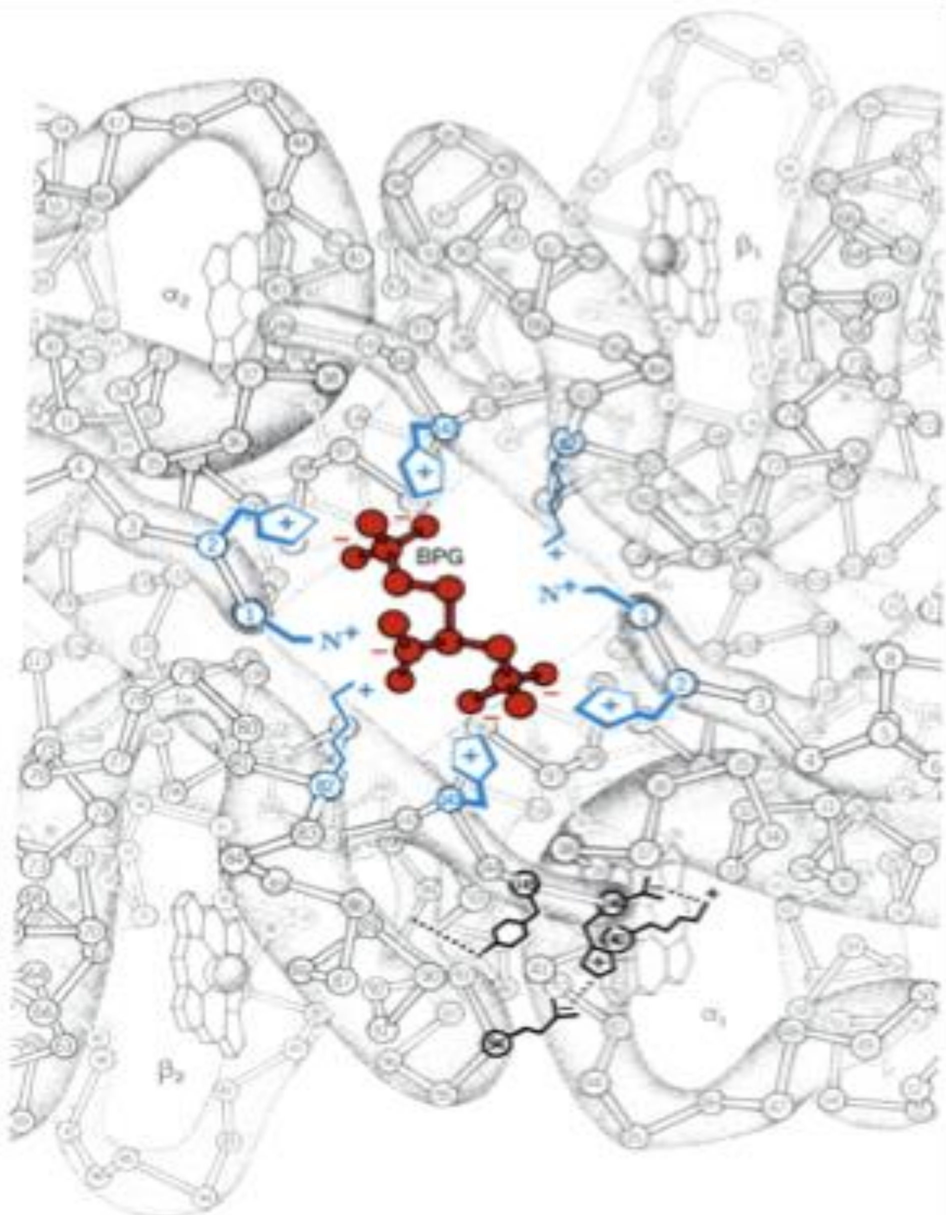
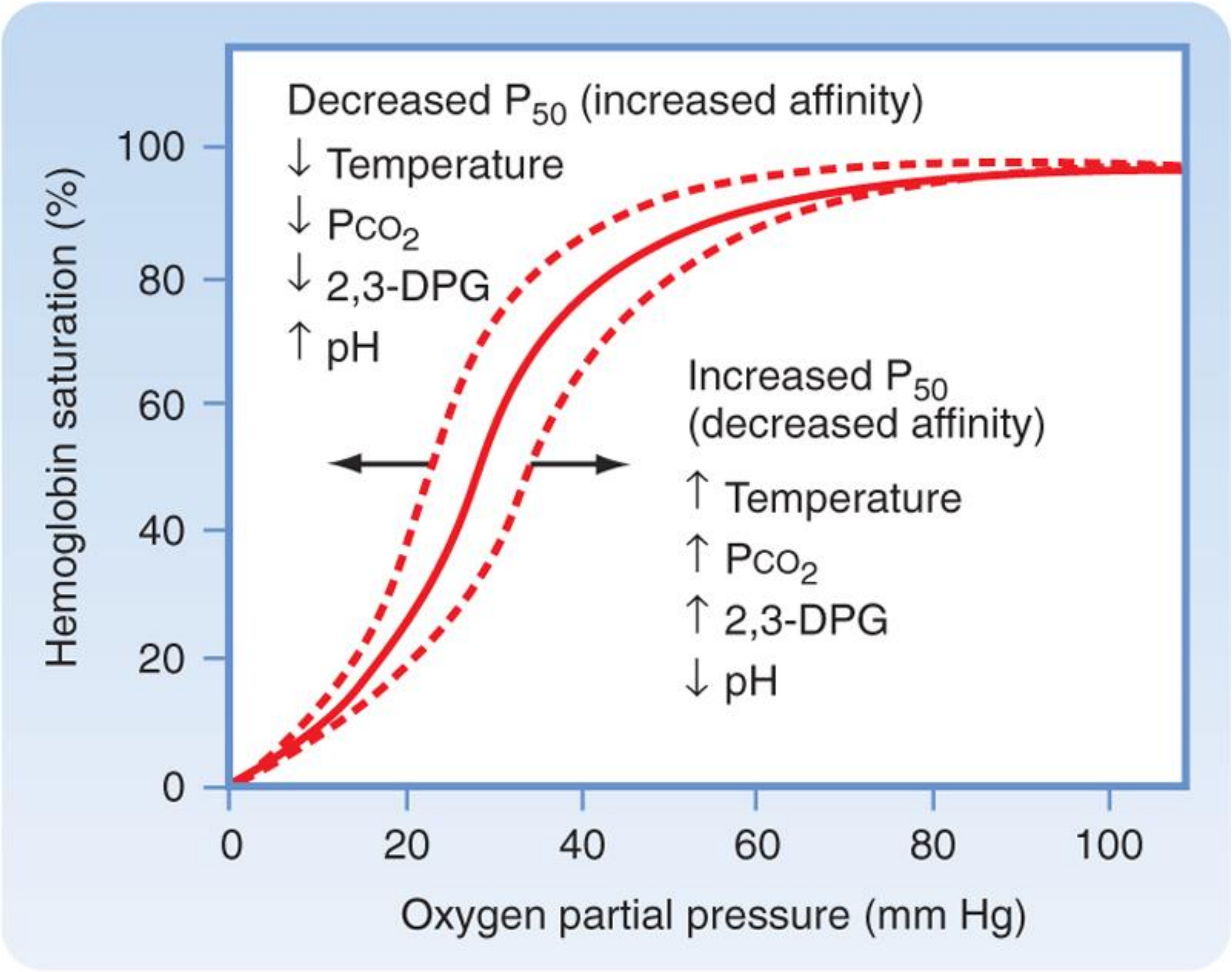


Figure 7-14



Koeppen & Stanton: Berne and Levy Physiology, 6th Edition.

Recap

- Morphology (physical structures)
- Sensitivity
- Genetic

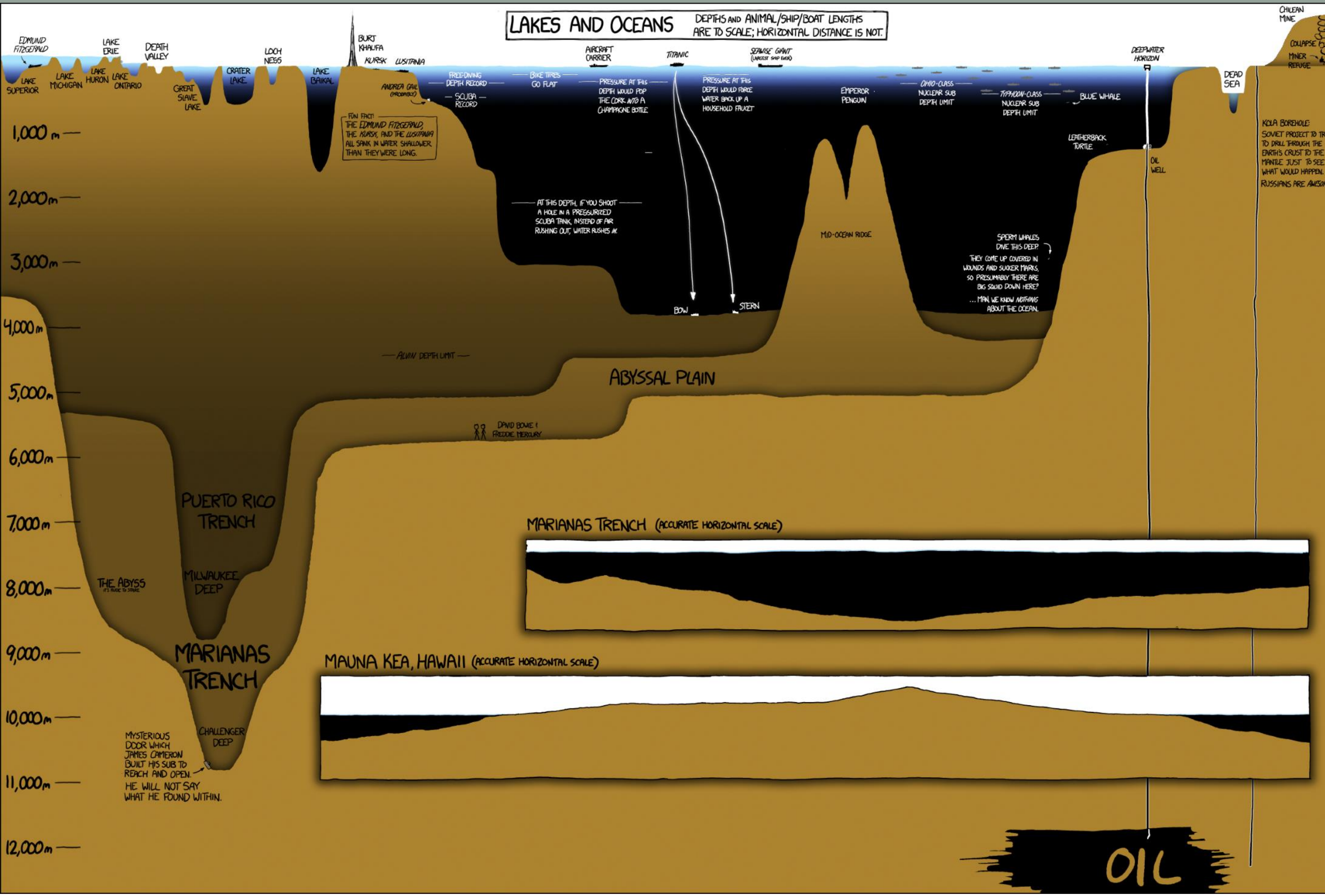

Deep Sea Diving Humans

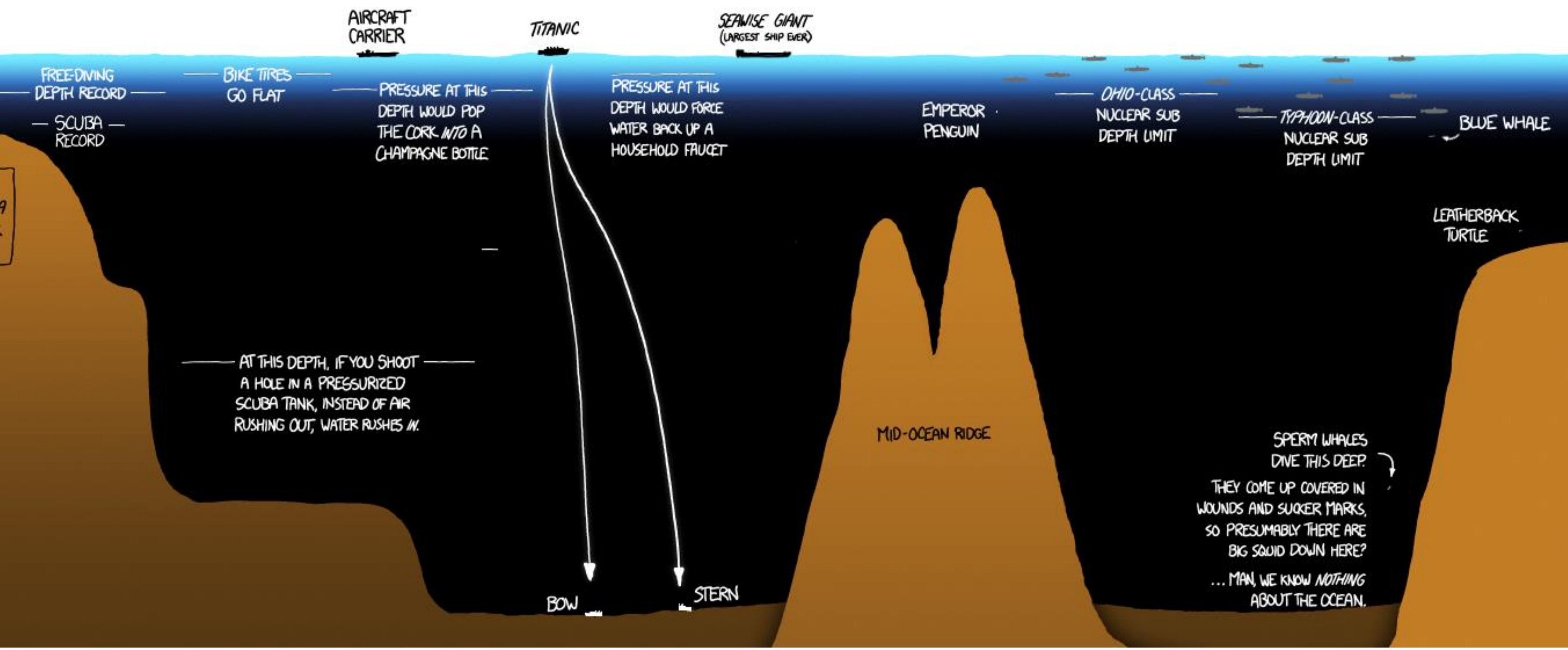
Problems Associated with Diving

? What factors will diving mammals/humans need to account for?

Factors

- Hypoxic Environment
- Increased Pressure
- Lower Temperatures
- Collapse of Airway
- Gas Release


LAKES AND OCEANS
DEPTHS AND ANIMAL/SHIP/BOAT LENGTHS ARE TO SCALE; HORIZONTAL DISTANCE IS NOT.
EDMUND FITZGERALD
LAKE SUPERIOR
LAKE MICHIGAN
LAKE HURON
LAKE ERIE
LAKE ONTARIO
DEATH VALLEY
GREAT SLAVE LAKE
CRATER LAKE
LOCH NESS
LAKE BAIKAL
BURJ KHALIFA
KURSK
LUSITANIA
ANDREA GAIL (PROBABLY)
FUN FACT: THE EDMUND FITZGERALD, THE KURSK, AND THE LUSITANIA ALL SANK IN WATER SHALLOWER THAN THEY WERE LONG.
FREE-DIVING DEPTH RECORD
SCUBA RECORD
BIKE TIRES GO FLAT
AIRCRAFT CARRIER
PRESSURE AT THIS DEPTH WOULD POP THE CORK INTO A CHAMPAGNE BOTTLE
TITANIC
SEAWISE GIANT (LARGEST SHIP EVER)
PRESSURE AT THIS DEPTH WOULD FORCE WATER BACK UP A HOUSEHOLD FAUCET
EMPEROR PENGUIN
OHIO-CLASS NUCLEAR SUB DEPTH LIMIT
TYPHOON-CLASS NUCLEAR SUB DEPTH LIMIT
BLUE WHALE
LEATHERBACK TURTLE
DEEPWATER HORIZON
OIL WELL
DEAD SEA
CHILEAN MINE
COLLAPSE
MINER REFUGE
KOLA BOREHOLE: SOVIET PROJECT TO TRY TO DRILL THROUGH THE EARTH'S CRUST TO THE MANTLE JUST TO SEE WHAT WOULD HAPPEN.
RUSSIANS ARE AWESOME.
1,000 m
2,000 m
3,000 m
4,000 m
5,000 m
6,000 m
7,000 m
8,000 m
9,000 m
10,000 m
11,000 m
12,000 m
AT THIS DEPTH, IF YOU SHOOT A HOLE IN A PRESSURIZED SCUBA TANK, INSTEAD OF AIR RUSHING OUT, WATER RUSHES IN.
BOW
STERN
MID-OCEAN RIDGE
SPERM WHALES DIVE THIS DEEP.
THEY COME UP COVERED IN WOUNDS AND SUCKER MARKS, SO PRESUMABLY THERE ARE BIG SQUID DOWN HERE?
...MAN, WE KNOW NOTHING ABOUT THE OCEAN.
ALVIN DEPTH LIMIT
ABYSSAL PLAIN
DAVID BOWIE + FREDDIE MERCURY
PUERTO RICO TRENCH
MILWAUKEE DEEP
THE ABYSS
IT'S RUDE TO STARE
MARIANAS TRENCH
CHALLENGER DEEP
MYSTERIOUS DOOR WHICH JAMES CAMERON BUILT HIS SUB TO REACH AND OPEN.
HE WILL NOT SAY WHAT HE FOUND WITHIN.
MARIANAS TRENCH (ACCURATE HORIZONTAL SCALE)
MAUNA KEA, HAWAII (ACCURATE HORIZONTAL SCALE)
OIL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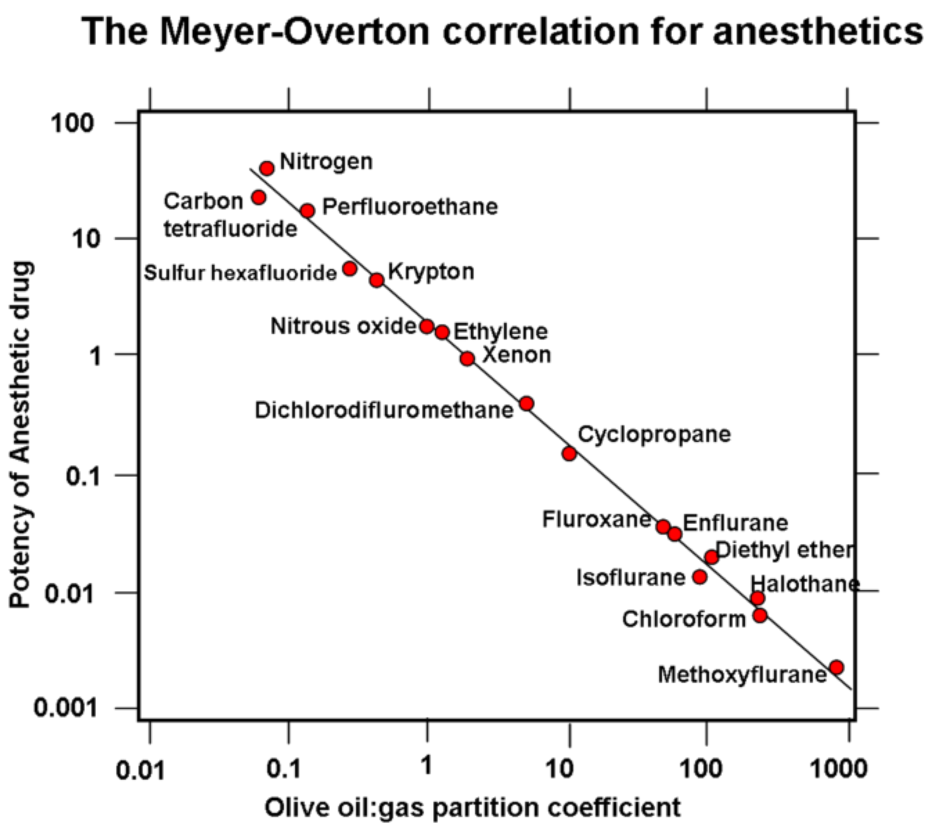
BOW
STERN

Total Air Pressure

Depth (ft)	Pressure (psia:atm)	Pound-force per square foot area
- 53,900 ft	1.47 psia : 0.1 atm	211
- 38,400 ft	2.54 psia : 0.2 atm	365
- 18,000 ft	7.35 psia : 0.5 atm	1,058
0 ft - sea level	14.7 psia : 1.0 atm	2,117
33 ft	29.4 psia : 2.0 atm	4,234
66 ft	44.1 psia : 3.0 atm	6,350
99 ft	58.8 psia : 4.0 atm	8,467
132 ft	73.5 psia : 5.0 atm	10,584
165 ft	88.2 psia : 6.0 atm	12,701

Inert Gas Narcosis

- Symptoms: confusion, impaired judgment, delayed response to stimuli, memory loss, anxiety, euphoria, hallucinations, & unconsciousness
- Symptoms appear at 30m (100ft) and increase in intensity
  - Led to deaths in several divers attempting to go below 120m (400ft)
- Gases dissolve into neuron membranes & interfere with synaptic transmission
  - May specifically antagonize certain receptors or interfere with ion permeability



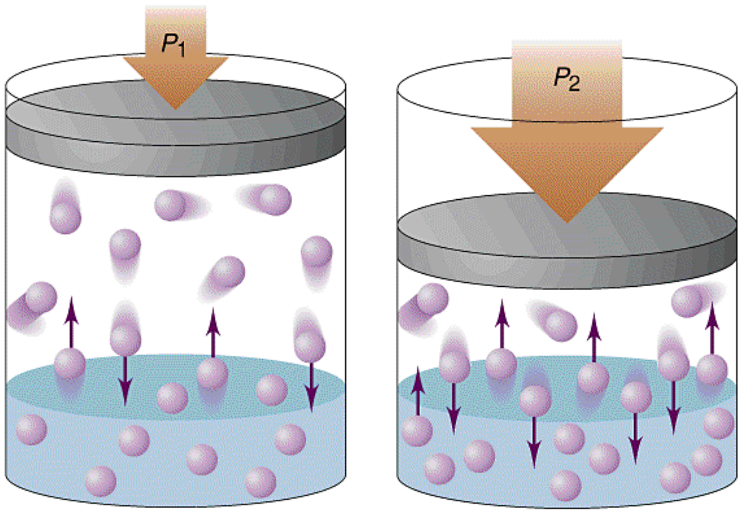
? Why?

Decompression Sickness

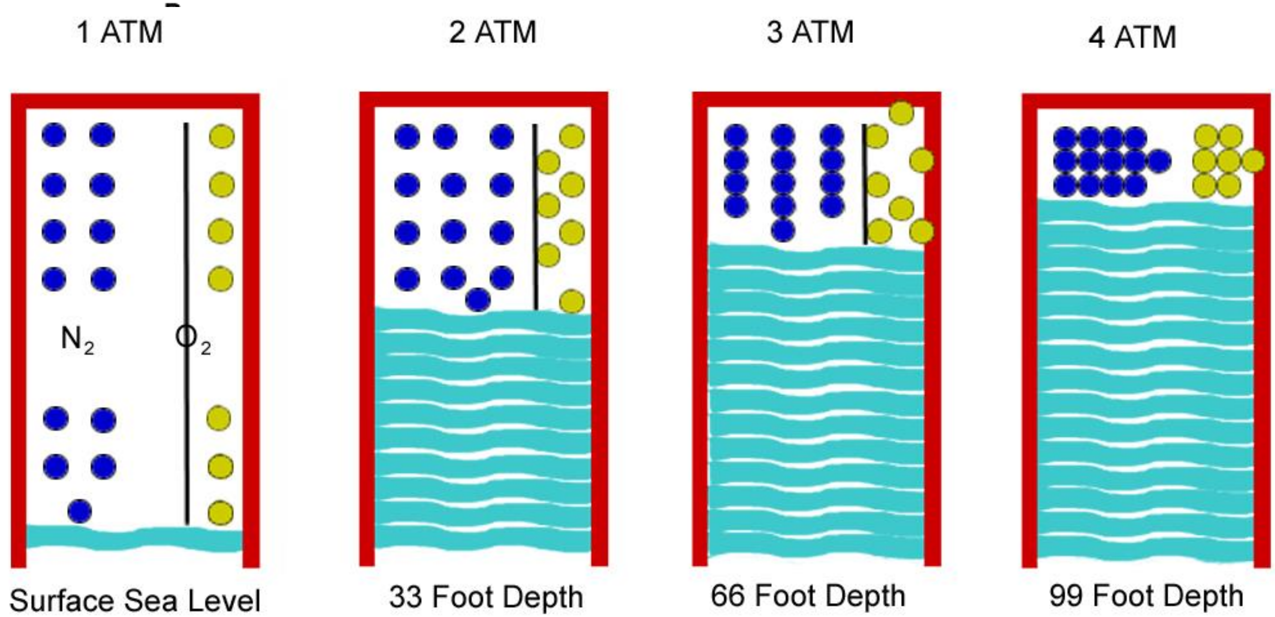
- Symptoms appear in 48 hours following a scuba dive
  - Joint pain ("the bends"), skin itch & rash, dizziness, vertigo, muscle weakness/paralysis, fatigue, headache, pulmonary distress, hypovolemic shock
  - During ascent, lag occurs before saturated tissues start releasing gases back into the blood
- Arterial gas embolism: gases expand, rupture lung tissue, & release gas bubbles into circulation, which may block arteries
  - NS symptoms: dizziness, blurred vision, muscle weakness/paralysis, unconsciousness, seizures
- Can reduce risk with saturation diving or 100% O_2 prebreathing

? Why?

Blood Gases



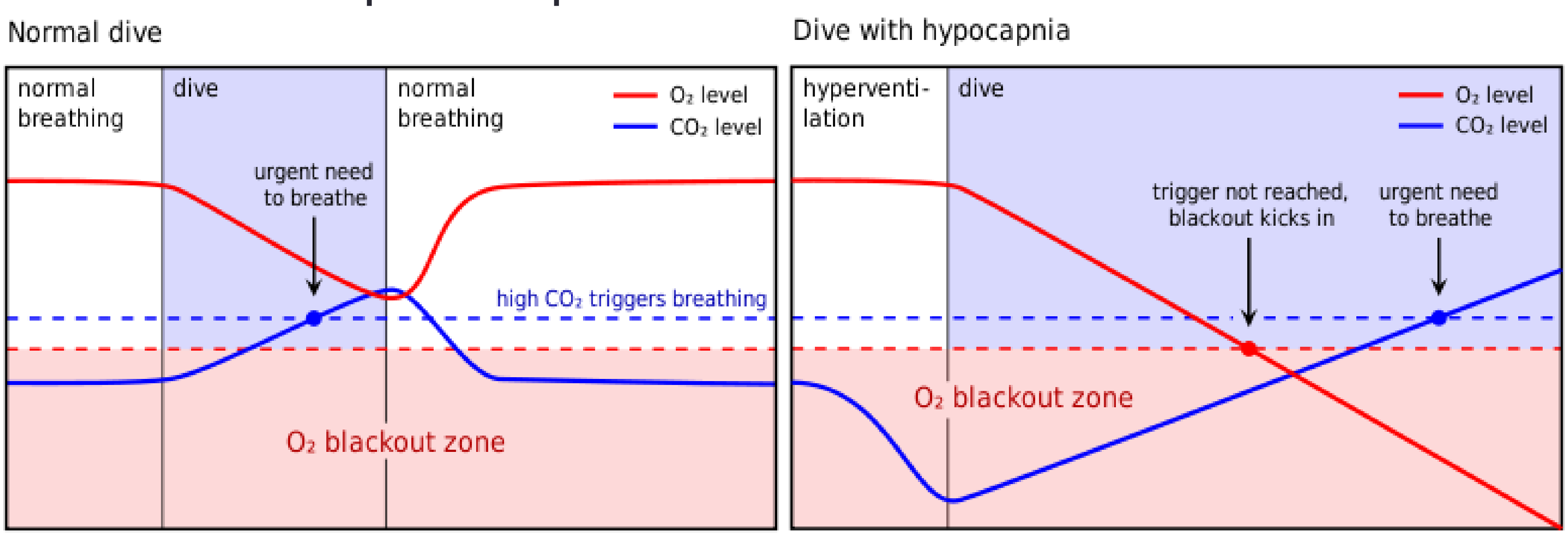
- Henry's Law: c = k*P
- Boyle's Law: $P_1V_1 = P_2V_2$



Shallow Water Blackout

? Why?

- Cerebral hypoxia near the end of a breath-hold dive
- Hyperventilation depletes CO_2 saturation (hypocapnia), but does not increase O_2 saturation
- CO_2 increases $[H^+]$, dropping blood pH and triggering a chemoreceptor response

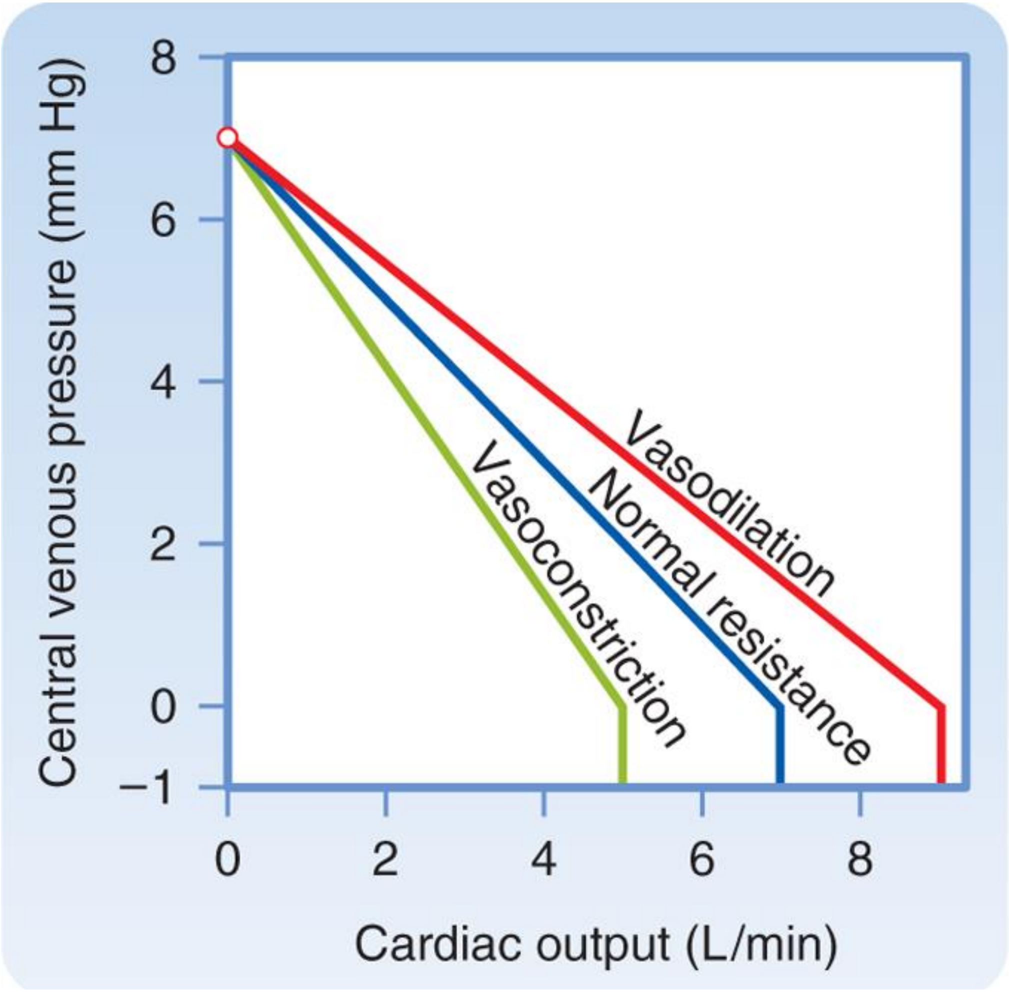


Japanese Pearl Divers (Ama)

Oxygen Conservation Reflex

- Cardiovascular
  - Bradycardia (trigemino-cardiac reflex) increases CBF via cariovagal motor medullary pathway
  - Peripheral vasoconstriction → ↓ BF to skin, ↓ CO, & ↑ MAP
  - Baroreceptor stimulation further decreases heart rate
  - ↑ Hematocrit
- Metabolism
  - ↓ blood pH
  - Low muscle perfusion → shift to anaerobic metabolism → ↑ organic acids (like lactic acid)

? How does this conserve oxygen?

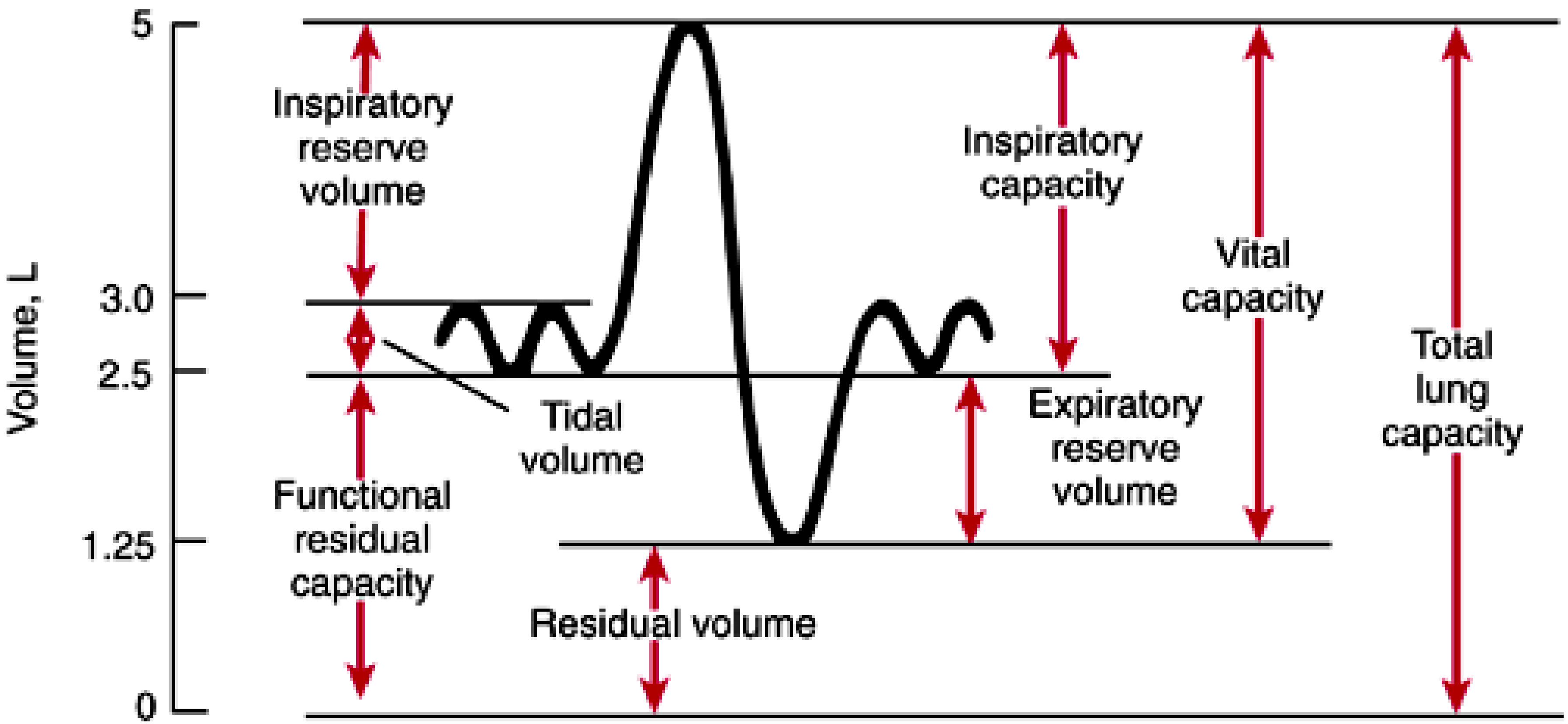


Central venous pressure (mm Hg)
8
6
4
2
0
−1
0
2
4
6
8
Cardiac output (L/min)
Vasodilation
Normal resistance
Vasoconstriction

Diving Adaptations

- Thermal regulations
  - Lower critical water temperature
  - Higher metabolic rate
  - Peripheral vasoconstriction
- Blunted ventilation response to hypercapnia
- 15% higher vital capacity than non-diving peers
- Bradycardia as low as 20bpm

Lung Capacity



Deep Sea Animals

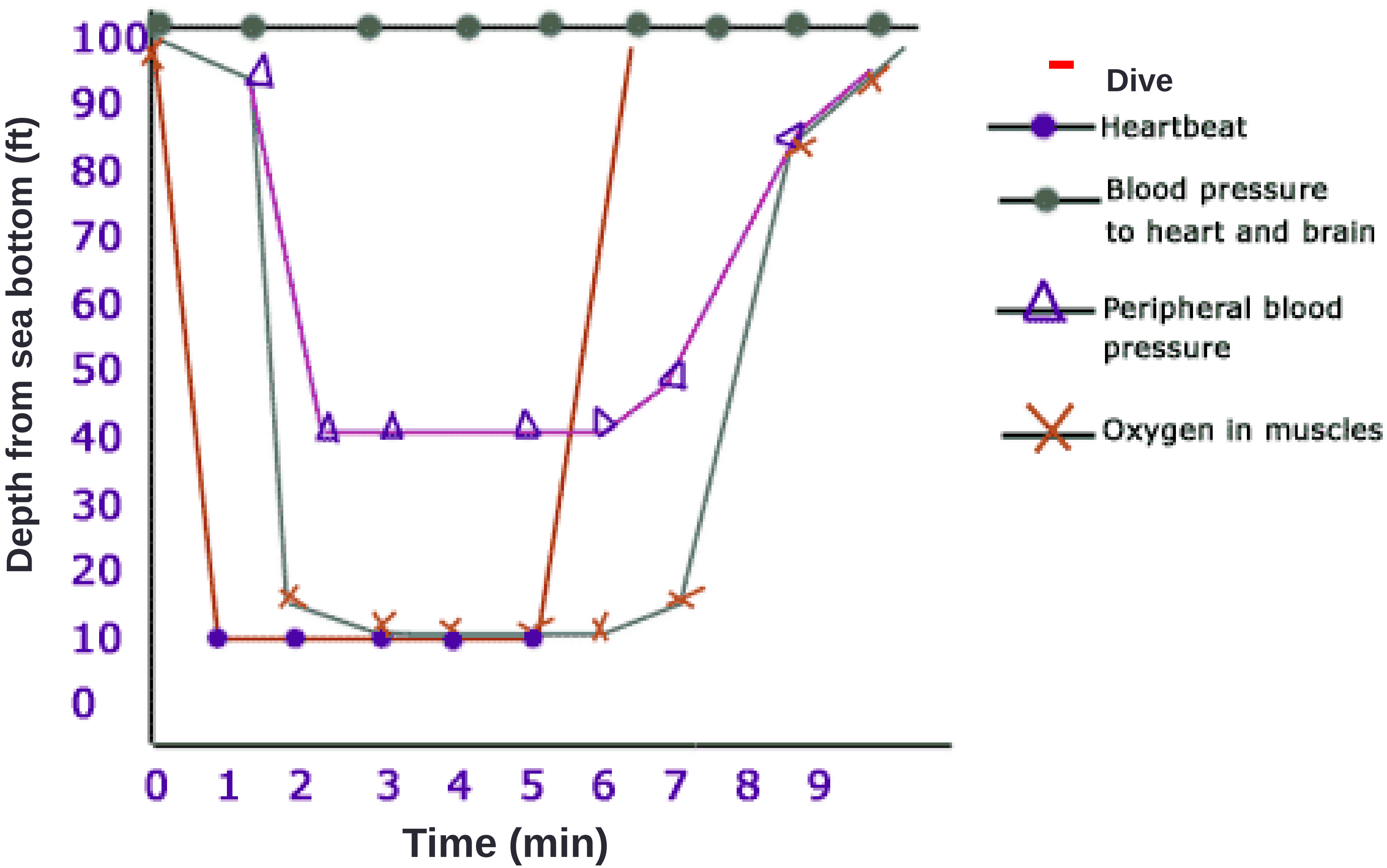
Mammalian Diving Reflex

- Three parts:

  - Apnea
  - Bradycardia
  - Peripheral Vasoconstriction

Additional part in marine mammals:

  - Blood Shift

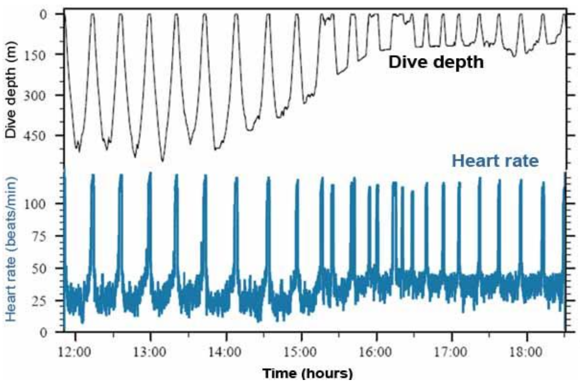

100
90
80
70
60
50
40
30
20
10
0
Depth from sea bottom (ft)
0
1
2
3
4
5
6
7
8
9
Time (min)
Dive
Heartbeat
Blood pressure to heart and brain
Peripheral blood pressure
Oxygen in muscles

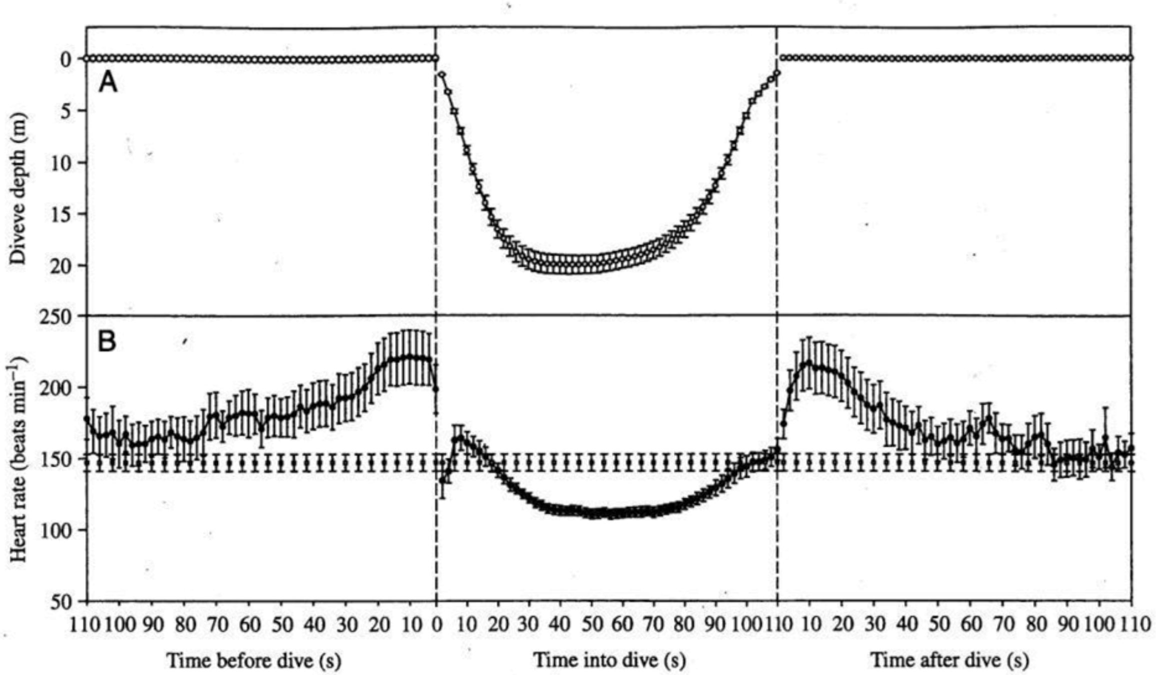
Mammalian Diving Reflex: Apnea

- Apnea: Temporary stop in breathing
- Stimuli: Receptors on face
    - Trigeminal nerve
- Prevents aspiration of water

Mammalian Diving Reflex: Bradycardia

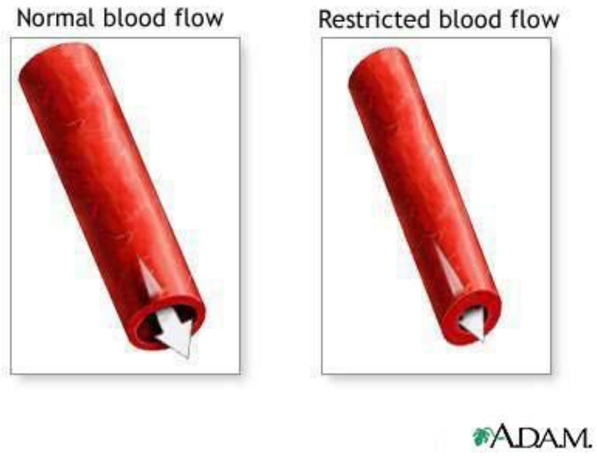
- Heart Rate Slows
  - Humans: 70% Pre-dive HR v. Marine Mammals: 5% Pre-dive HR





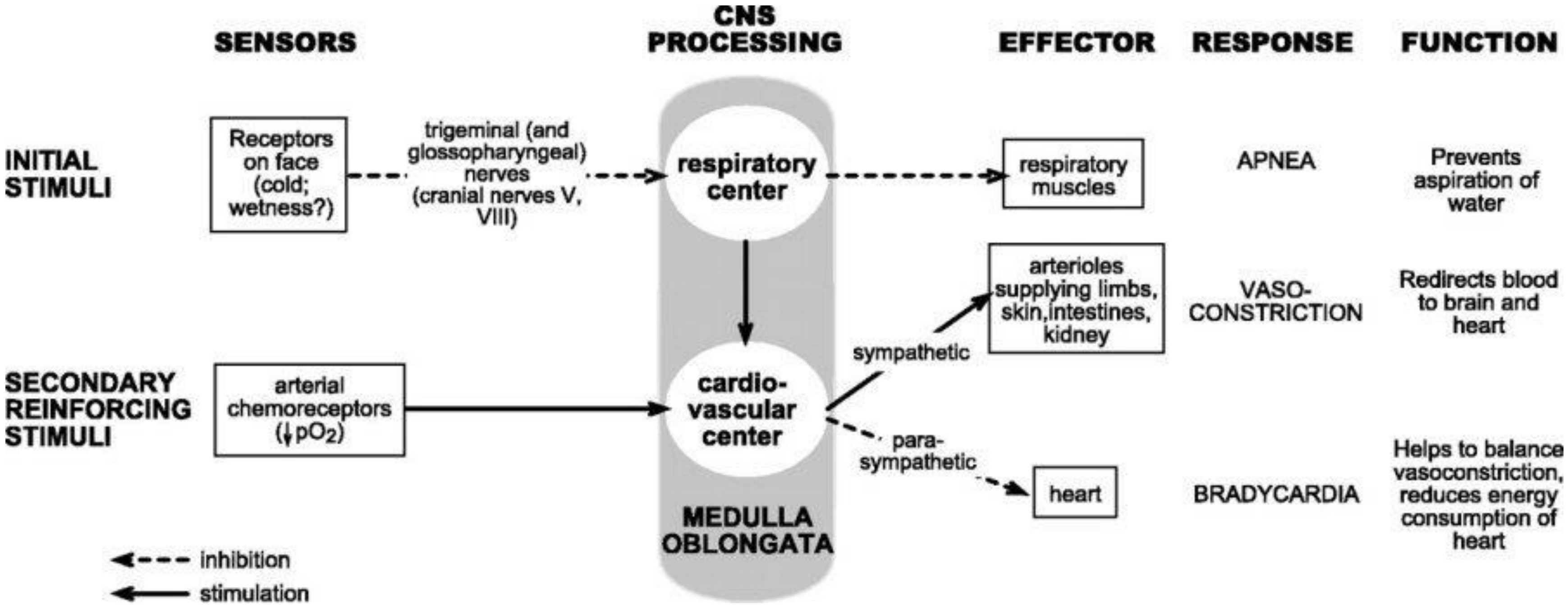
Mammalian Diving Reflex: Vasoconstriction

- Arteries constrict to limit blood flow to viscera and muscles
- Lactic Acid is blocked



? Why do you want to block lactic acid?

Mammalian Reflex Overview



Specialized Mammalian Diving Response

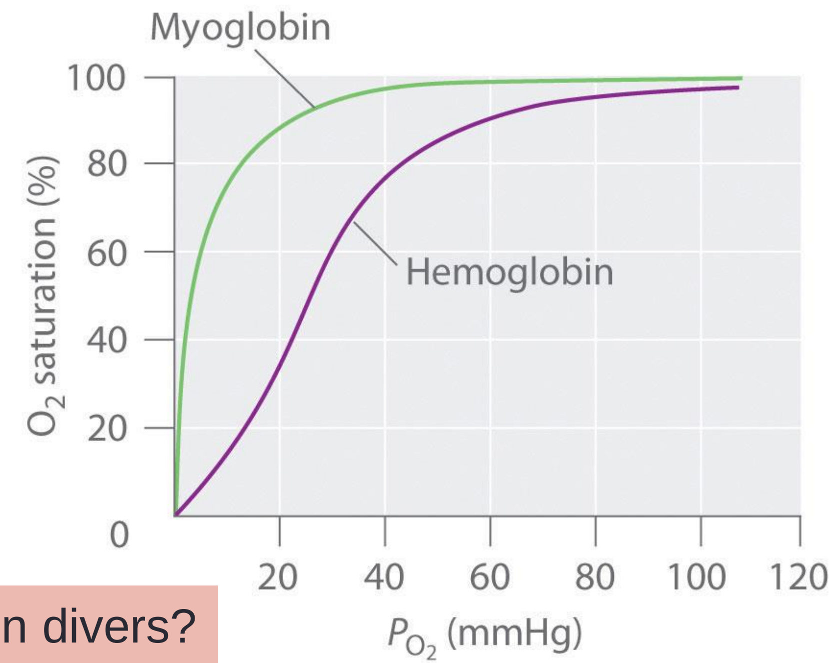
- Blood Shift
  - Blood vessels in the periphery contract leaving more blood volume in the torso
  - Creates a pressure differential in the lungs→ which leads to an influx of venous blood into the lung cavity

? If blood is directed away from the legs why is this beneficial? (Hint: Where will they get energy?)

  - Prevents “lung squeeze” by filling the capillaries of the alveoli

Hemoglobin and Myoglobin

- Comparison:
  - Terrestrial Mammals:
    - 14-17 g hemoglobin / 100 mL blood
    - 1 g myoglobin / 100 g muscle
  - Marine Mammals:
    - 21-25 g hemoglobin / 100 mL blood
    - 3-7 g myoglobin / 100 g muscle



? Why is Hb elevated in long-duration divers?

Oxygen Stores

- Main oxygen stores are in the blood and muscles

- Determinants of the rate of blood O2 storage depletion
  - Changes in heart rate
  - Accompanying changes in renal and splanchnic blood flow
  - Degree of muscle perfusion during diving

Species	mL O_2 kg^{-1}	Lung %	Blood %	Muscle %
Human	20	24	57	15
Odontocetes	35	22	30	48
Otariids	40	13	54	33
Phocids	60	7	65	28
Sea Otter	55	55	29	16
Manatee	21	33	60	7

Aerobic Diving Limit (ADL)

Amount of time an animal may spend diving before an increase in blood lactate levels occurs

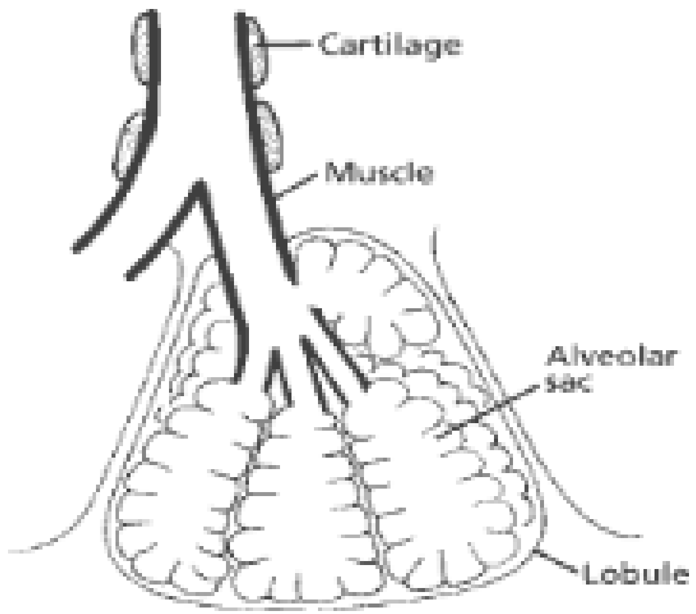
Factors:

- Oxygen Store Depletion Rates
- Lowest Tolerable Level of Blood Oxygen Store

cADL = [total blood oxygen stores (in blood/muscle/lung) / oxygen demand]

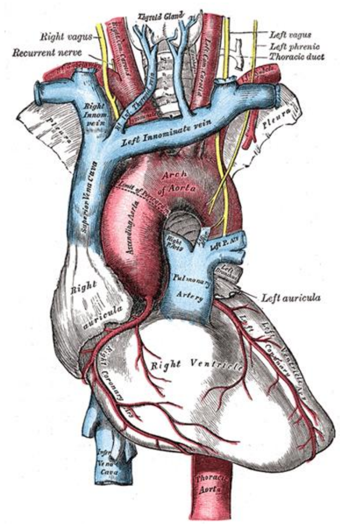
Respiratory Adaptations

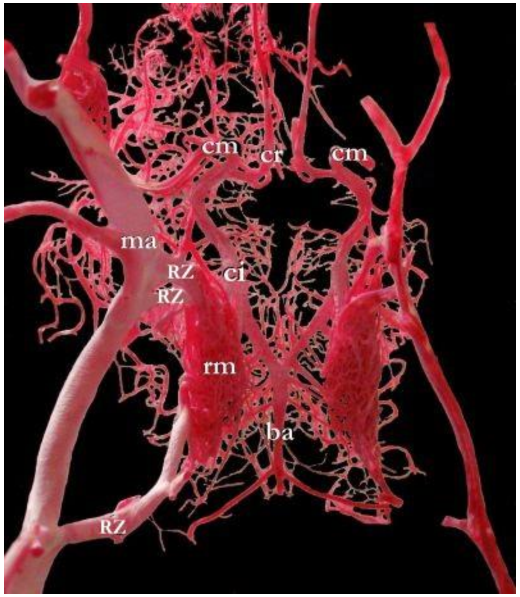
- Rigid Airways
- Collapsible Lungs with Flexible Chest Walls
- Vascularized Alveoli
- Sphincter Muscles



Cardiovascular Adaptations

- Changes in Heart Rate and Cardiac Output
- Vasoconstriction
- Aortic Bulb Expansion
- Retia Mirabilia





Increased Blood Volume

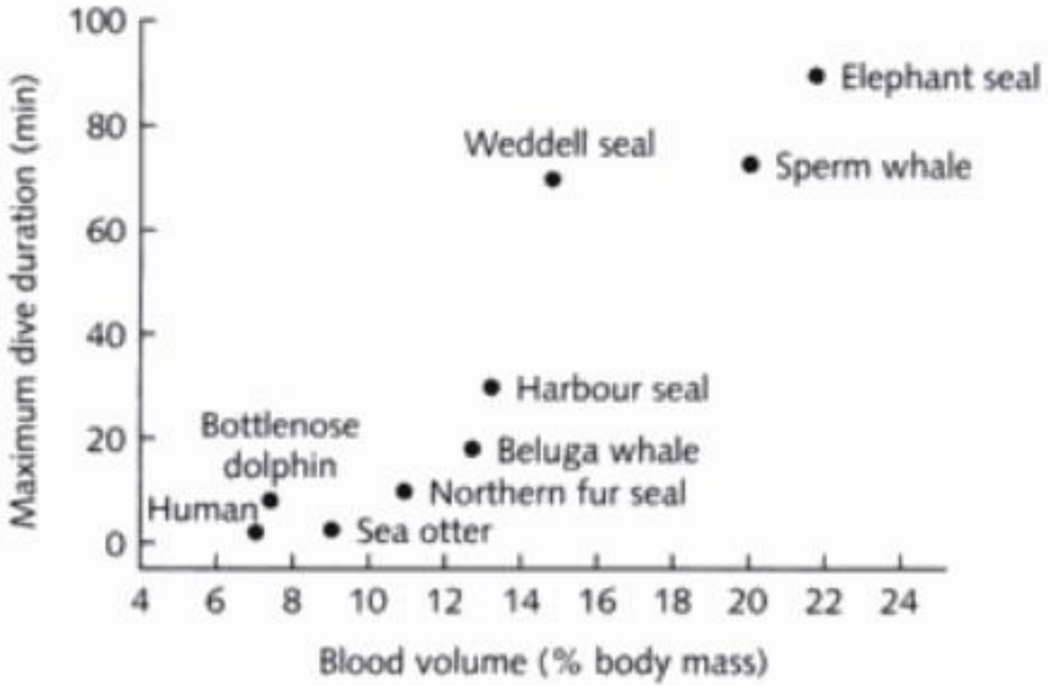
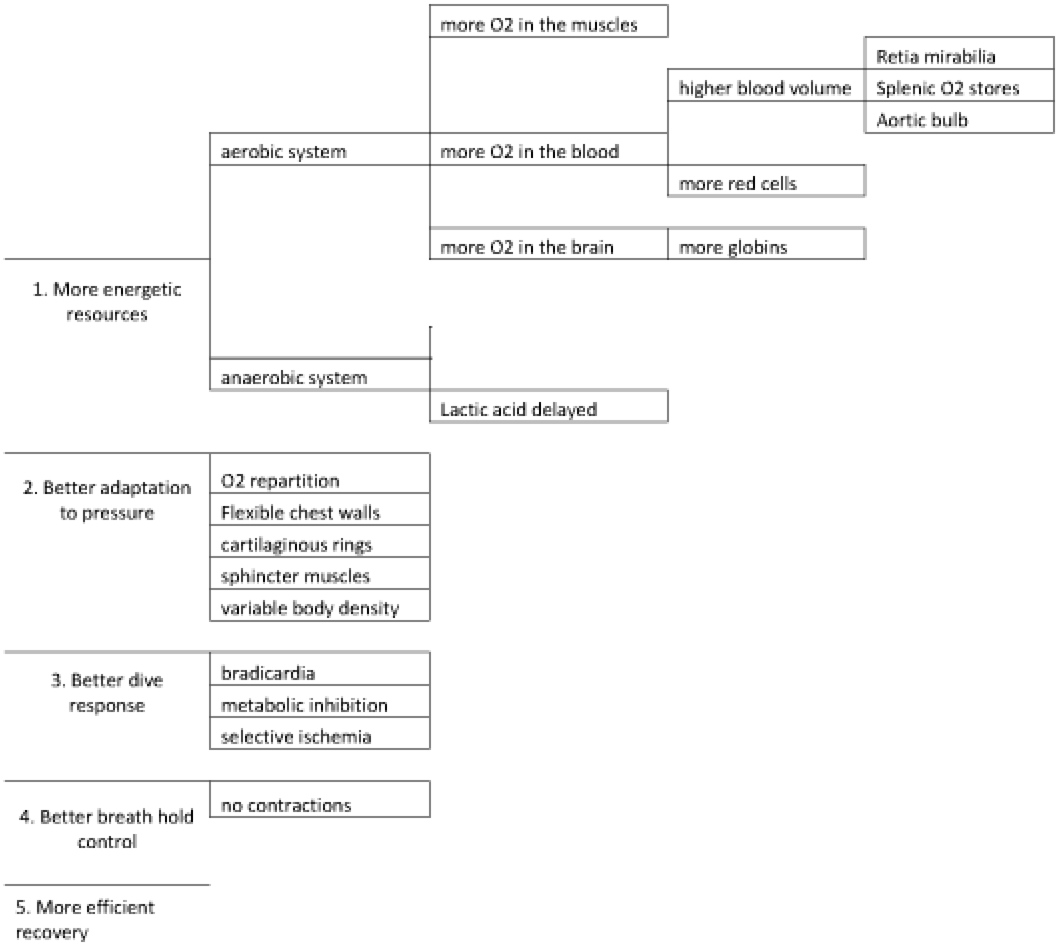


Fig. 3.8 Blood volume of marine mammals as a percentage of body mass in relation to maximum dive duration. (Data from Kooyman 1989.)

Advantages

- Efficient ventilation
- Enhanced oxygen storage
- Regulated transport and delivery of gases
- Extreme hypoxic tolerance
- Pressure tolerance

Review


more O2 in the muscles
Retia mirabilia
higher blood volume
Splenic O2 stores
Aortic bulb
aerobic system
more O2 in the blood
more red cells
more O2 in the brain
more globins
1. More energetic resources
anaerobic system
Lactic acid delayed
2. Better adaptation to pressure
O2 repartition
Flexible chest walls
cartilaginous rings
sphincter muscles
variable body density
3. Better dive response
bradicardia
metabolic inhibition
selective ischemia
4. Better breath hold control
no contractions
5. More efficient recovery

Sea Otter

Maximum Depth: 100 m

Maximum Duration of Breath Hold: 4 min

Otter Adaptations

- Partially calcified trachea rings
- Densest fur of all mammals
- Larger chest volume

Weddell Seal

Maximum Depth: 626 m

Maximum Duration of Breath Hold: 82 min

Seal Adaptations

- Higher concentration of oxygen is stored in myoglobin
- Efficient O_2 Storage
- Higher Blood Volume
- Spleen Adaptations
- Kidney Adaptations

Consequences for Immature Animals

- Young mammals have difficulty diving beyond very shallow depths.

?

What biological phenomena could reduce their ability to dive?