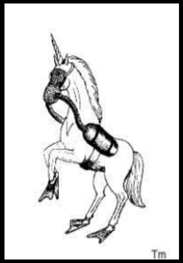
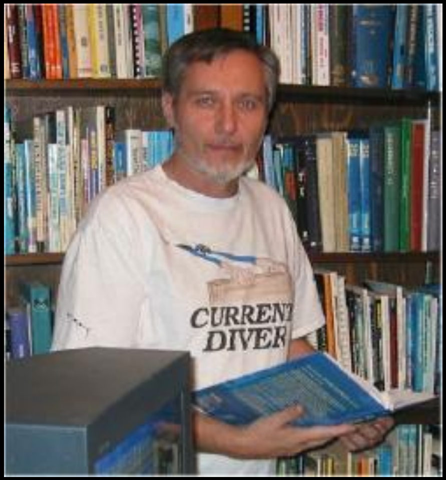
Dive Physiology

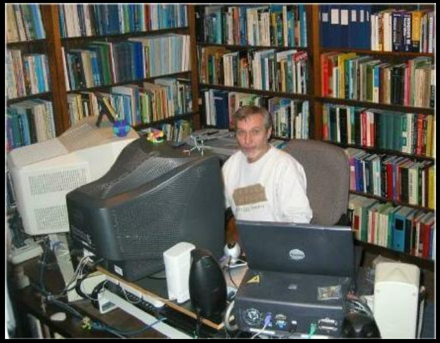
LPT

Your Instructor

U of MI Diving Safety Coordinator
AAUS sanctioned Diving Safety Officer
Internationally rated 3 - star instructor (CMAS)
National Master Scuba Instructor (President's Council)
> 100 Diving Certifications
> 200 Diving Publications
> 1,200,000 visitors to "Diving Myths & Realities" web site
Library: one of the best resources in North America
Scuba Diver since 1977
Scuba Instructor since 1980
DAN Instructor since 1991
EAN_x Instructor since 1992
Ph.D. Biochemistry







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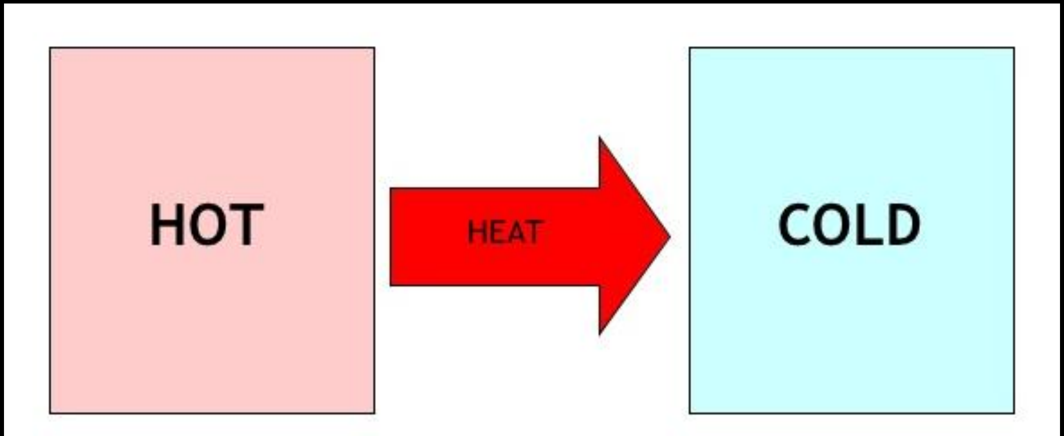
Heat

Heat is a Fluid



Flows from hotter to colder
until
temperatures are equal

Cannot stop movement
Protection comes from slowing process

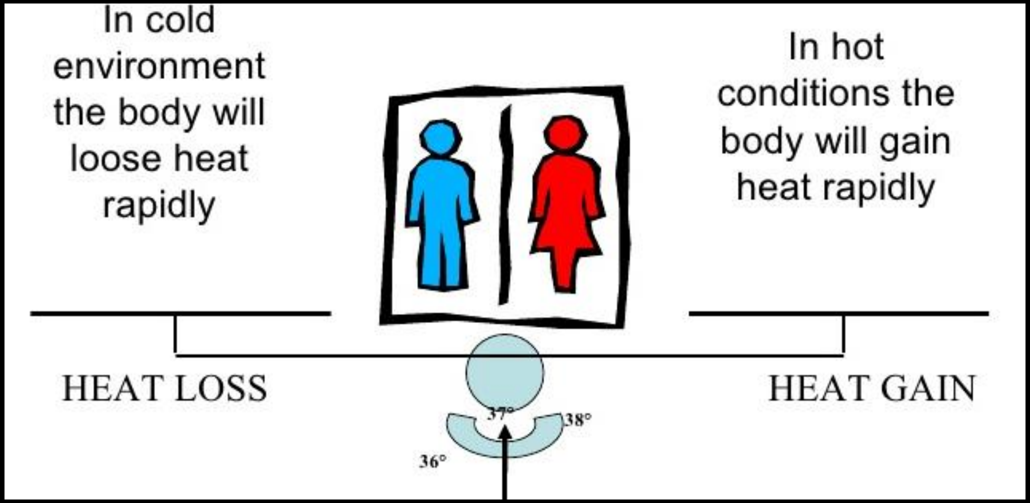
Thermal Balance

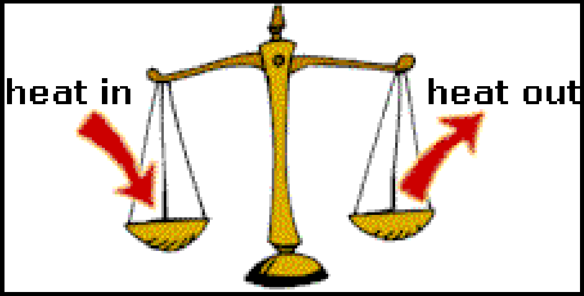
Heat Out:

Environment
- **Conduction**
- **Convection**
- **Radiation**

Cooling
- **Respiration**
- **Perspiration**
- **Excretion**

Disease





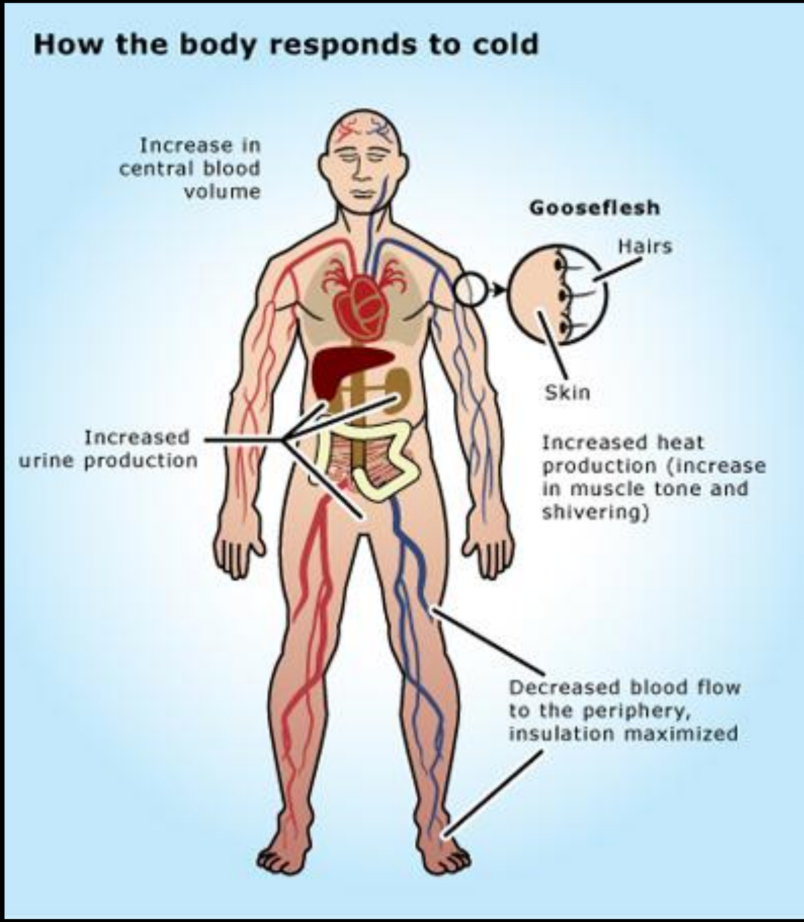
Heat In:

Metabolism

Muscle Movement

Environment
- **Conduction**
- **Radiation**

Humans are Tropical Critters
Better coping with heat than cold



Hot	Cold
Vasodilation Arterioles dilate (enlarge) so more blood enters skin capillaries and heat is lost.	**Vasoconstriction** Arterioles get smaller to reduce blood going to skin: keeping core warm.
Sweating Sudorific glands secrete sweat which removes heat when water changes state.	**Shivering** Rapid contraction and relaxing of skeletal muscles. Heat produced by respiration.
Pilorelaxation This means the hairs flatten.	**Piloerection** Hairs on skin stand up.
Stretching Out By opening up, the body was a larger surface area.	**Curling Up** Making yourself smaller so smaller surface area.

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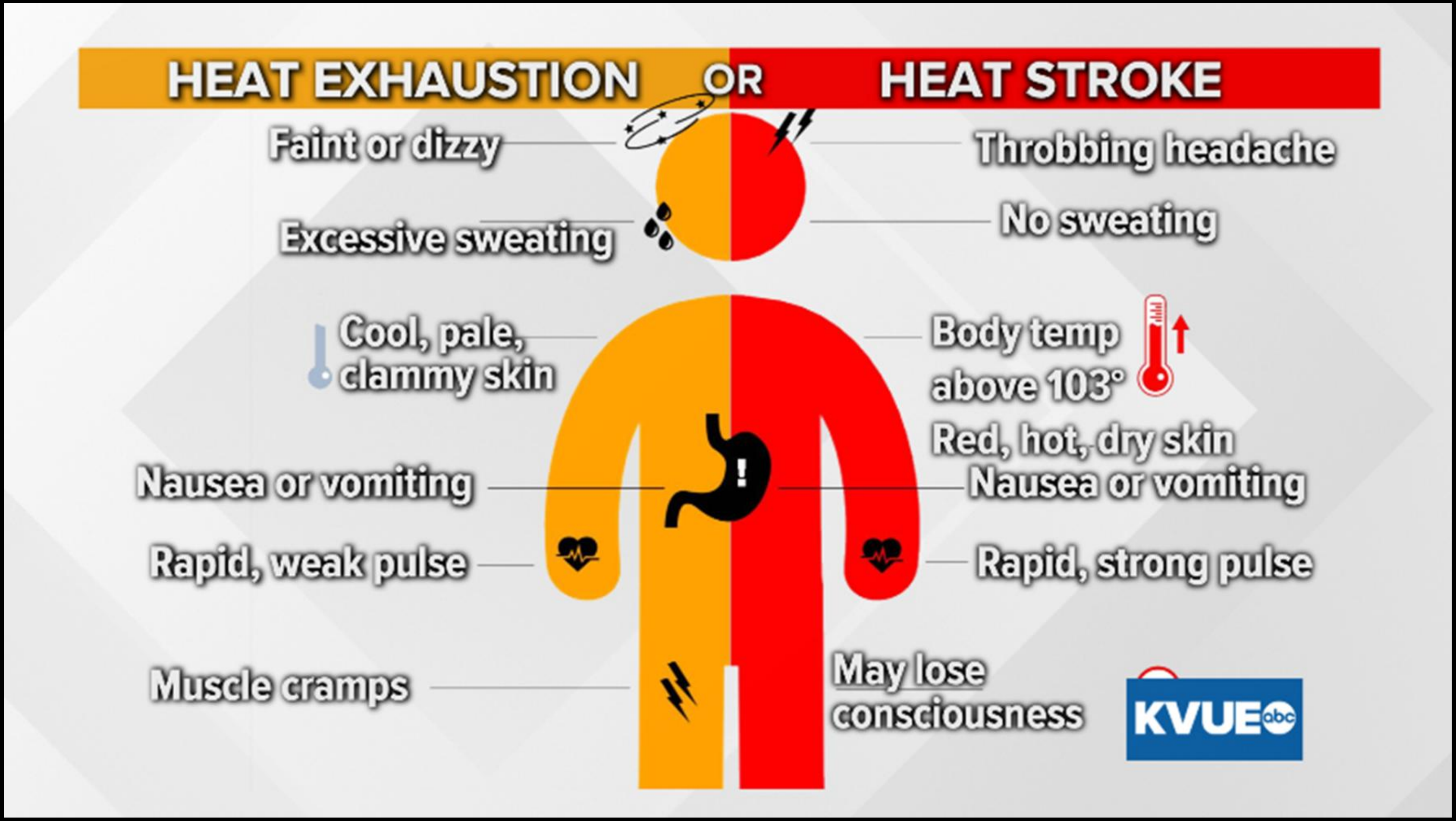
Hyperthermia

Hyperthermia

Body temperature too high



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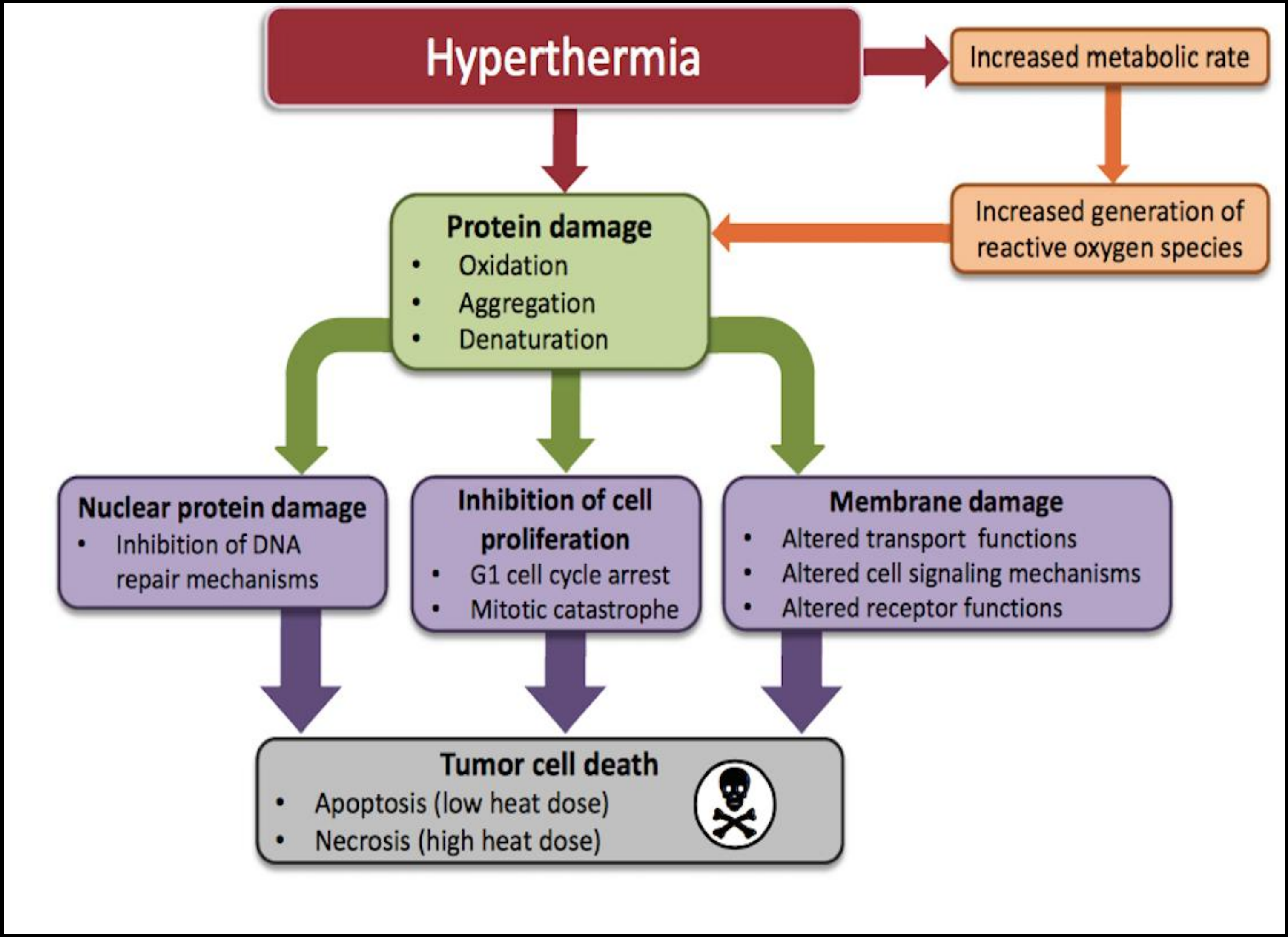
Hyperthermia: Symptoms

Hyperthermia: Biochemistry



Hypothermia

Must Understand Heat Loss to Protect From the Cold

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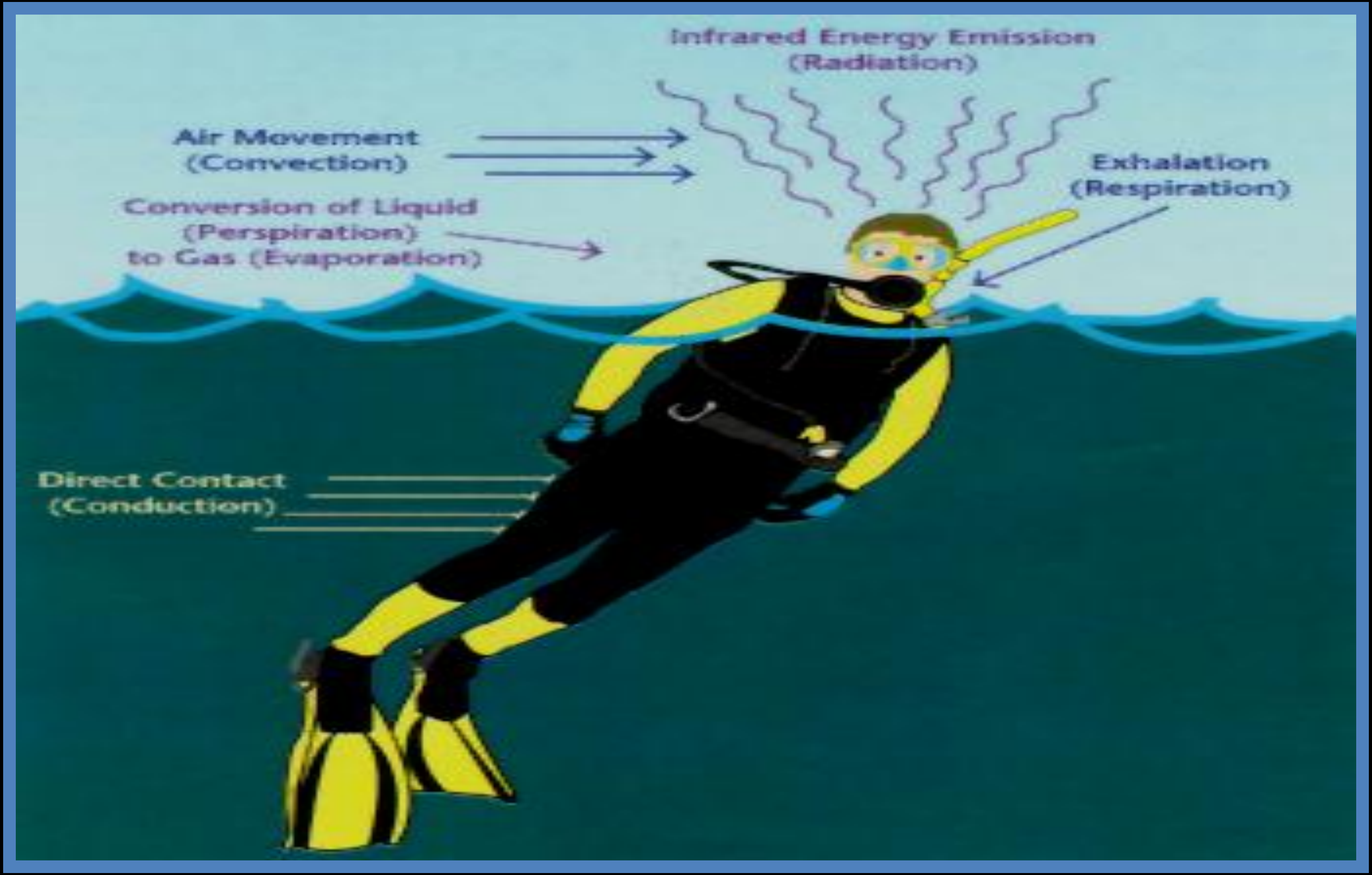
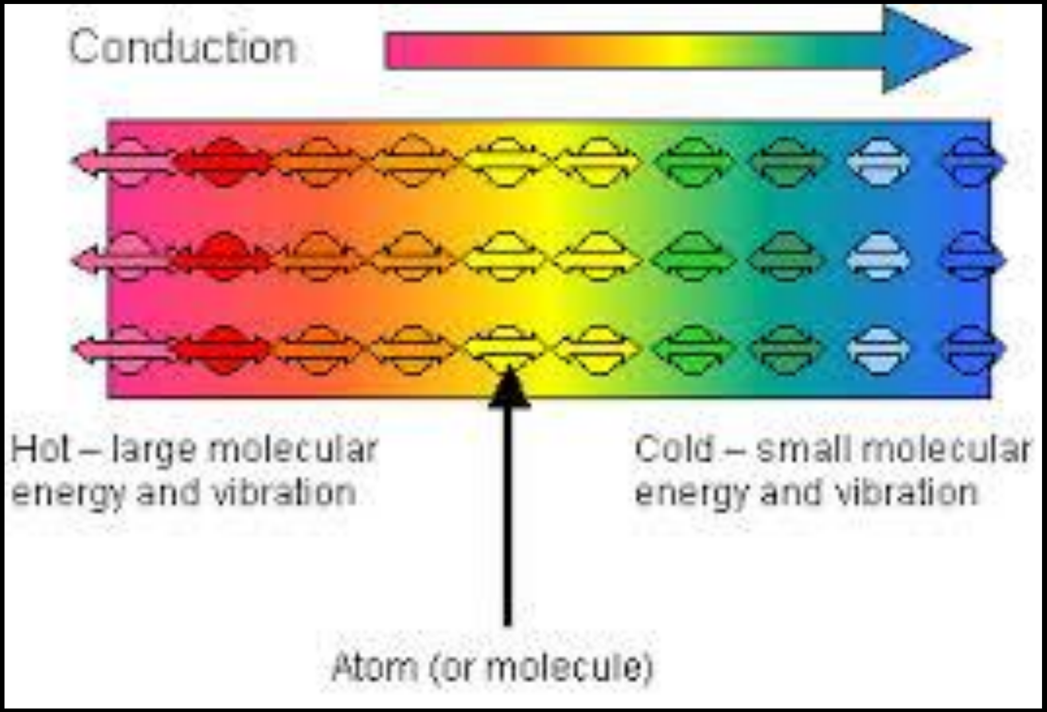
Ignoring (or Not Understanding) Heat Loss

It is always the "not known" that poses the greatest risk

In-Water Heat Loss



Thermal Loss: Conduction

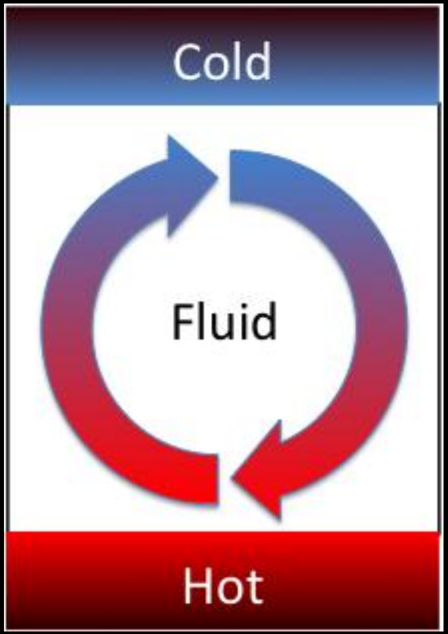


Water removes heat
~ 25 x faster
than dry, still air
at same temperature

Direct transfer of energy at the molecular level

- Major source of in-water heat loss
  - Heat loss to water
  - Heat loss warming breathing gas

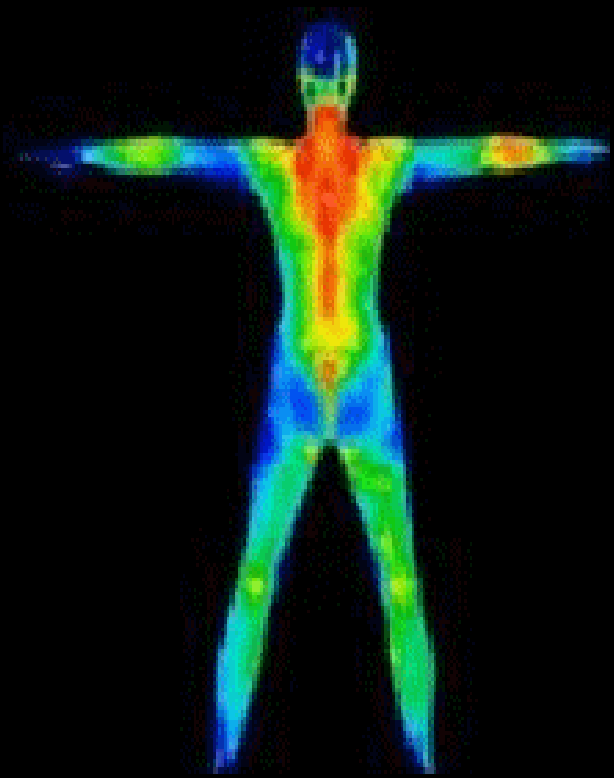
Thermal Loss: Convection



Moving liquid removes heat
Continual process

Wet suits restrict convective flow

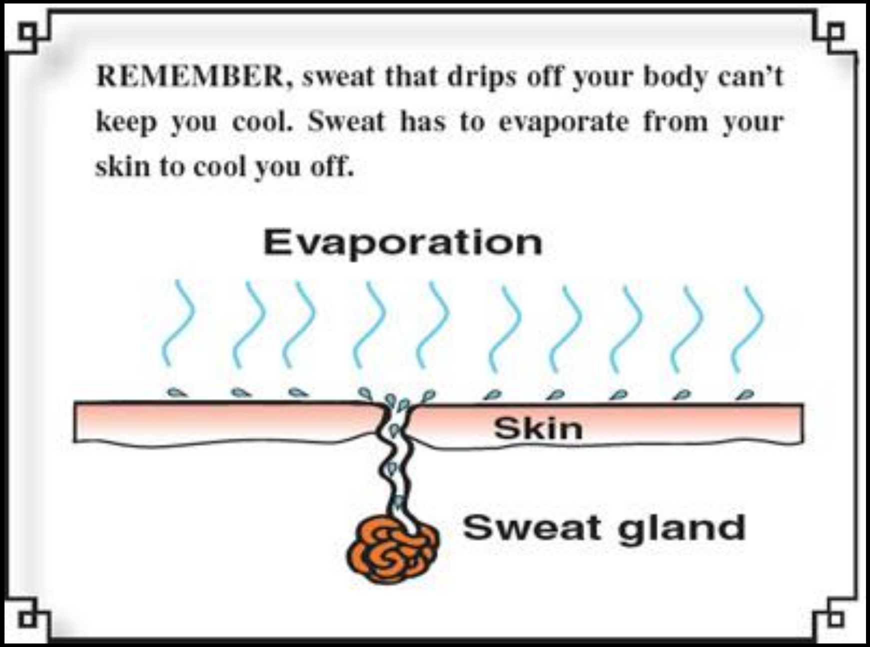
Thermal Loss: Radiation



Emission of infra red radiation

Minor problem in the water

Thermal Loss: Evaporation / Respiration



Change of state:
Liquid → gas
Requires energy

9.72 kcal / mole

Pre-dive sweating
Insensible perspiration
Humidifying dry breathing gas

Simplistic View of a Biochemist:

Heat = Life

Cold Robs Heat

No Heat = No Life

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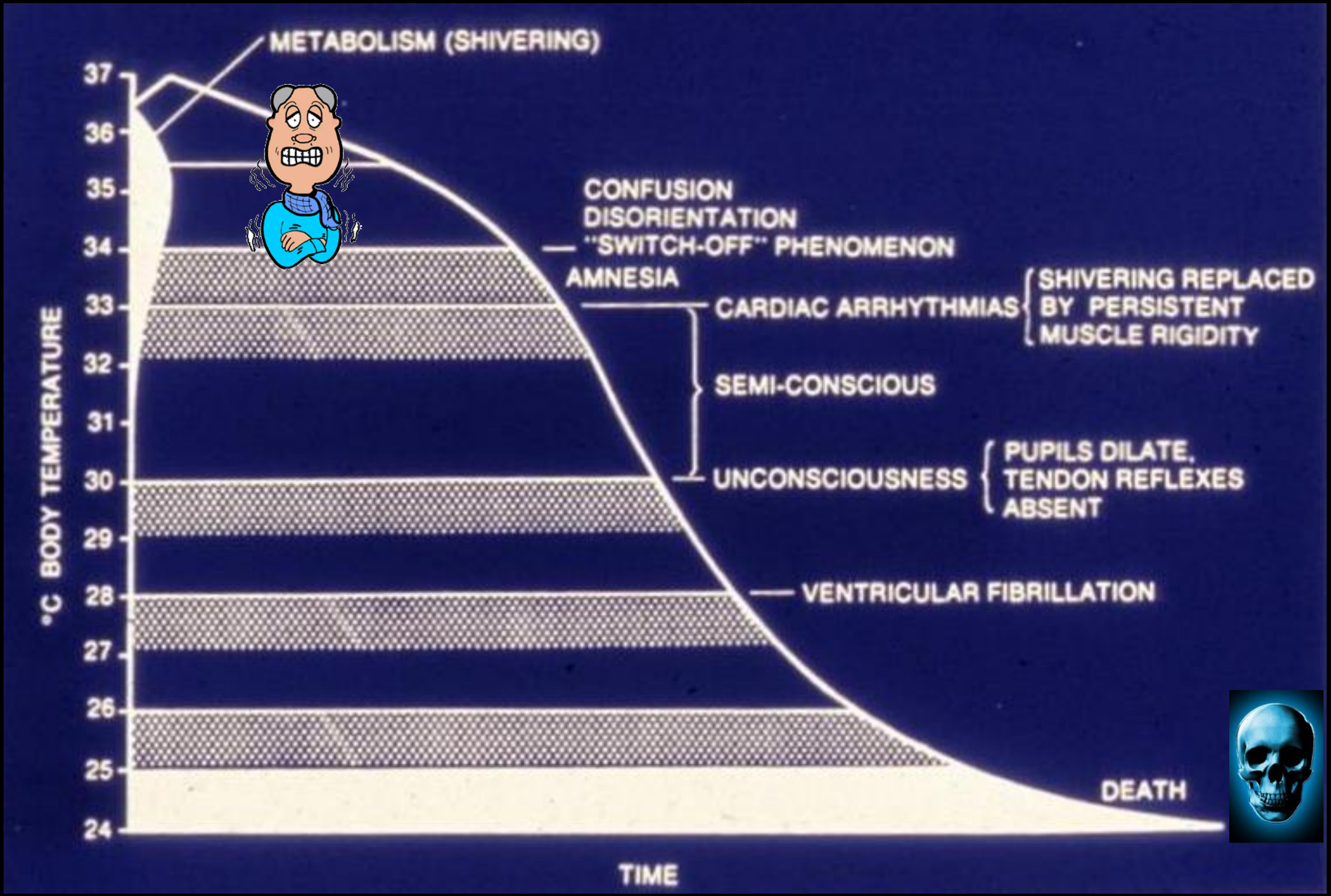
Body Response to Temperature Loss



First Shiver: Abort the dive!

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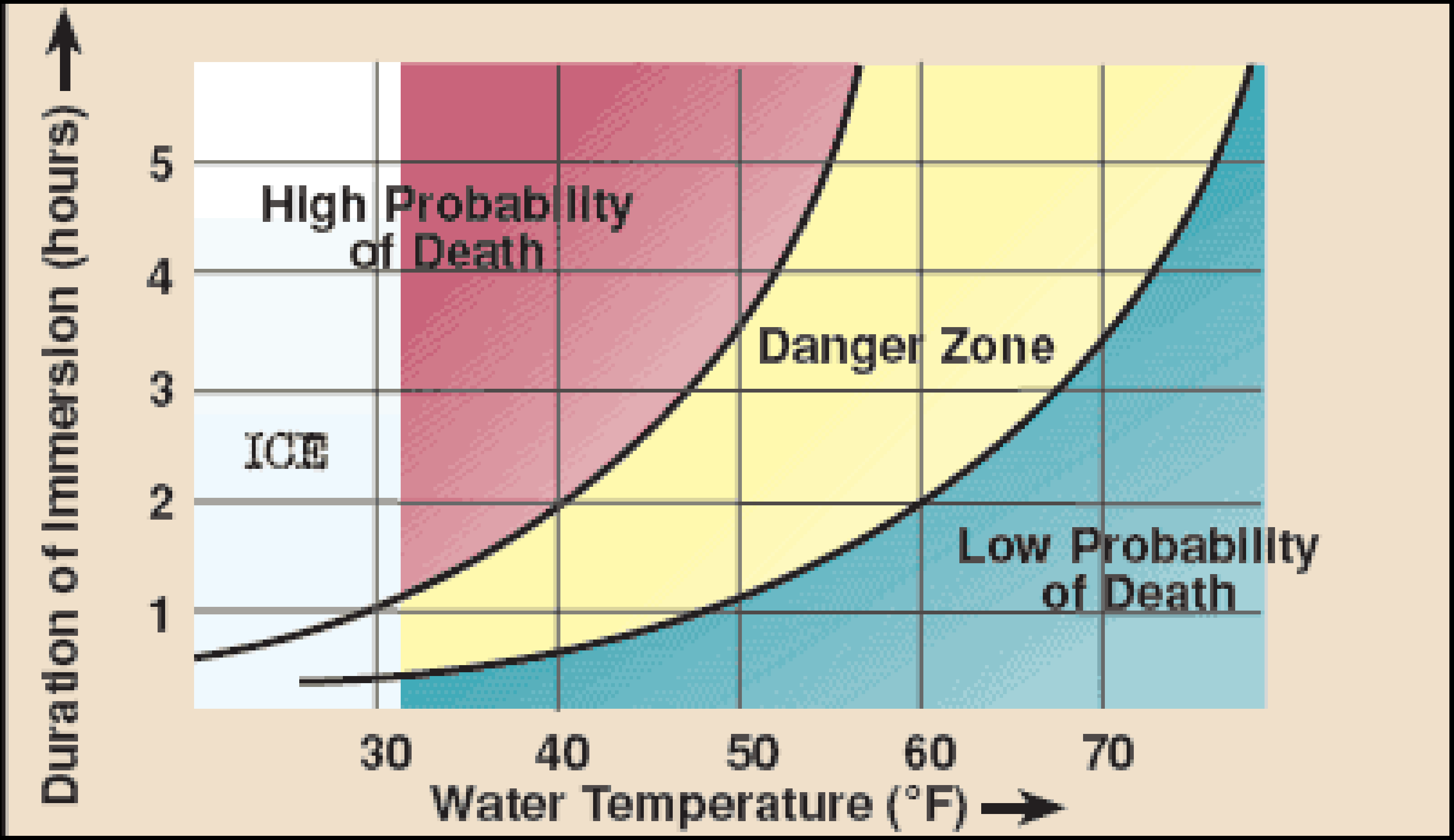
Estimated Unprotected In-Water Survival Time



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Wind Chill Can Lead to Substantial Heat Loss

Wind Chill Chart

Wind (mph)	Temperature (°F)																	
Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Frostbite Times: 30 minutes / 10 minutes / 5 minutes

$$\text{Wind Chill (°F)} = 35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T= Air Temperature (°F) V= Wind Speed (mph)

Effective 11/01/01

Cold

Cold:

Major physiological stressor

Major obstacle to diving participation

Major obstacle to limited bottom time

Thermal protection is part of life support

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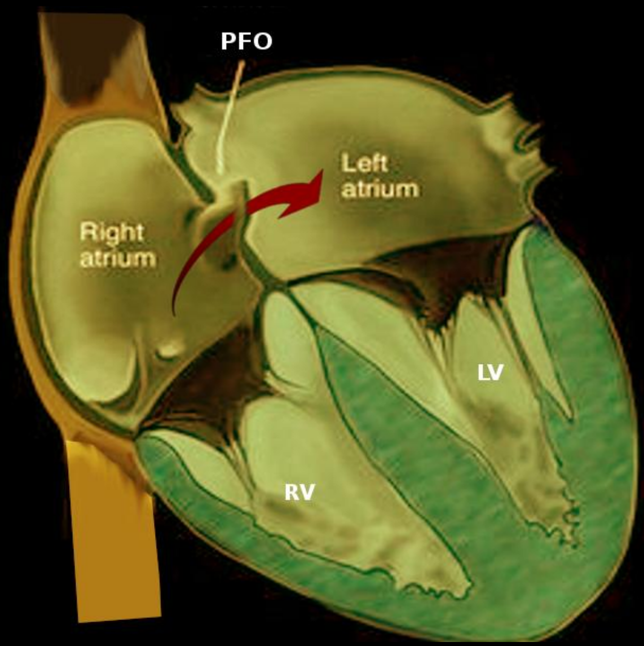
Patent Foramen Ovale



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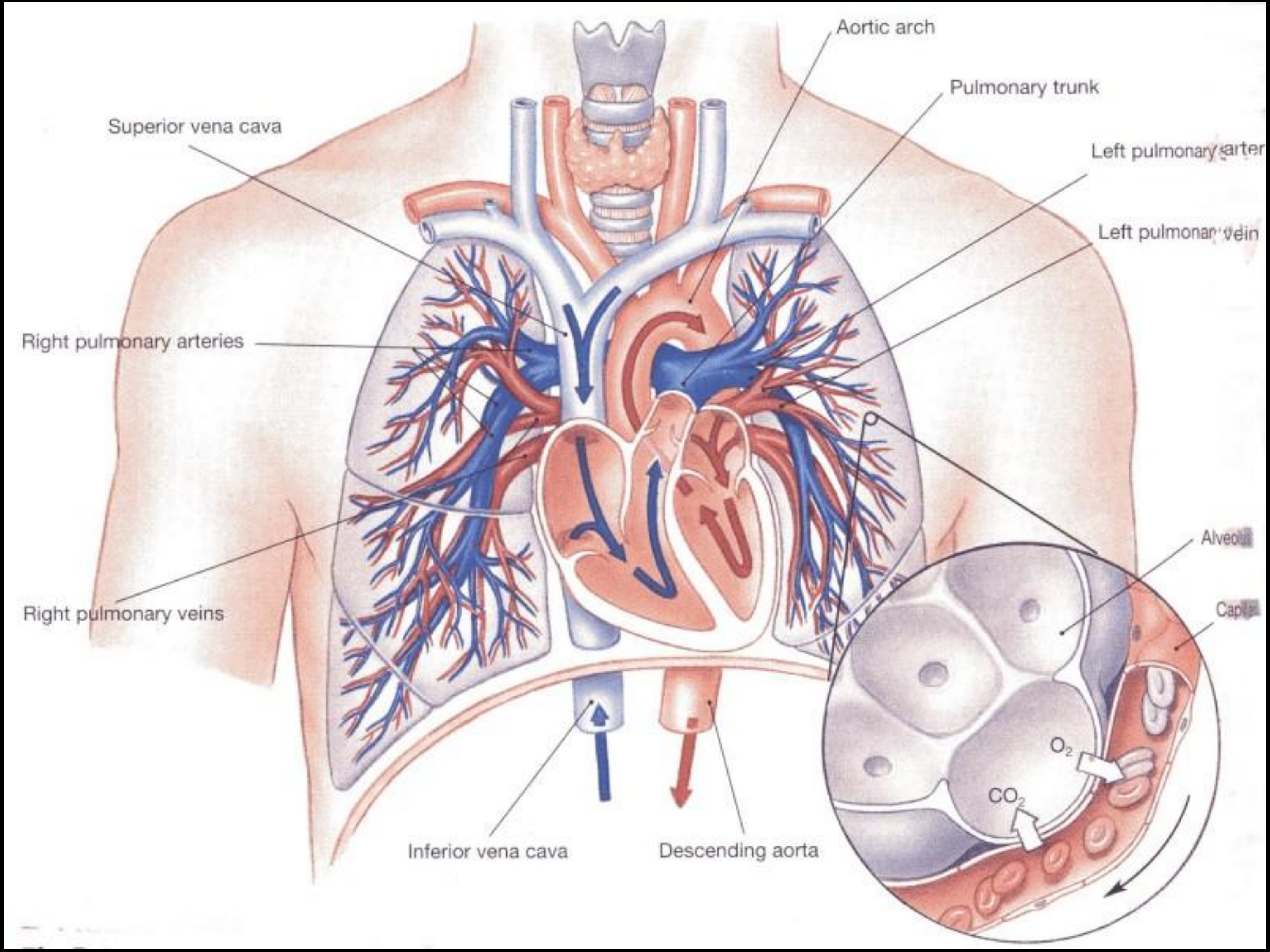
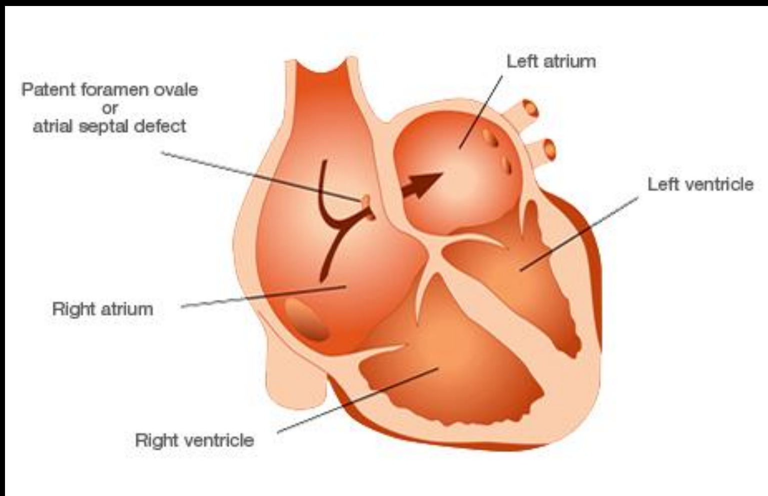
General Heart-Lung Circulation



Patent Foramen Ovale

Opening in septum secundum



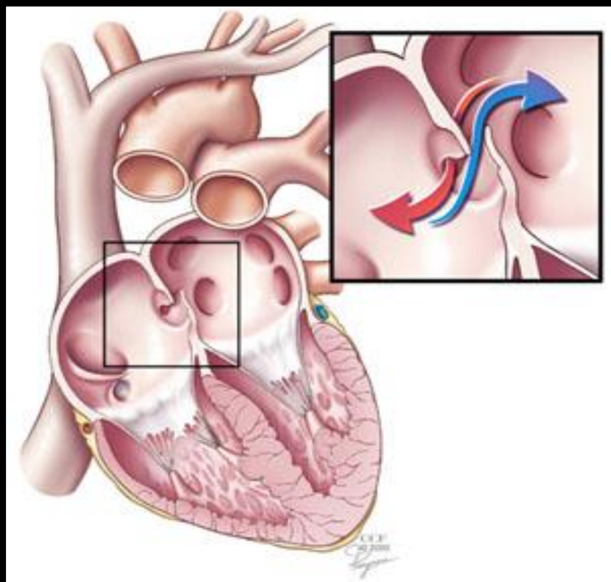
Patent: open
Foramen: aperture in tissue or bone
Ovale: oval shaped

Present in:
Unborn (mom functions as lungs)
~25 – 30 % of population
~ 6% large opening
~ 5% of serious DCS cases

PFO:
Some blood flow bypasses the lungs (bubble filter)
Bubbles in circulation: can pass into arterial circulation
(Best to assume we bubble on every dive ascent)
Possible source of CNS lesions seen in brain and spinal cord

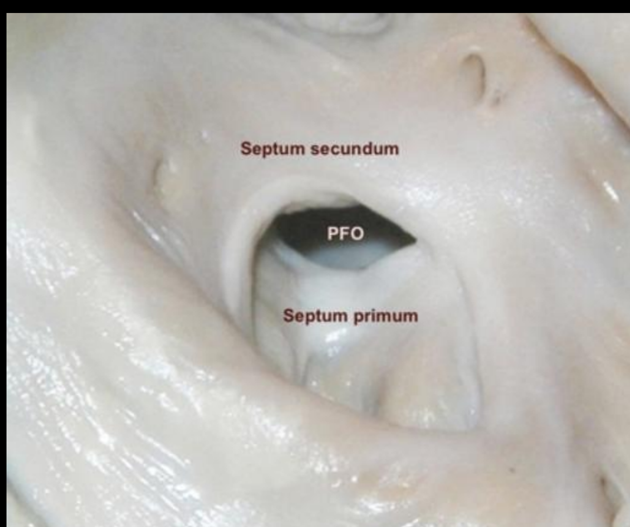
PFO: Allows Direct Path to Arterial Circulation

Bubbles can move into arterial circulation

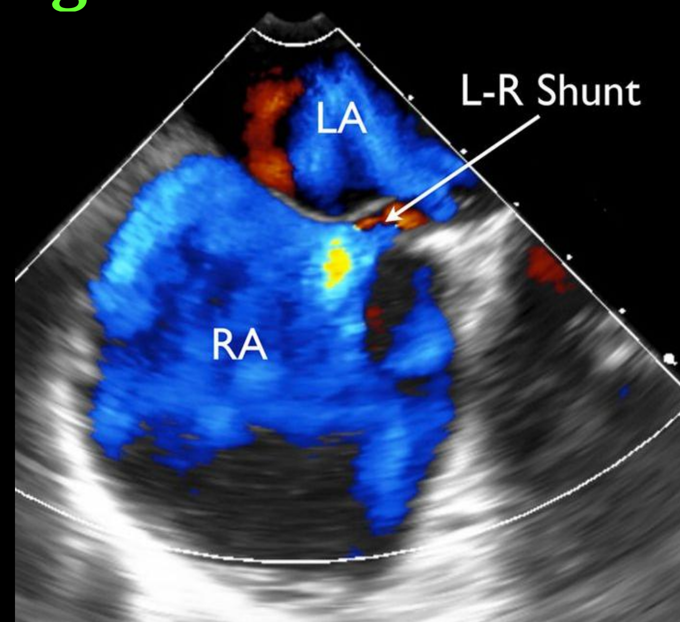


Can lead to:

- CNS lesions
- Severe neurological DCS
- Air embolism on descent



Diagnosed with Ultrasound



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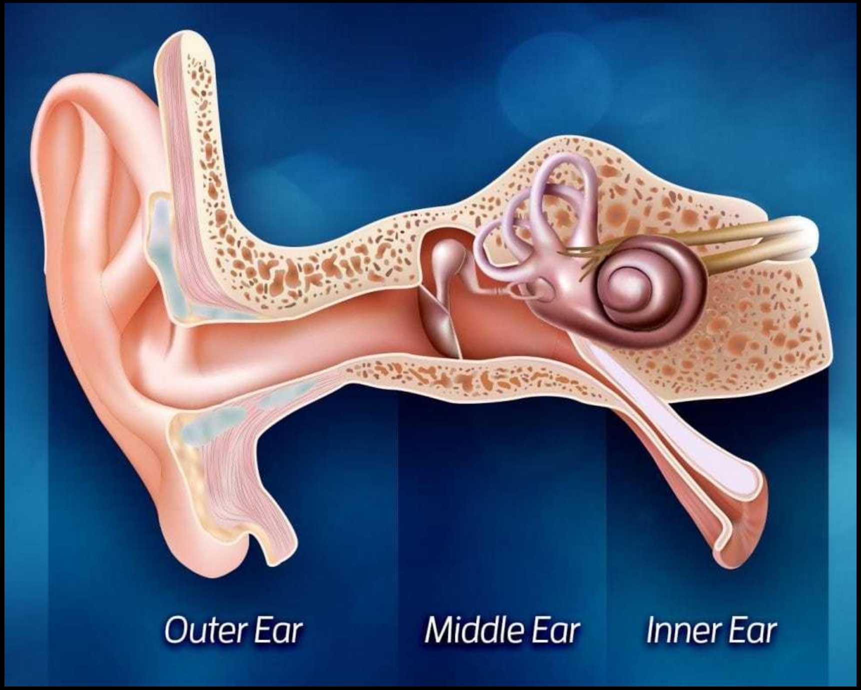
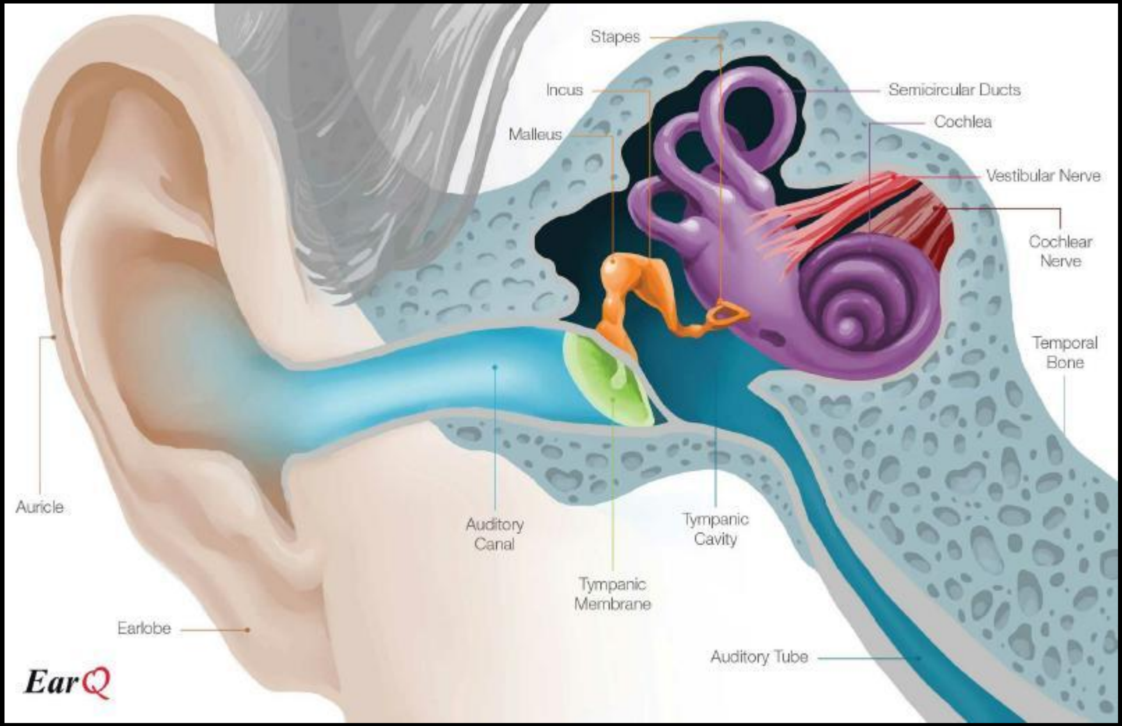


Ear Issues

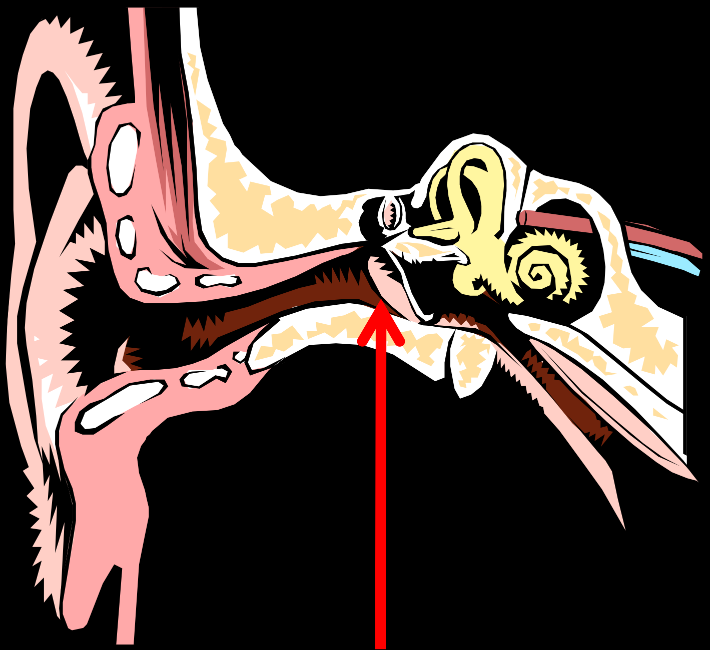
“Clearing” The Ears



> 80 % of basic students suffer ear barotrauma on first open water
George Hapur (Canadian Hyperbaric Physician)

Equalizing (“Clearing”) Middle Ear Pressure

“Clearing” equalizes pressure across the tympanic membrane



Tympanic Membrane
Separates Outer and Middle Ear
Transmits Vibrations to Middle Ear

On Descent:
Outer Pressure > Middle Ear Pressure
Tympanic Membrane Moves Inward

On Ascent:
Middle Ear Pressure > Outer Pressure
Tympanic Membrane Moves Outward

Too much movement (~ 8 fsw change) can rupture the ear drum
Possible ear infection from water entering the middle ear

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“Clearing” Techniques:
(Most often a problem on descent)

Common Techniques:
Valsalva: Pinch nostrils and blow
Toynbee: Pinch nostrils and swallow

For all descents:
- Start prior to descent
- Slowly move feet first
- Look up

If feeling pressure:
- Ascend a bit to relieve
- Extend jaw forward

Do NOT swallow
- Air in stomach can expand on ascent
- This can rupture the stomach

The Valsalva Maneuver

Pinch Nostrils and Gently Blow
Most Taught Technique

Vigorous Valsalva - Dangerous technique

Builds Internal Pressure
Transmitted via CSF to Brain
Possible Round Window Rupture
Can drive bubbles thru PFO (if present)
Possible air embolism on descent
Can Constrict Eustachian Tubes

Frenzel Technique

Developed During WWII For German Stuka Pilots

Rapid pressure increase during descent
Pilots needed both hands on control stick
Frenzel developed for hands free clearing

Frenzel Technique

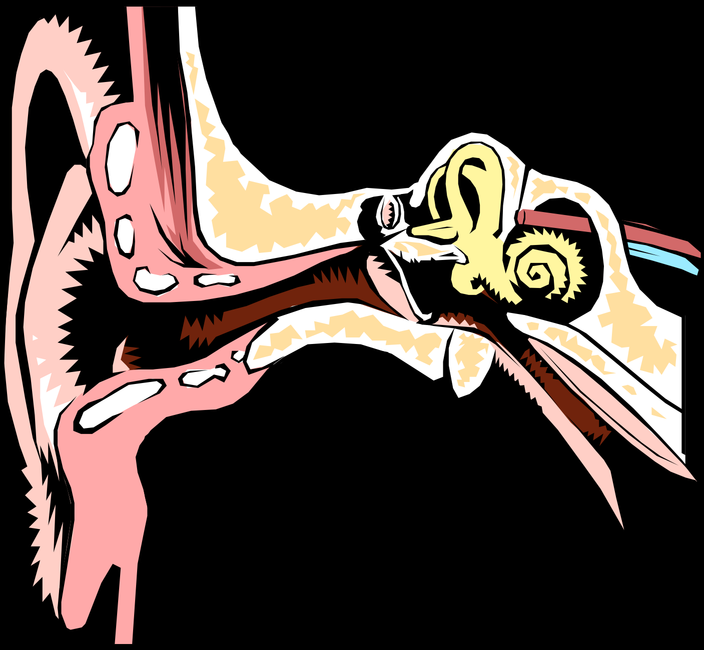
Hands Free Equalization of Ear Pressures

Place tongue on the roof of the mouth… as far forward as possible
Hold tongue there
Imagine (‘cause you can’t physically do this):
  Driving the tongue through the top of your head
The “ tongue flick” sends a gentle flow of air up the Eustachian tube

You should hear a “click” in each ear
  From the air flow hitting the back of the tympanic membrane

Avoids all the issues with Valsalva
Safest method of equalizing ear pressures

“Clearing” While Ascending



Valsalva is opposite of need

Need to decrease middle ear pressure

Pinch nostrils and gently suck

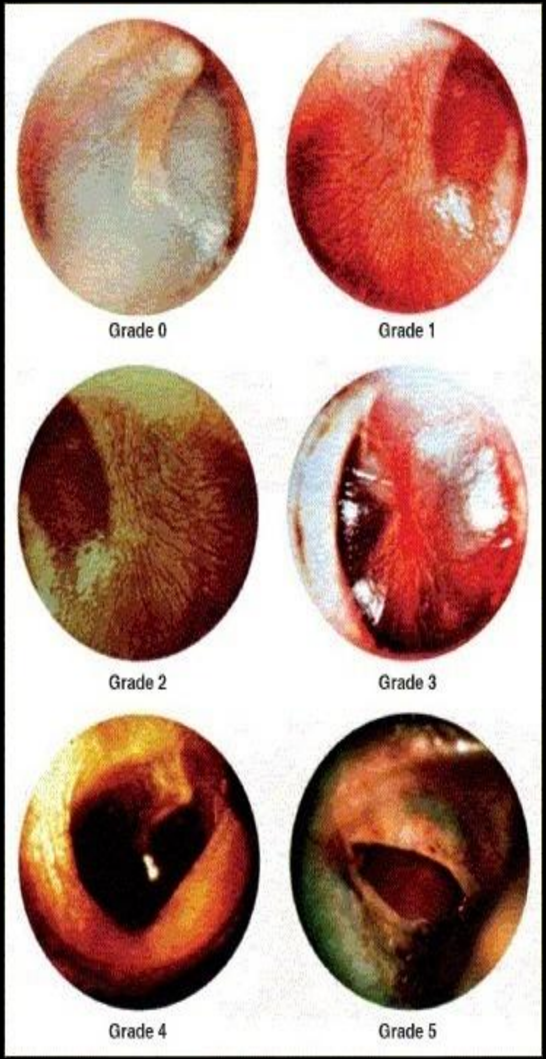
Middle Ear Barotrauma

Symptoms of mild ear barotrauma:
pain in the ear
difficulty hearing or mild hearing loss
dizziness
feeling of fullness and pressure in the ear

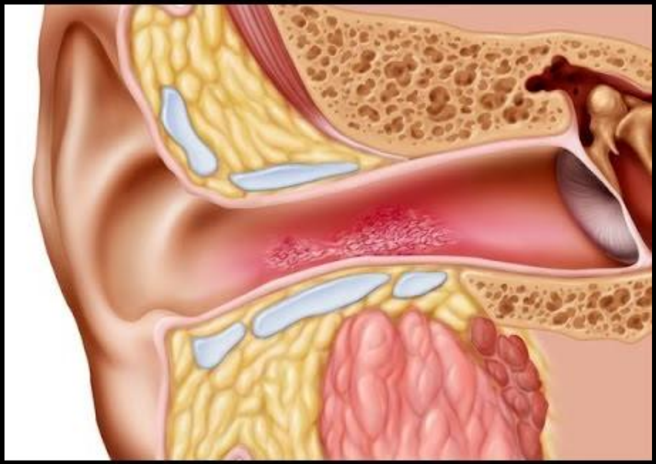
Symptoms of moderate to severe ear barotrauma:
damage to the eardrum
tearing allows water to enter middle ear ➔ infections
bleeding from the ear
increased pain in the ear
constant feeling of pressure and fullness in the ear
moderate to severe hearing loss

Unequal response
pressure different
sensation of spinning
termed alternobaric vertigo

Tympanic Membrane

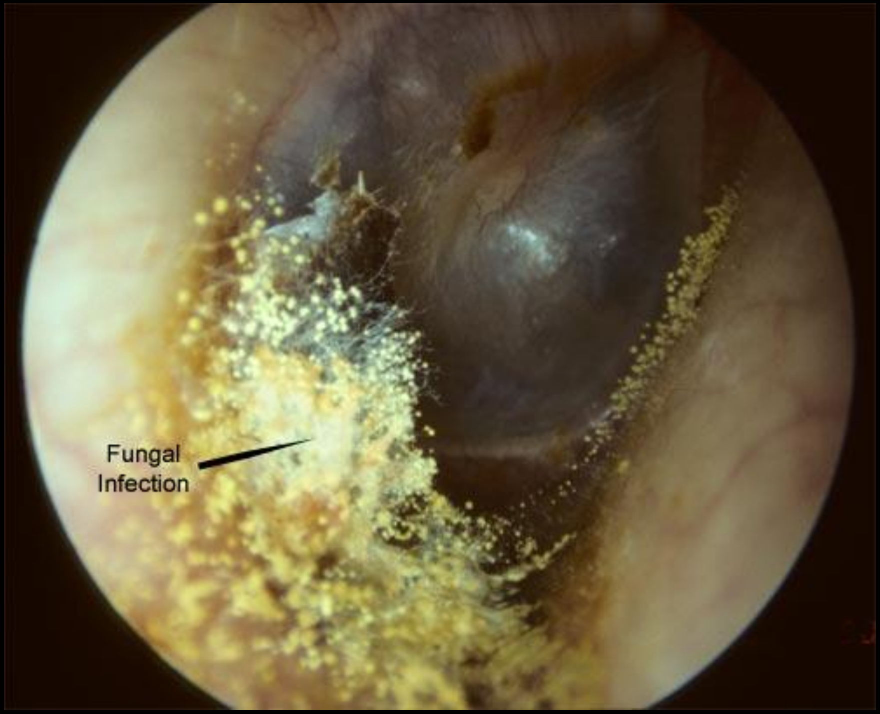


Swimmer's Ear (Otitis Externa)



Most freshwater contains microbes and fungi
They survive well in warm, dark places
They do not survive well in acidic environments

Prevention:
Rinse ears with vinegar after every diving day
Avoid alcohol in ear: dissolves protective ear wax



Near Drowning

Near Drowning

Drowning: Death by submersion
Near Drowning: Surviving unconscious submersion

Drowning Sequence:

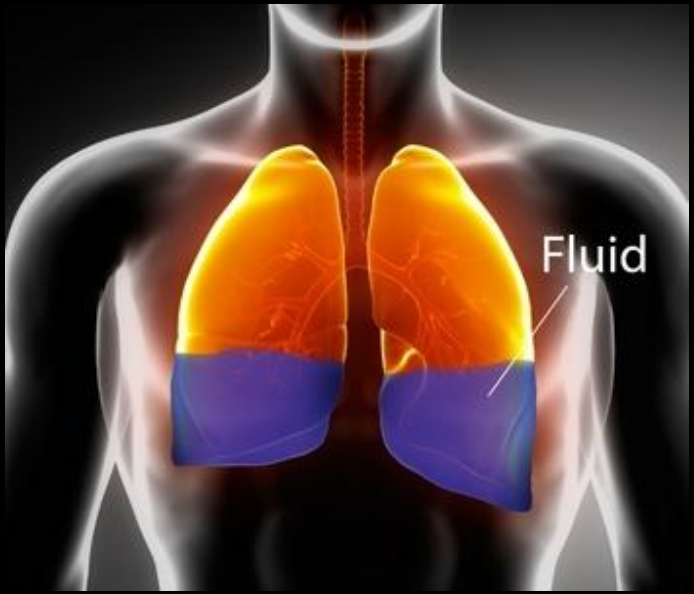
- **Struggling**
- **Water enters airway**
- **Airway closes (laryngospasm) ➔ Seizure, Hypoxia**
  - **(Dry Drowning ~ 15 % of cases)**
- **Laryngospasm relaxes**
- **Water enters lung**
- **Lungs cannot function when filled with water**
- **Eventual death**

Survival odds improved:
Little struggling, very cold water, very young, good condition
Aggressive first response

Near Drowning

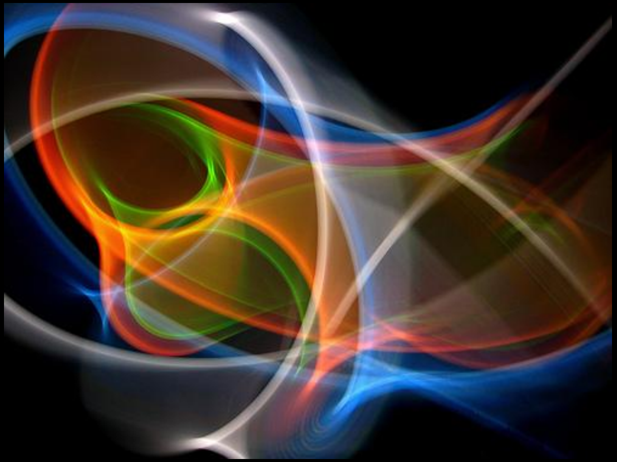
Symptoms:

- Difficulty breathing
- Chest pain
- Cyanosis (Bluish lip color)
- Abdominal distention
- Confusion
- Coughing
- Frothy sputum
- Irritability
- Unconsciousness

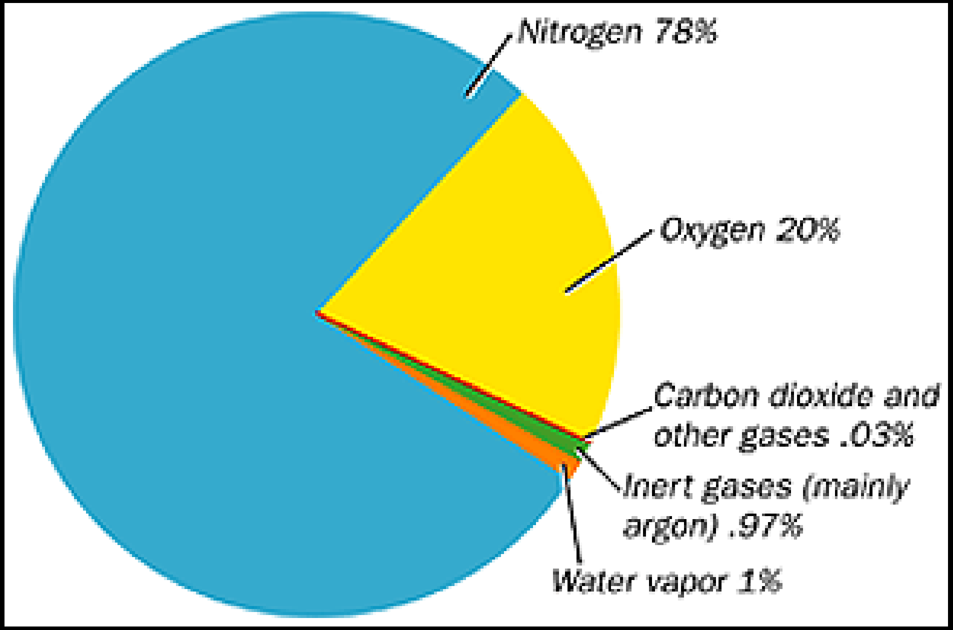



Gases





Gases in Air



Composition of Dry Air

Gas		Concentration	
Name	Symbol	Volume %	ppmv
Nitrogen	N_2	78.084	780,840
Oxygen	O_2	20.947	209,470
Argon	Ar	0.934	9,340
Carbon dioxide	CO_2	0.033	330
Neon	Ne	0.001820	18.20
Helium	He	0.000520	5.20
Methane	CH_4	0.000200	2.00
Krypton	Kr	0.000110	1.10
Sulfur dioxide	SO_2	0.000100	1.00
Hydrogen	H_2	0.000050	0.50
Nitrous oxide	N_2O	0.000050	0.50
Xenon	Xe	0.000009	0.09
Ozone	O_3	0.000007	0.07
Nitrogen dioxide	NO_2	0.000002	0.02

Notes:
-- ppmv = Parts per million parts by volume
-- Water vapor varies up to maximum of 4 volume percent
-- The total volume percent of the listed gases does not equal exactly 100 percent due to rounding numbers

Oxygen: necessary for life

- We "burn fuel" $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$
- Too little oxygen (hypoxic) ➔ no life
- Too much oxygen (hyperoxic) ➔ toxic reactions

Nitrogen: considered physiologically inert

- Involved in nitrogen narcosis & DCS (DCI)
- Dilutes oxygen in air; limits combustion

Others

- Most not considered in this class … assumed part of nitrogen component

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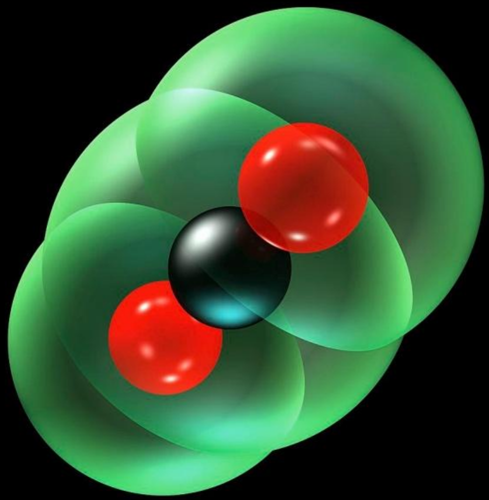
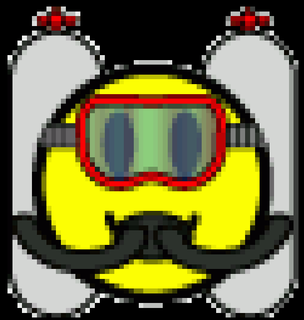
Air as a Breathing Mix

Air:
- Relatively inexpensive
- Commonly available
- Most common underwater breathing mix

But, N_2 causes problems at deeper depths:
- Decompression Sickness
- Nitrogen Narcosis

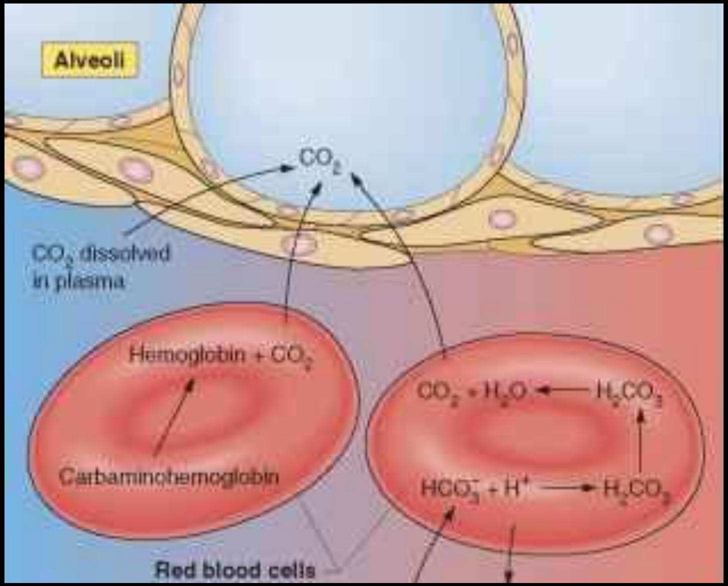


Carbon Dioxide (CO_2)



Carbon Dioxide (CO_2)

- Carbon Dioxide
  - Metabolic waste product
  - Potent vasodilator
  - Helps maintains blood pH
  - Breathing "Trigger"
- Excess levels in blood most undesirable
  - CO_2 produced faster than eliminated



CO_2 Production:

Resting: 300 mL/min

Working: 2000 mL/min

(unfit person has >> production)

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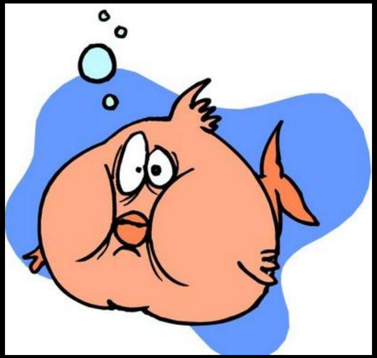
Carbon Dioxide (CO_2): Major Problem in Diving

Sources of Carbon Dioxide:

- Contaminated Gas (very rare)
- Work load exceeding ventilation
- "Skip Breathing"
- Poor ventilation (equipment dead space)
  - snorkel
  - poor regulator
  - full face mask

Cardinal Rule of Diving

“Never Hold You Breath”



But, you hold your breath every time you breathe with a regulator

Breathing On Surface:

Inhale … exhale … hold

Breathing With Regulator:

Inhale … hold … slow exhale … hold

During the hold, you are:

- holding breath (embolism risk)
- building up CO_2

Don’t consciously extend the “hold phase”

(called “skip breathing”)

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Hypercapnia (High CO_2)

A CO_2 "Hit"

Slight CO_2 build-up

Increased respiration (attempt to vent)

Poor ventilation

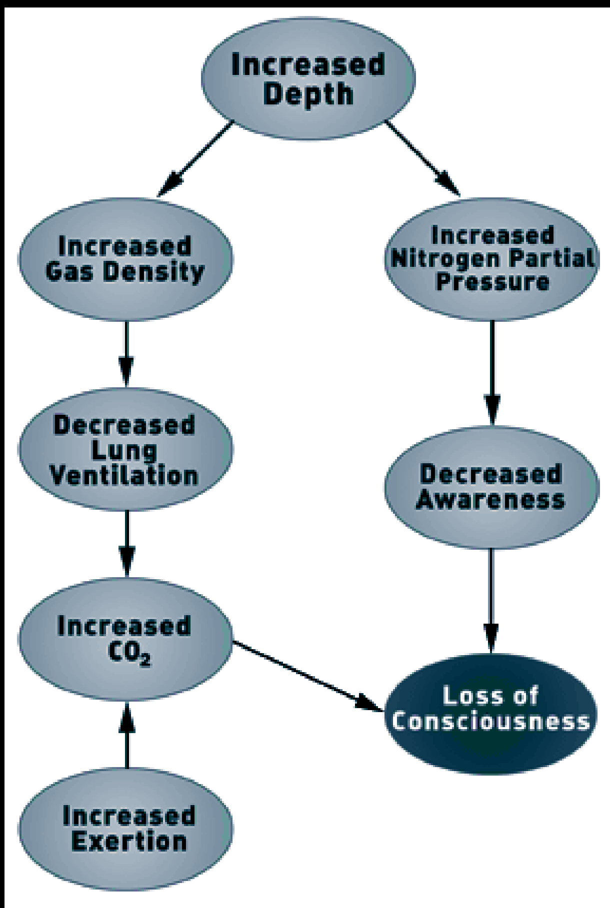
CO_2 continues to increase

High CO_2 perceived as "regulator not working"

Suspicion: many "out of air" emergencies are CO_2 hits

CO_2 Cascade

Carbon dioxide exacerbates most dive maladies



Gas	Density gram/liter of gas
Nitrogen	1.1009
Helium	0.1573
Oxygen	1.2572
Neon	0.7930
Argon	1.5696

Mix	Density gram/liter of gas
Air at 1 ATA	1.138
Air at 99 FSW	4.552
32% Nitrox at 99 FSW	4.605

Increased O_2 in EAN_x raises density
Greater density increases work of breathing

Israeli military studies:
Breathing EAN_x increases CO_2 retention

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Hypercapnia (High CO_2)

Studies show oxygen-enriched air promotes CO_2 retention

Higher the O_2 concentration, the greater the effect

Greater density at depth requires more work to breathe

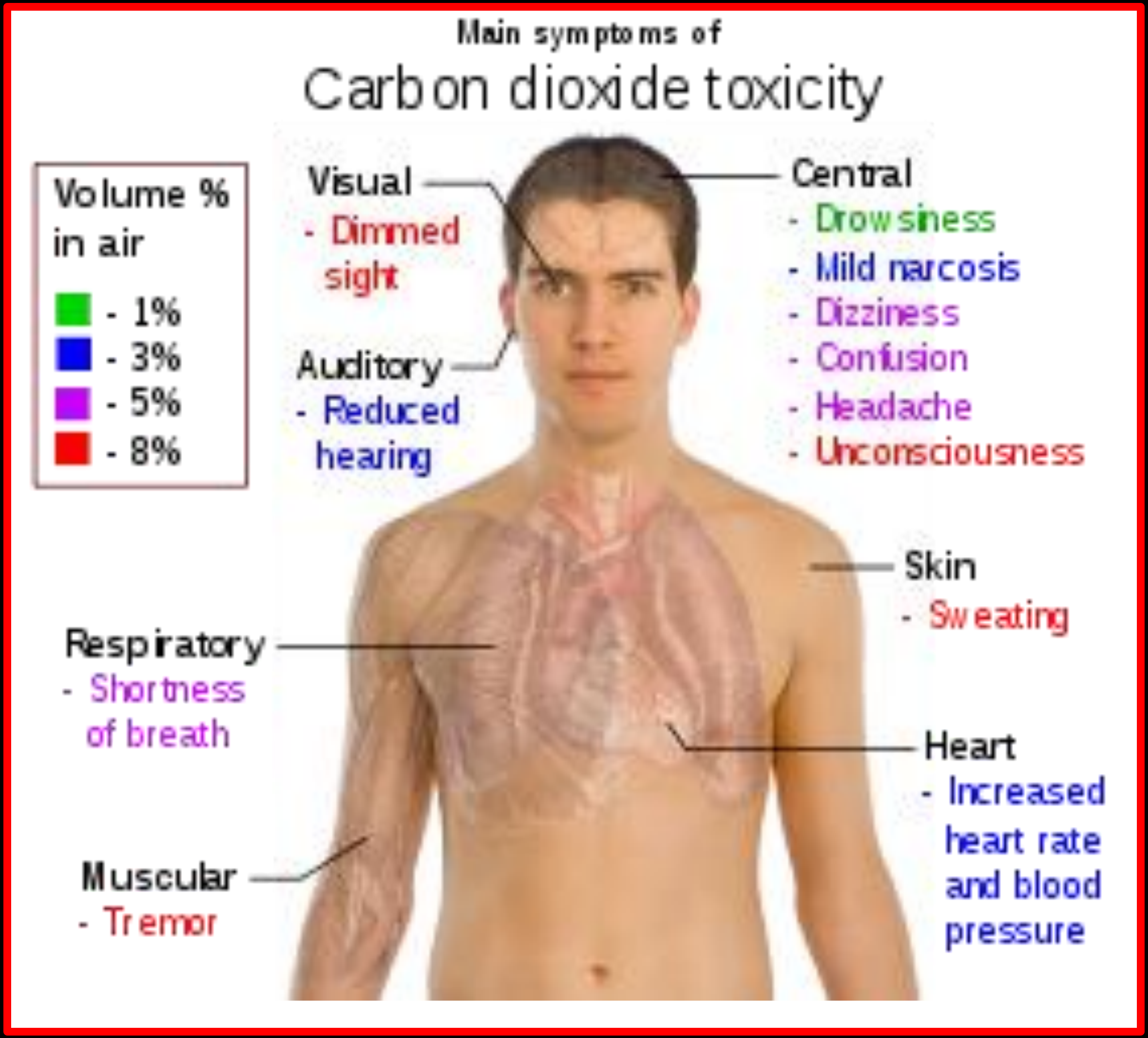
Important to monitor breathing

Suspect CO_2 build-up ➔ Stop

Breathe slowly (Imagine STOP sign)

Until breathing returns to normal

Hypercapnia (High CO_2)



Main Diving Issues:

Respiratory Starvation

Headache

Center of forehead

Shallow Water Blackout

Shallow Water Blackout

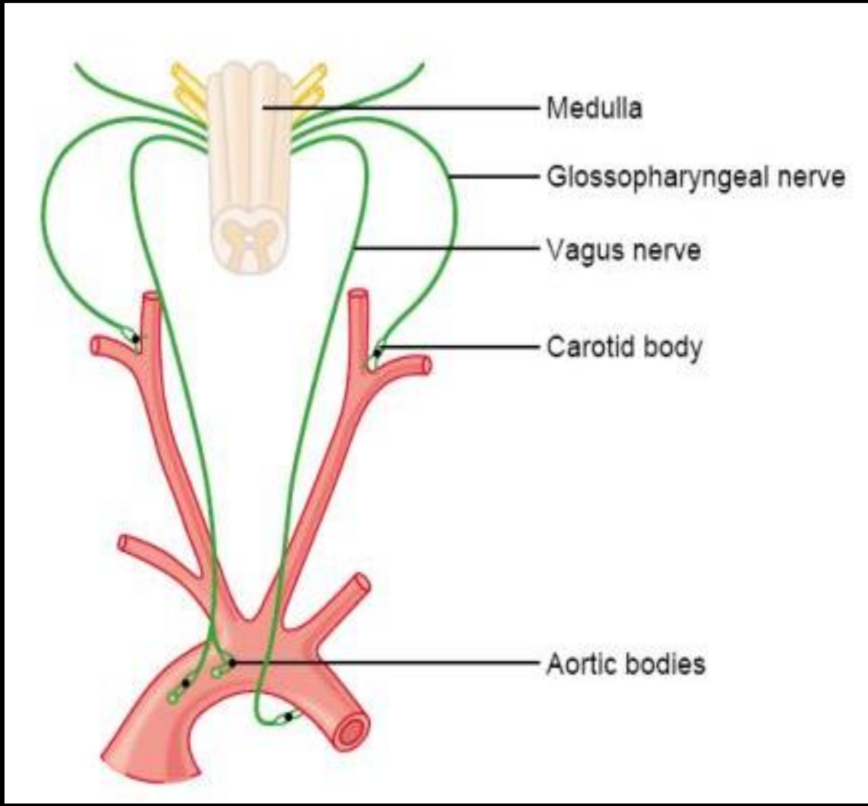
Problem During Ascent:

- Skin Diving
- Free Diving
- Only Using Mask & Snorkel

Associated with pre-dive hyperventilation

Ventilation exceeds metabolic demands

Shallow Water Blackout



Carotid Body:

Chemoreceptor

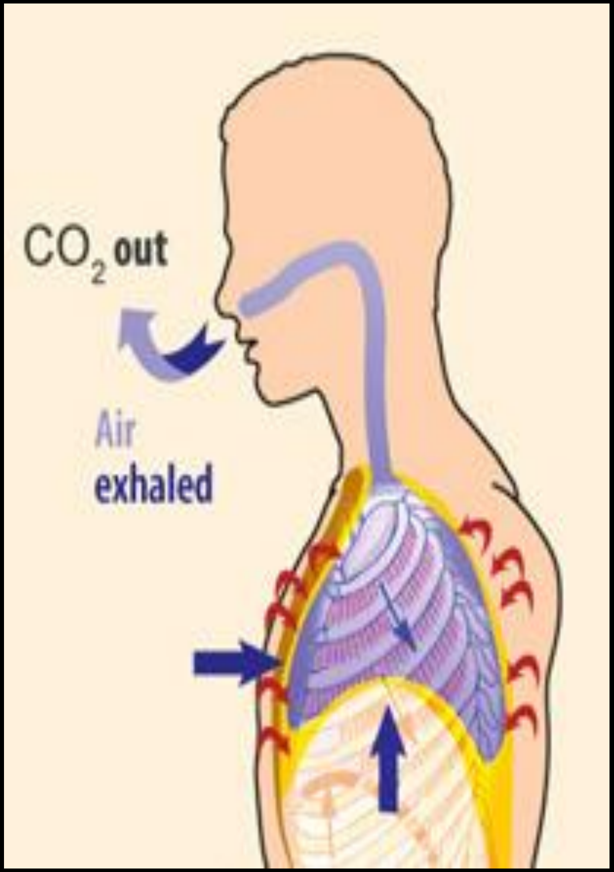
Senses CO_2 & O_2

High CO_2 communicates to respiratory center
"Need to breathe NOW to ventilate xs CO_2"

Shallow Water Blackout

To avoid "Breathe now" from high CO_2
To extend bottom time

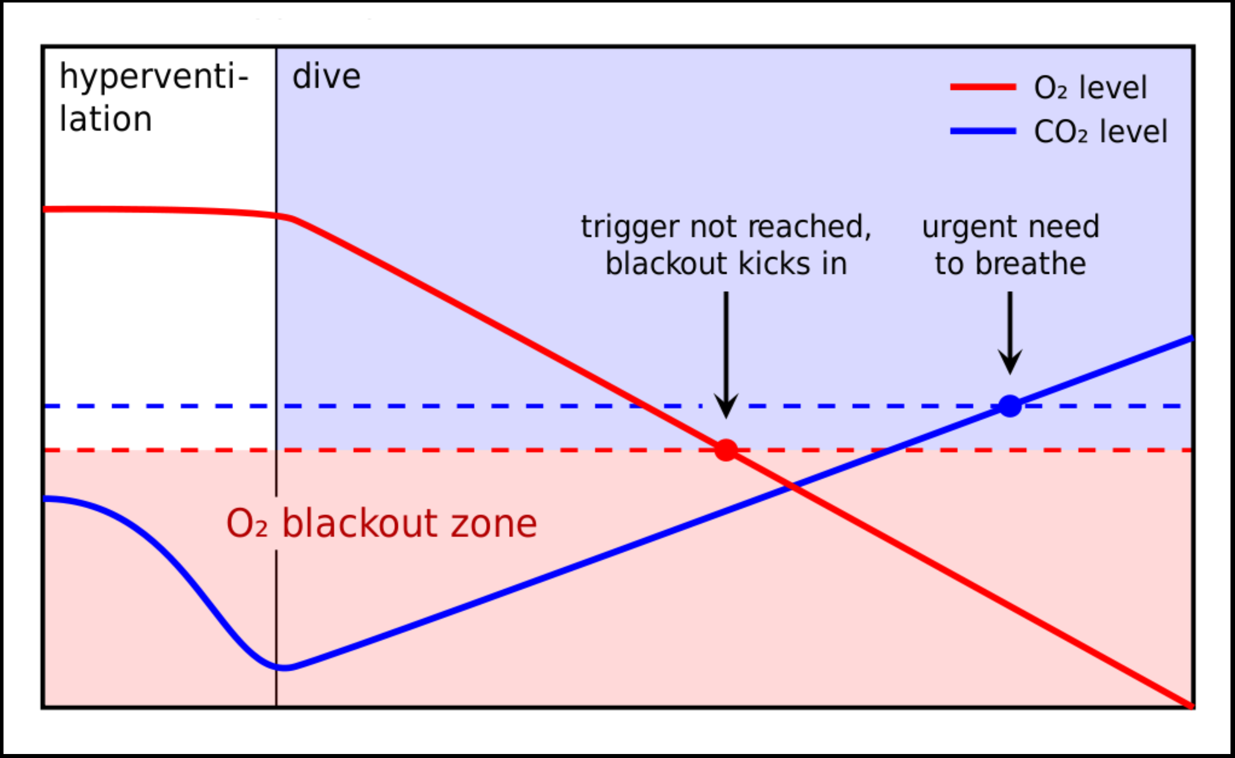
Divers will hyperventilate
- **Rapid deep exhalations**
- **Drops blood CO2 levels**



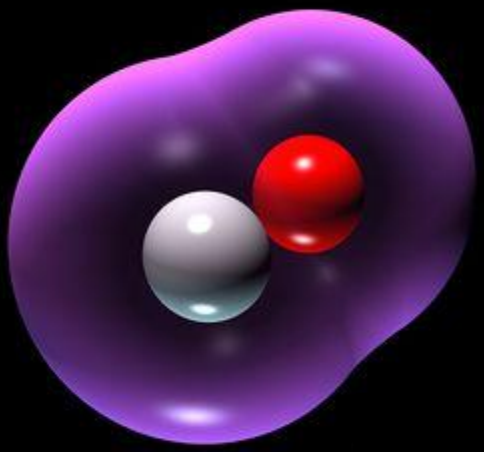
Shallow Water Blackout

During Free Dive:

- Metabolism consumes blood oxygen
- Reach "blackout" (not enough O_2)
- Before CO2 triggers "Need to breathe"



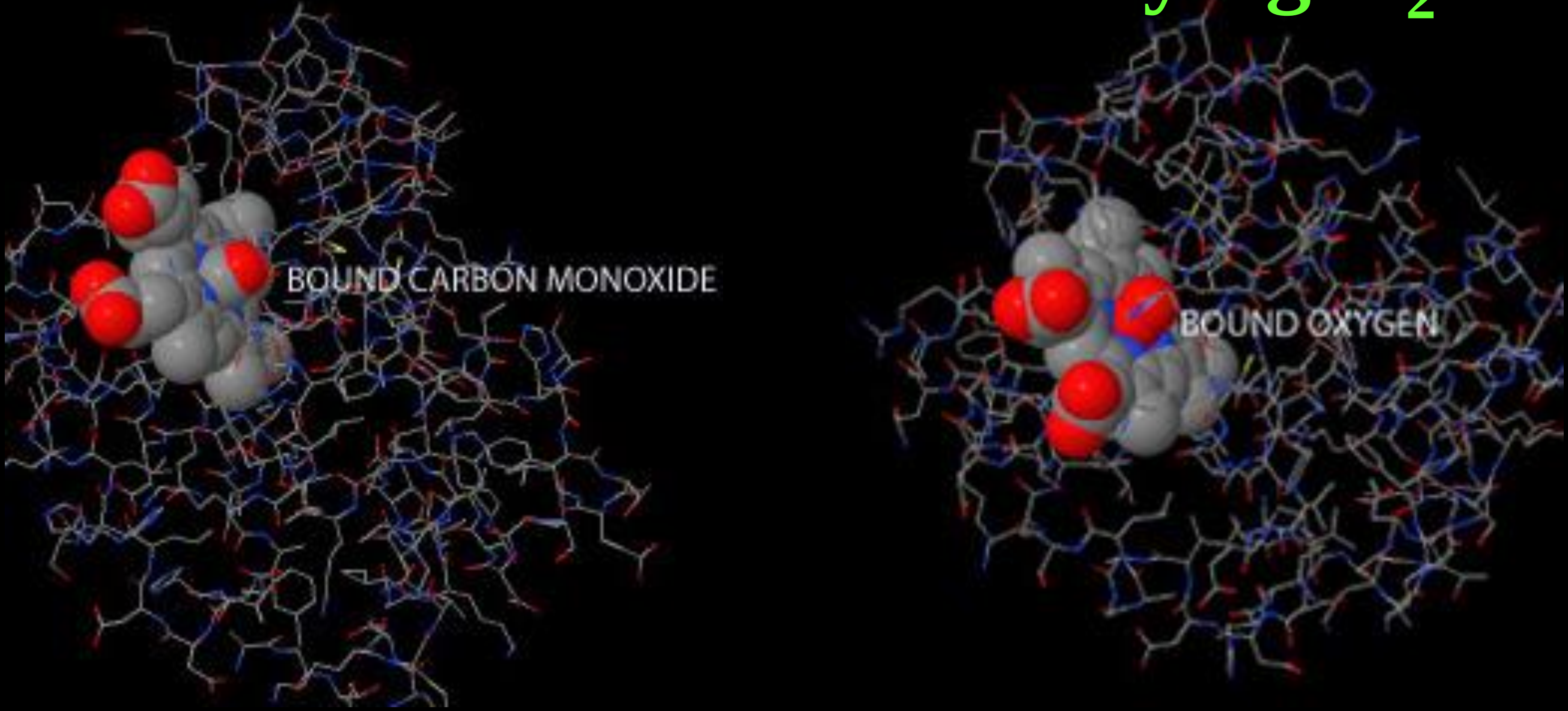
Shallow Water Blackout



Carbon Monoxide (CO)

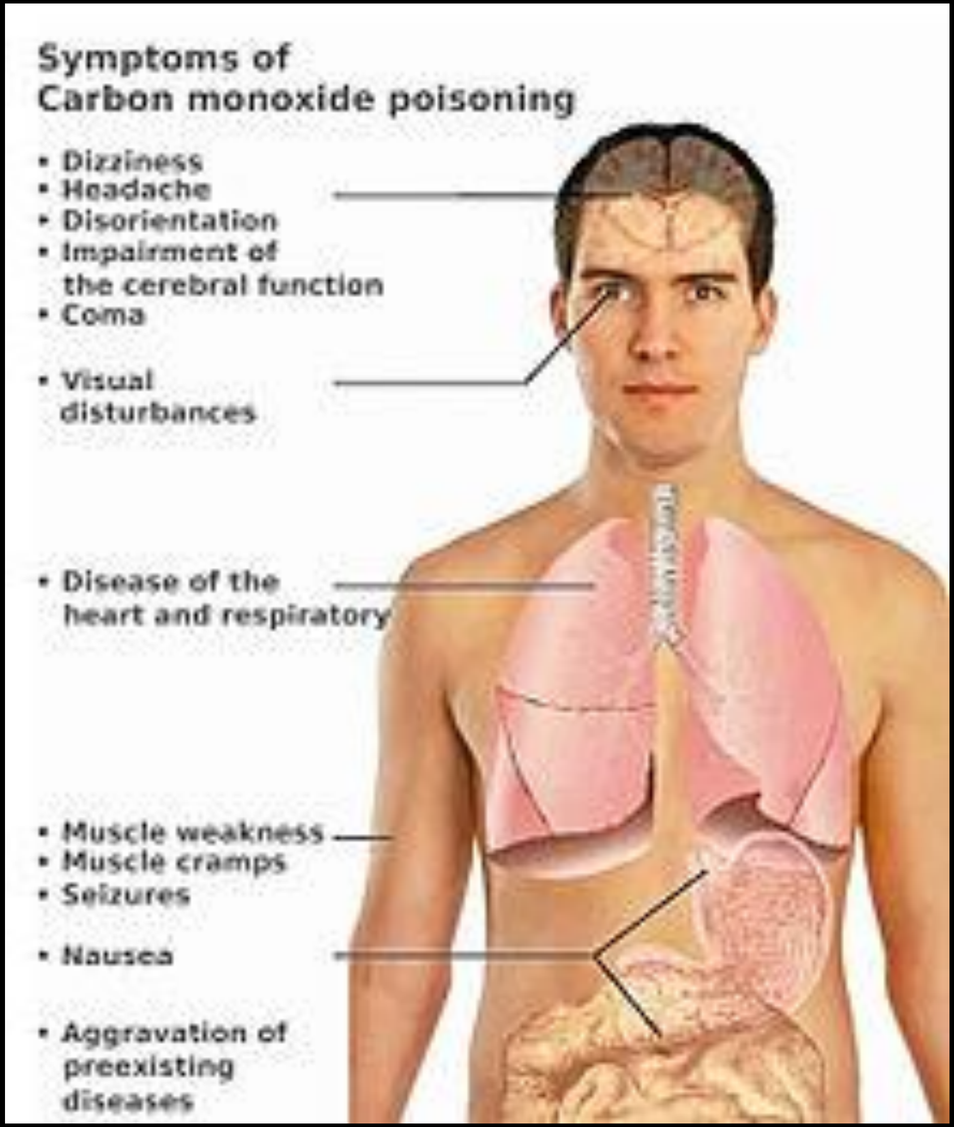
CO Binds To Heme In Hemoglobin ~250 X Stronger than O2

Prevents Heme from carrying O_2



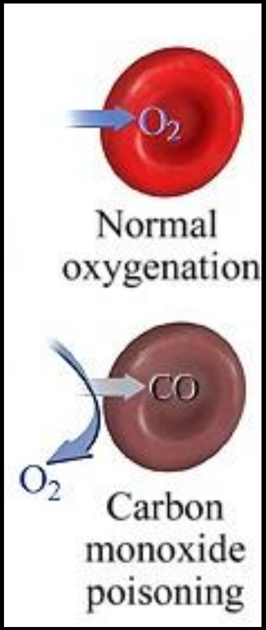
Too Much CO ➔ No O_2 ➔ Lethal

Carbon Monoxide (CO)



From incomplete combustion:

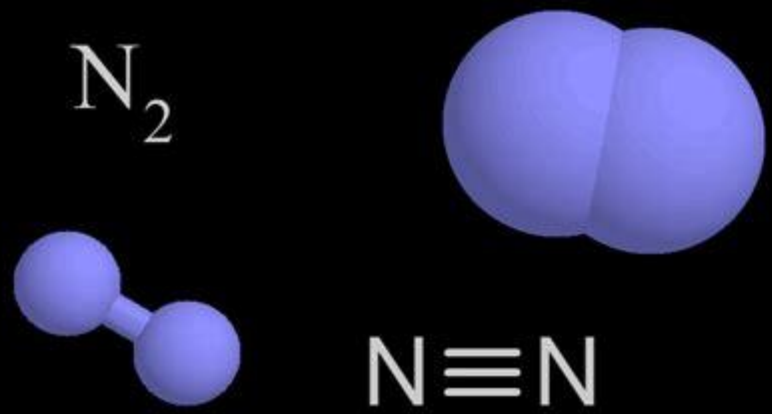
- Compressor oil
- Engine exhaust
- Cigarette smoke
- Kerosene heaters



Humans metabolism releases CO

Minor amount: factor in closed environments (habitats, subs & space capsules)

1 cigarette: more CO than USN allows in their breathing gas



Nitrogen

Nitrogen Narcosis

Nitrogen Narcosis

Narcosis:

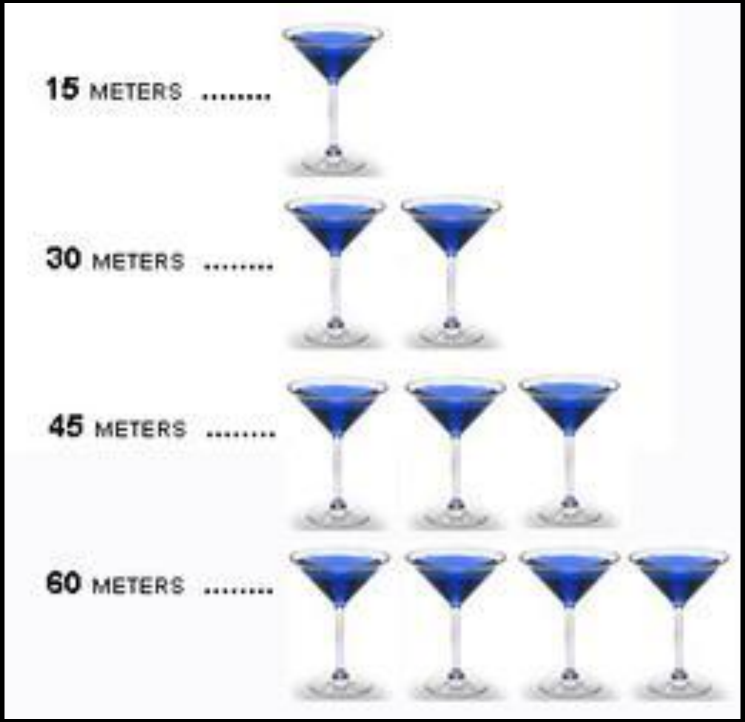
Pronounced “anesthetic effect”

Observed when breathing N_2 containing mixes at depth

Deeper the depth, more intense the effect

So-called Martini’s Law: (Not considered valid)

Every ~50 fsw of depth = 1 dry martini on an empty stomach



Many Gases Have a Narcotic Potency

Gas	Relative narcotic potency
Ne	0.3
H_2	0.6
N_2	1
O_2	1.7
Ar	2.3
Kr	2.5
CO_2	20
Xe	25.6

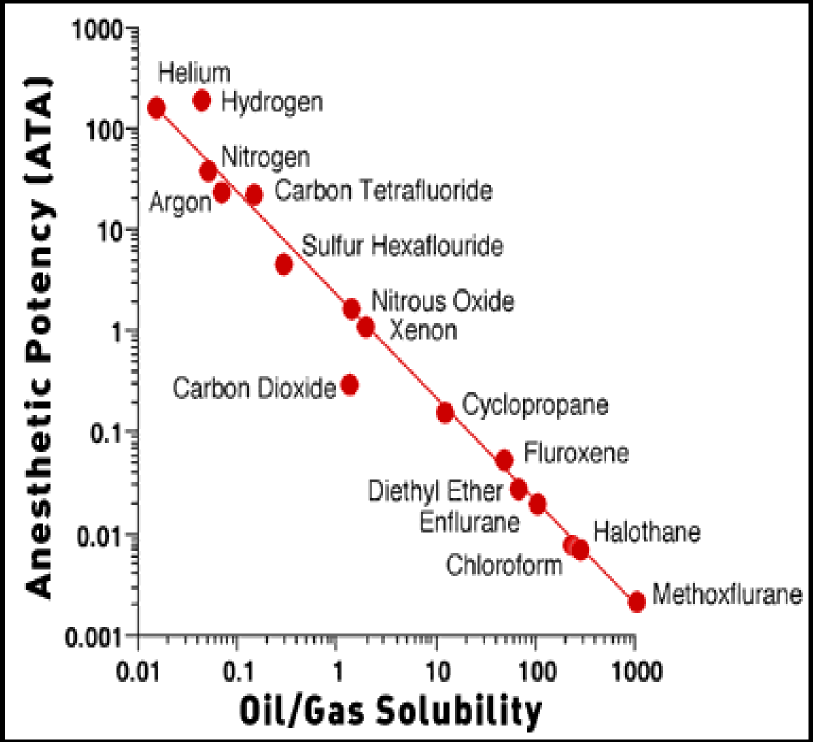
Meyer-Overton Theory of Anesthesia

Gases dissolve in nerve tissue myelin (lipid layer)

Altered electrical conduction of nerves

Oxygen metabolized, does not build up

Diminishes at-depth narcotic potency



Lipids NOT total picture

GABA receptors involved

Complex Problem
Not all understood

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Nitrogen Narcosis

Signs & Symptoms

Warm, clear water: euphoria ("Laughing Gas" as model)

- Tendency to giggle
- Tunnel vision (syncope)
- Idea fixation (repetitive behaviors)
- Shortened attention span
- Declining neuro-muscular coordination
- Numb lips
- Inability to concentrate

Cold, limited visibility water: dread

- Sense of being stalked ("It" is out there … somewhere)
- Loss of confidence (sense of helplessness)
- Intense anxiety

Nitrogen Narcosis

Symptoms exacerbated by:

- cold
- work load (CO_2)
- anxiety
- fatigue
- drugs
- alcohol
- menses (?)

Symptoms:

Typically noticeable ~ 100 fsw, but onset as shallow as ~ 60 fsw

- Sense of well-being: masks CNS impairment
- May be not be noticed by affected diver
- Individually variable
- CNS impairment increases with time / depth
- Ascent relieves problems; typically, no residuals

Underwater “Narcosis Test”

“OK” signal is “automatic reflex”
Often NOT reliable indicator

Narcosis Test
(for cognitive processing)
Show 1 to 4 fingers to diver
Diver adds 1 to # fingers
Shows added count

Nitrogen Narcosis: Classic Myth

Narcosis is reason for 130 fsw sport diving depth limit

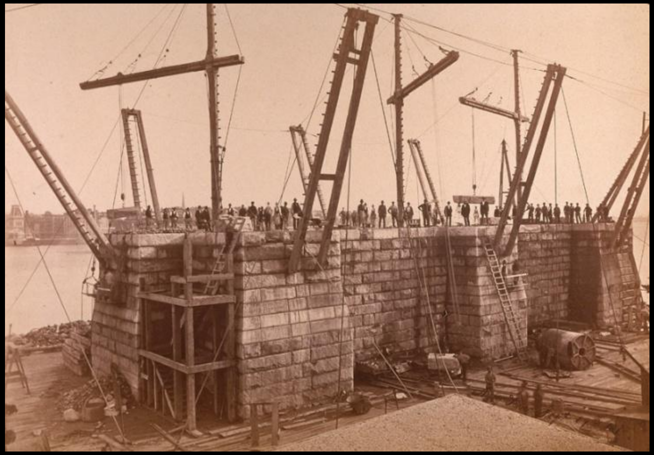
Turns out,
130 fsw is US Navy limit to use vintage scuba on a salvage dive
‘cause
At the time diving rules were established,
Double hose regulators would not support hard working below 130 fsw

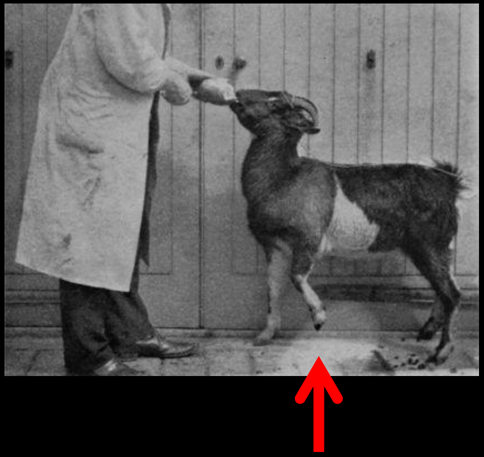

"Bubble Trouble": Decompression Sickness

Origin of “The Bends”

Building of Brooklyn Bridge (1870’s)
Caisson workers experienced pain on surfacing
Assumed postures similar to women dancing “Grecian Bend”
Wanted to return to work to lessen the pain
Being “Bent” was an insult

Established:
Caisson's disease and
Sponge Diver’s disease
Same malady





Haldane used goats to develop dive tables (1930’s)
Goats forelimbs would bend on too rapid ascents
So, they were “bent”
Developed ascent tables that would not bend goats

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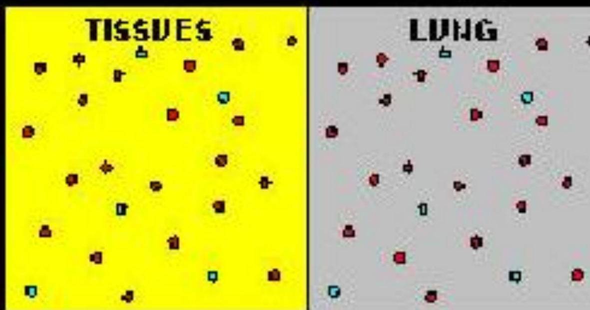
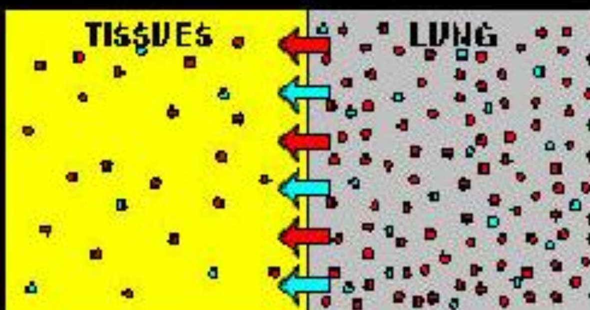
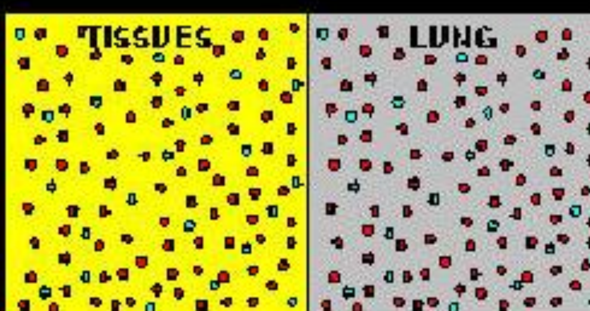
Gases at Depth



On the surface:
Gases diffuse across cell membranes
Concentration reaches equilibrium
Each gas acts independently



On descent:
Gases diffuse across cell membranes
Movement based on gas pressures
Each gas acts independently



At depth:
Gases diffuse across cell membranes
Concentration reaches equilibrium
For all components in breathing gas

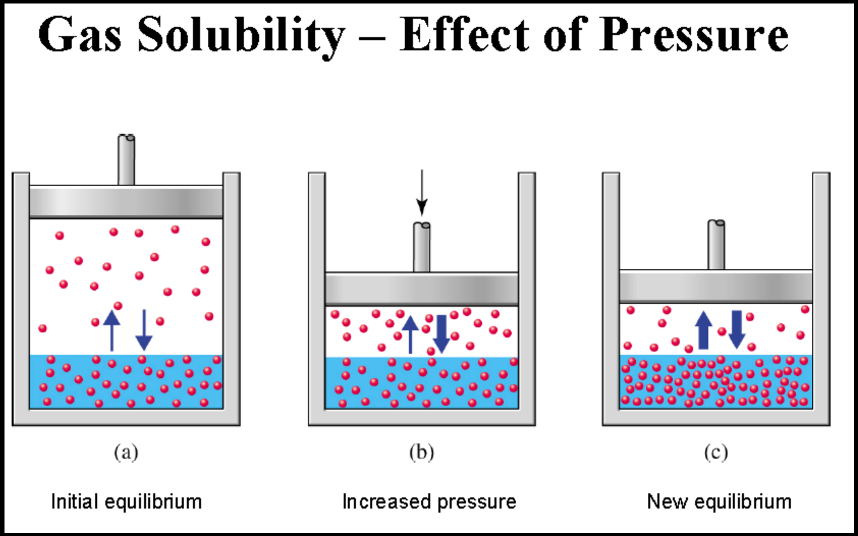
Gases at Depth

Gases eventually equilibrate tissue gas pressure with environment
Increased depth increases amount of dissolved gas
Nitrogen: accumulates … not used by metabolism

Different tissues (solubility compartments) build up gas at different rates
- Compartment nitrogen level is mathematically approximated
- Basis of decompression tables

No correlation between a biological tissue and a mathematical compartment

Different models will use
- Different number of tissue compartments
- Different mathematical expressions to approximate gas concentration



Nitrogen Partial Pressures:

Surface: 0.79 x 1 ata = 0.79 ata

99 fsw: 0.79 x 4 ata = 3.16 ata

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Decompression Sickness

On ascent, gas pressure in tissues greater than ambient

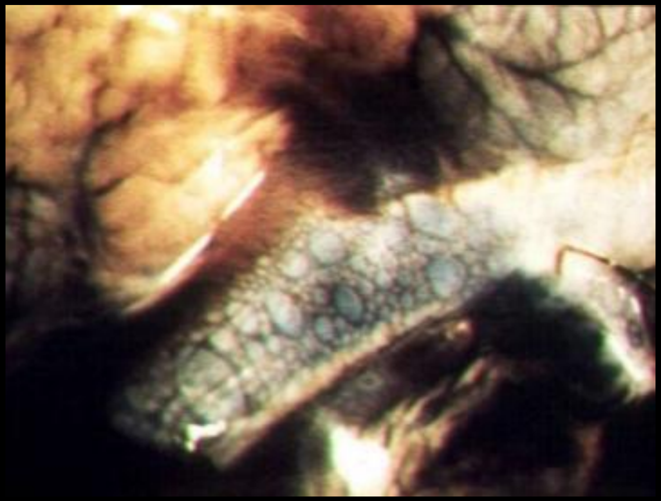
Gas bubbles out of tissues

Bubbles may form on dive (diver / profile dependent)

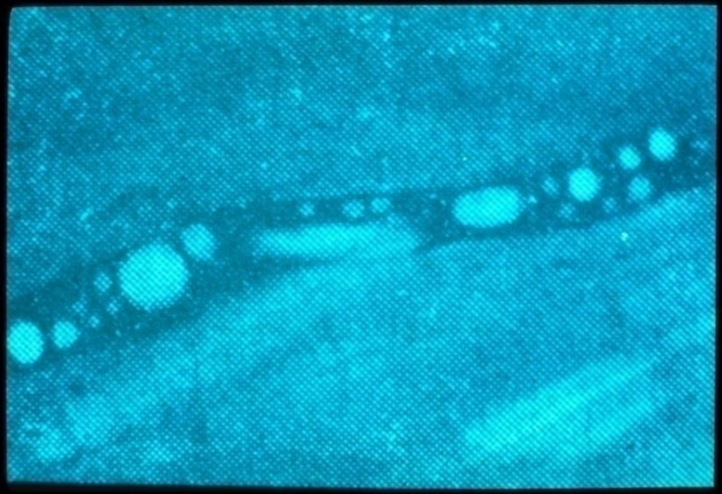
Some dives /divers may not show significant bubbles)

Too many bubbles: Decompression Sickness (DCS)

Symptoms observed depend on where bubbles form



Bubbles in Tissue



Bubbles in Veins

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Bubble Trouble

Most bubbles safely eliminated via venous circulation and lungs

Too many bubbles overwhelm physiology

Proteins of coagulation cascade react to gas bubbles in tissues

coat bubble and initiate clotting at site of bubble

Electron micrograph of protein coated bubble

Arrow points to platelet adhering to coagulation protein coat

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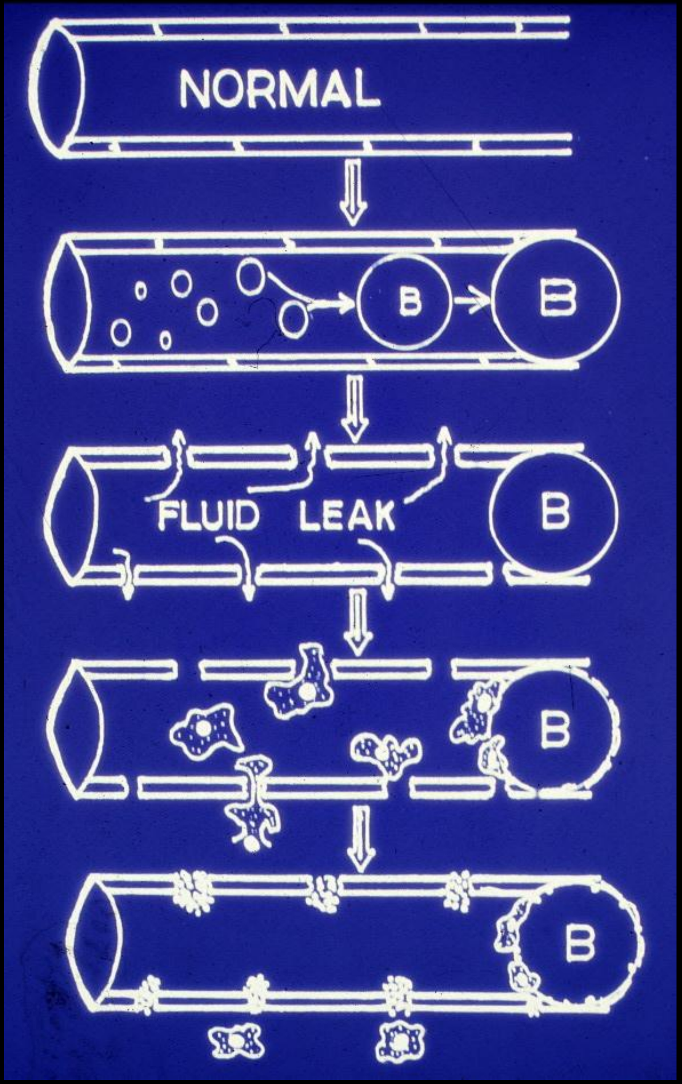
Bubble Trouble

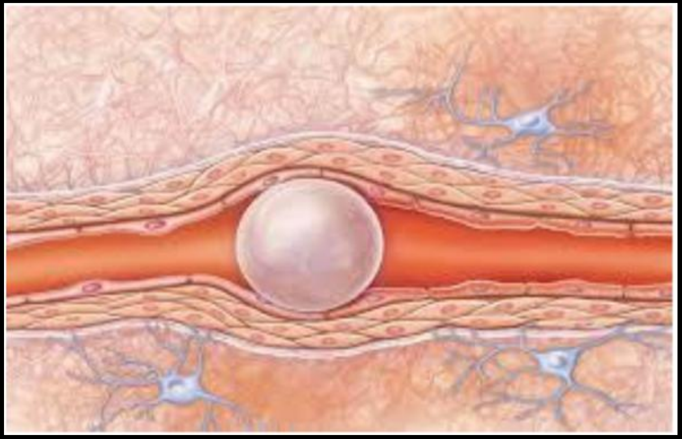


Bubbles in capillaries block flow

- **Pressure builds up**
- **Vessel walls split**
- **Fluid leakage**
- **Activation of inflammatory response**

Very complex biochemical complications

Much still not understood



Symptoms Depend on # Bubbles and their Location

Frequency and Onset of Symptoms

Symptoms	Frequency
local joint pain	89%
arm symptoms	70%
leg symptoms	30%
dizziness	5.3%
paralysis	2.3%
shortness of breath	1.6%
extreme fatigue	1.3%
collapse/unconsciousness	0.5%

Time to onset	Percentage of cases
within 1 hour	42%
within 3 hours	60%
within 8 hours	83%
within 24 hours	98%
within 48 hours	100%

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Bubble Trouble

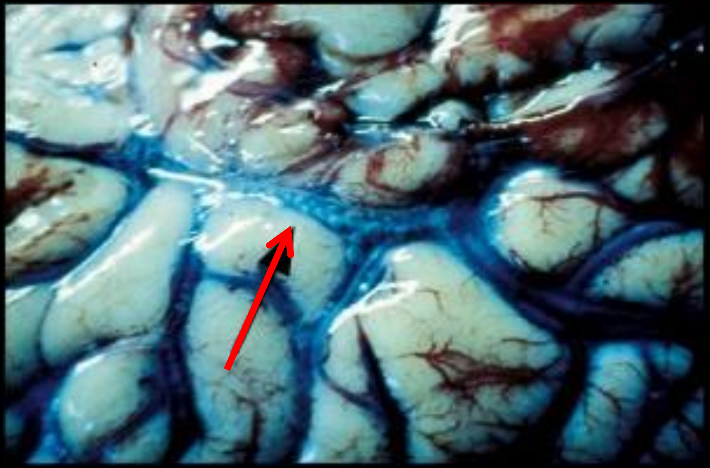
Bubble trouble assumed to be primarily a "too much N_2" malady

N_2 builds up

- abundance of N_2 in breathing mix
- increased time / depth drives N_2 into tissues
- N_2 not used in metabolism
- Over abundant N_2 escapes tissues on ascent

Basis of oxygen-enriched air

- Obvious remedy: decrease amount of N_2 in breathing mix
- Use gas involved in metabolism (oxygen)



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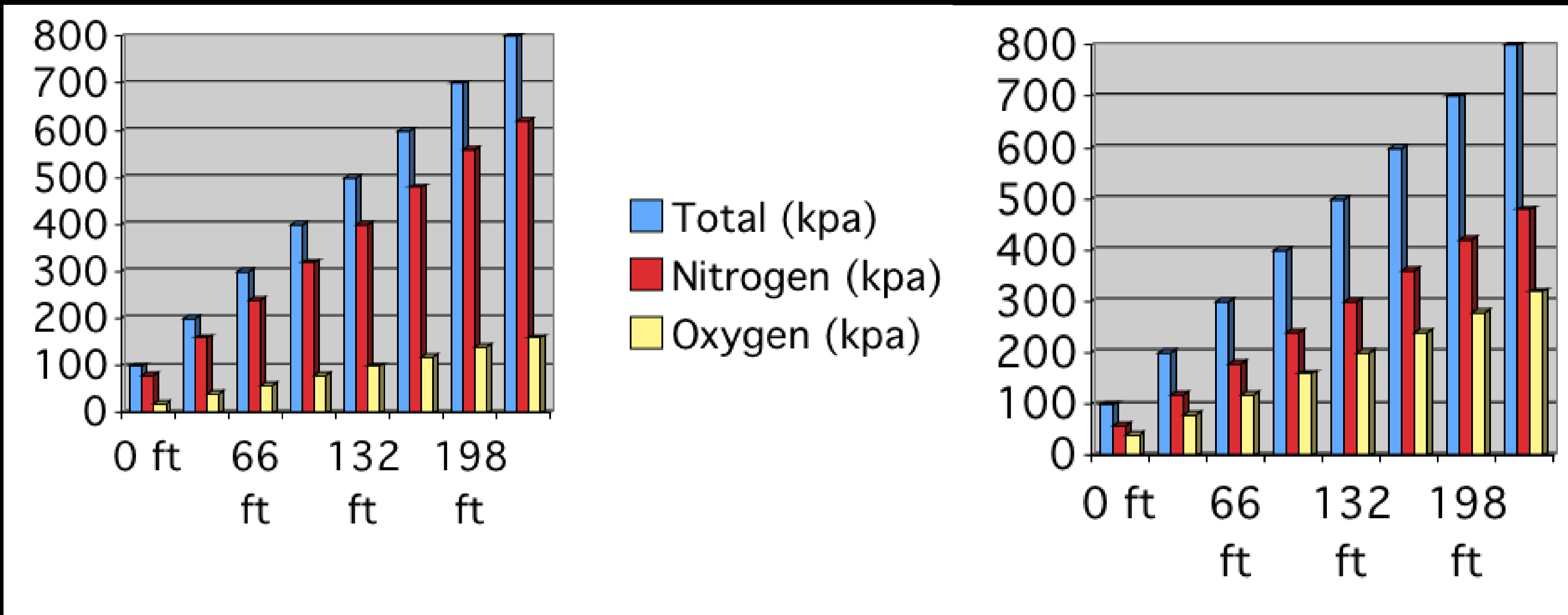
Oxygen Enriched Air Reduces Nitrogen Tissue Loads

Breathing Air **Breathing EAN_{32}**

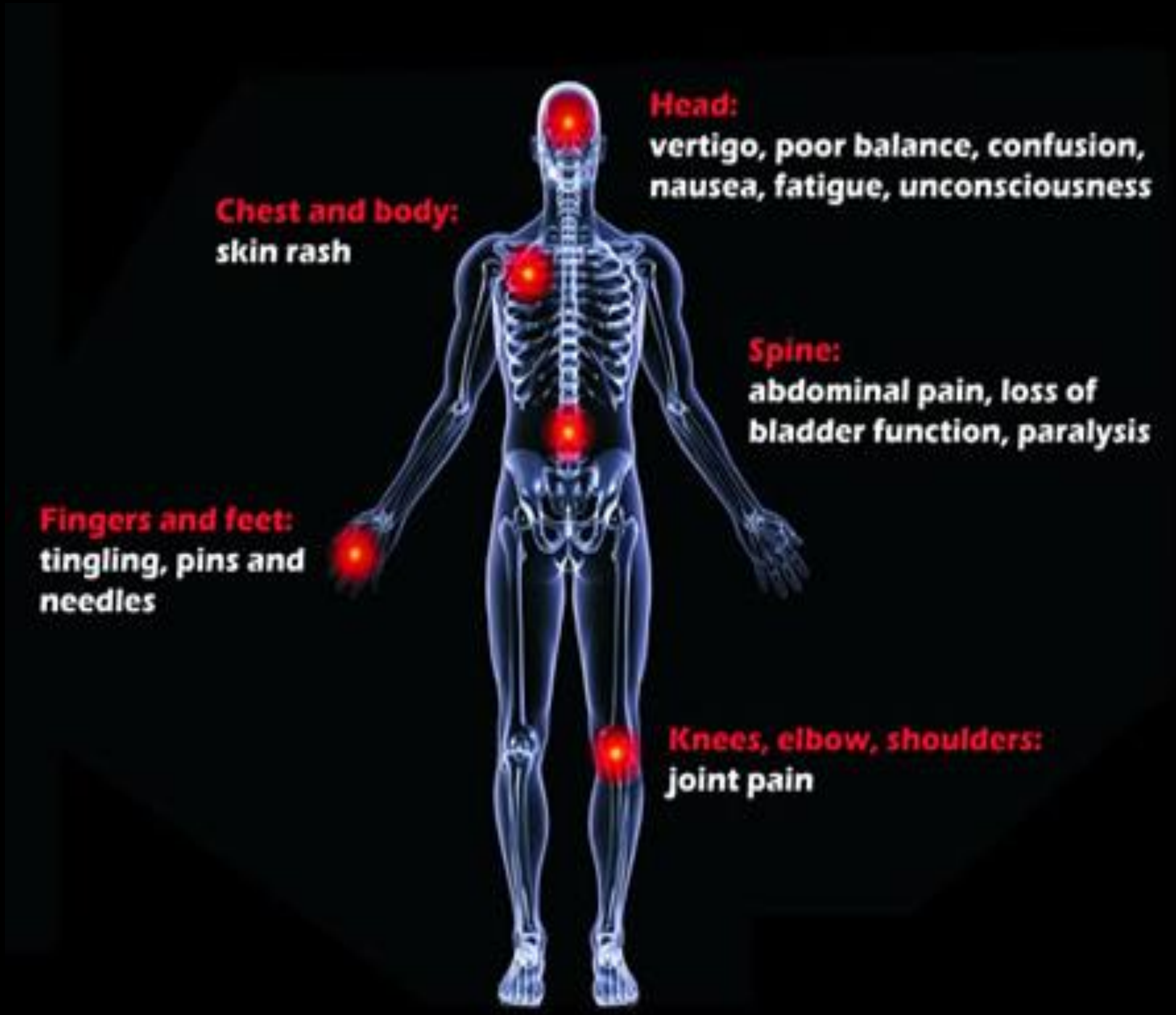


Primary advantage of oxygen enriched air

Decompression obligation depends on N_2 tissue load

Decompression obligation reduced by replacing N_2 with O_2

Too Many Bubbles: Decompression Sickness



Type I (Pain Only)
- Musculoskeletal Insult
  - limb or joint pain
- Itching
- Skin rash
- Localized swelling

Type II (CNS Involved)
- Spinal Involvement
  - numbness / tingling
  - bi-lateral paralysis
  - no bladder function
  - loss of sexual response
- Inner ear (staggers)
- Lungs (chokes)
- Cardiac arrest
- Type I on ascent

DAN:
> 60% of DCS involve depths > 80 fsw

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Skin Bends

Signs & Symptoms:

Skin discoloration
  Purplish and flat
Compared to a rash:
  More reddish and "textured"
Itching

Most often:

Chamber dives
Females
Hot shower post-dive

~ 20% show neurological involvement

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DCS Risk Factors

The following conditions are considered to increase DCS risk:

dive (deeper depth/longer time) profile
older age
obesity (poor physical condition)
dehydration
poor circulation (tight clothing)
illness
scar tissue
alcohol (12 hours pre or post dive)
fatigue
strenuous exercise during dive
cold
repetitive dives
multiple ascents / descents on same dive
multi day diving
history of DCS
being female (?)
misuse of dive tables / dive computers

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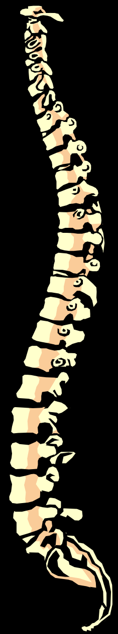
Serious DCS Cases Involve Spinal Cord

Bi-lateral dysfunction/numbness
May increase with time
May result in permanent dysfunction
Affects Ability to:
- walk
- excrete
- have sex



Every dive is gambling with spinal cord function:
Your body chemistry on the day you dive
Best tactic: Love your spinal cord: dive conservatively

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Lowering Bubble Formation

Minimize risk by:

Not "pushing" tables
Slow ascents
especially "shallow"
Safety Stops
Staying hydrated

Agonizingly slow:
Monitor with gauges

Ascent Rate: A Compromise

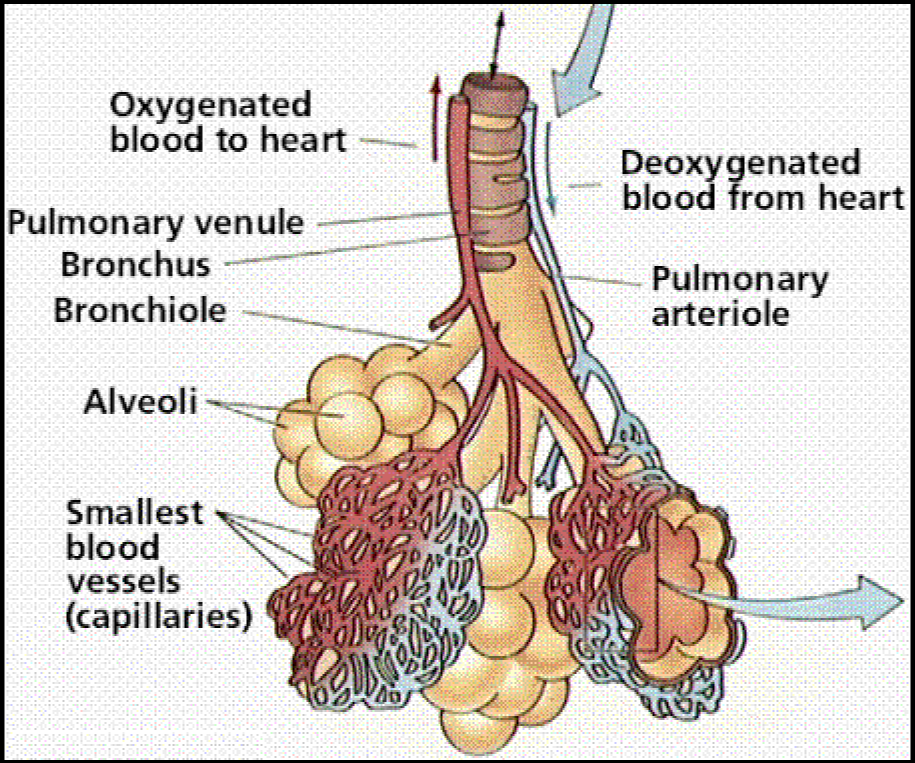
US Navy Combat Swimmers: ~120 fsw / min
US Navy Salvage Divers: ~25 fsw/min

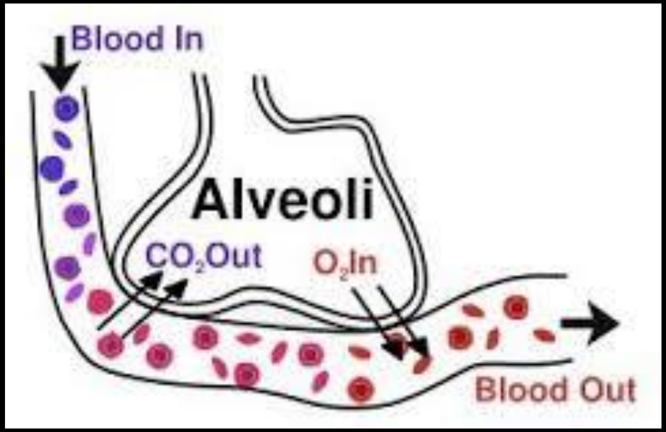
US Navy Compromise: 60 fsw / min

No correlation to physiology

Arterial Gas Embolism (AGE)

Alveoli: Site of Gas Exchange





Alveoli:

One cell thick

(allows gas exchange)

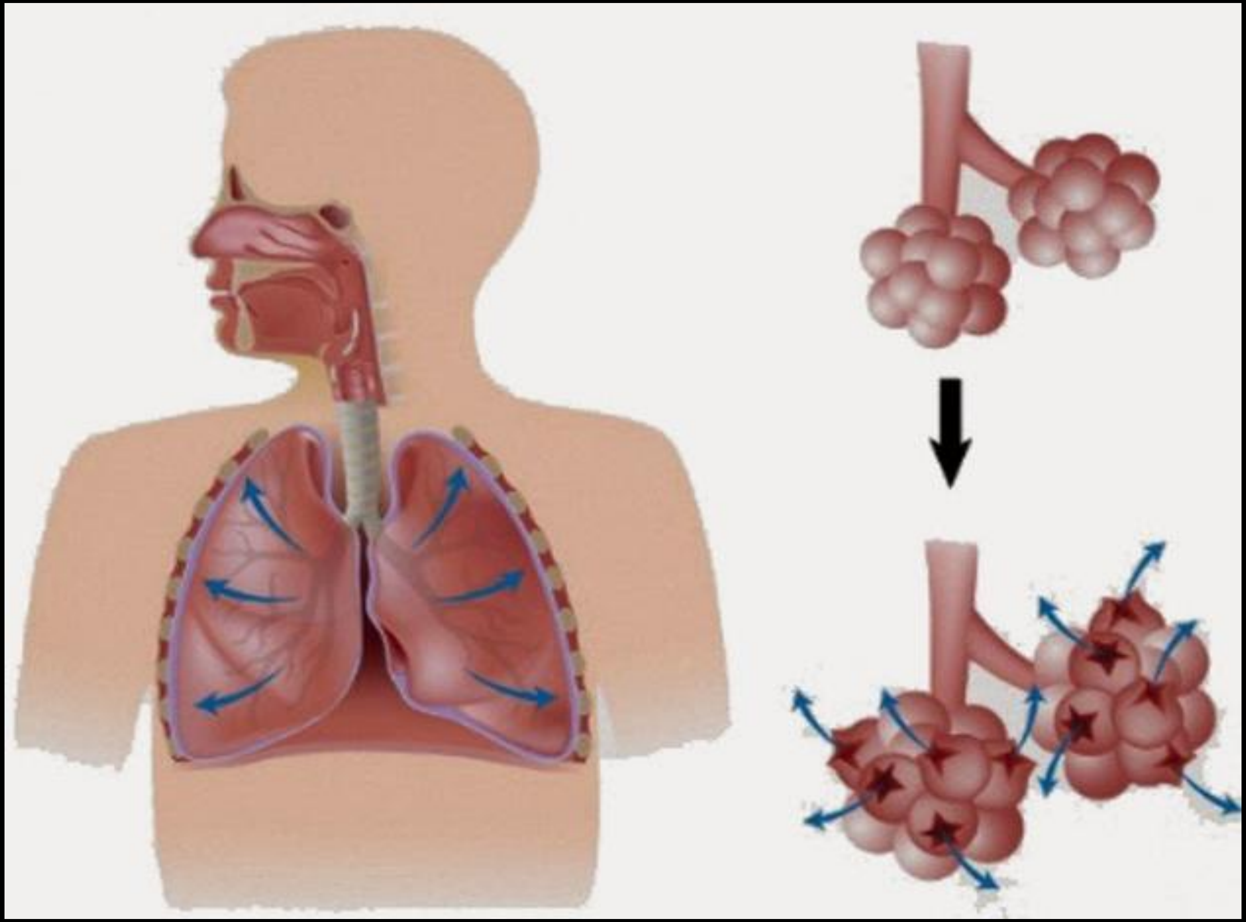
Rupture: D P ~ 1.5 psi

Pulmonary Barotrauma of Ascent

Expanding gas in alveoli exceeds capacity

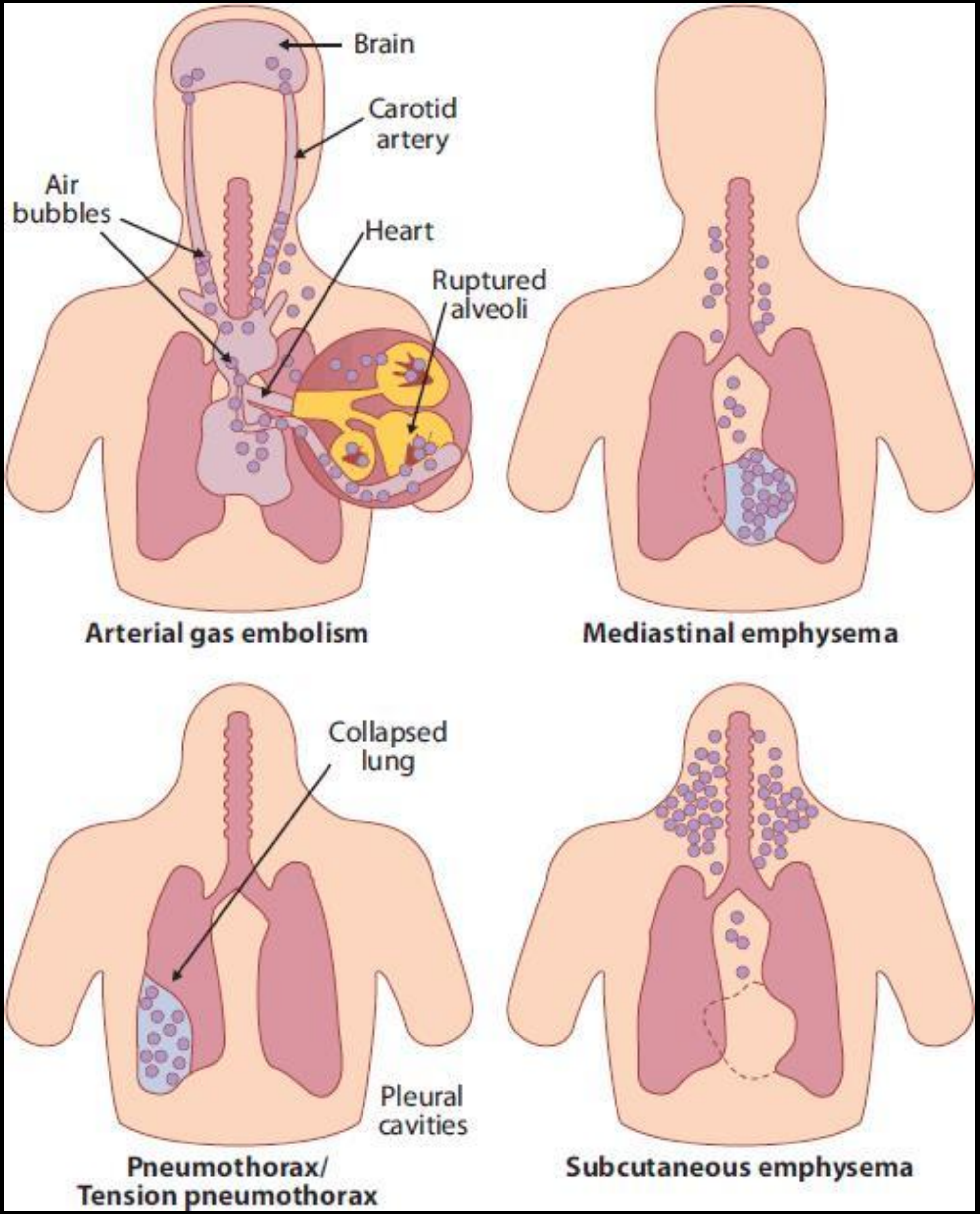
Alveoli tissue tears

Gas escapes



Pulmonary Barotrauma of Ascent

Ruptured Alveoli:
If Gas Goes:
Under Skin:
Subcutaneous Emphysema
Chest Cavity:
Mediastinal Emphysema
Against Lung:
Pneumothorax
Into Arterial Circulation:
Air Embolism



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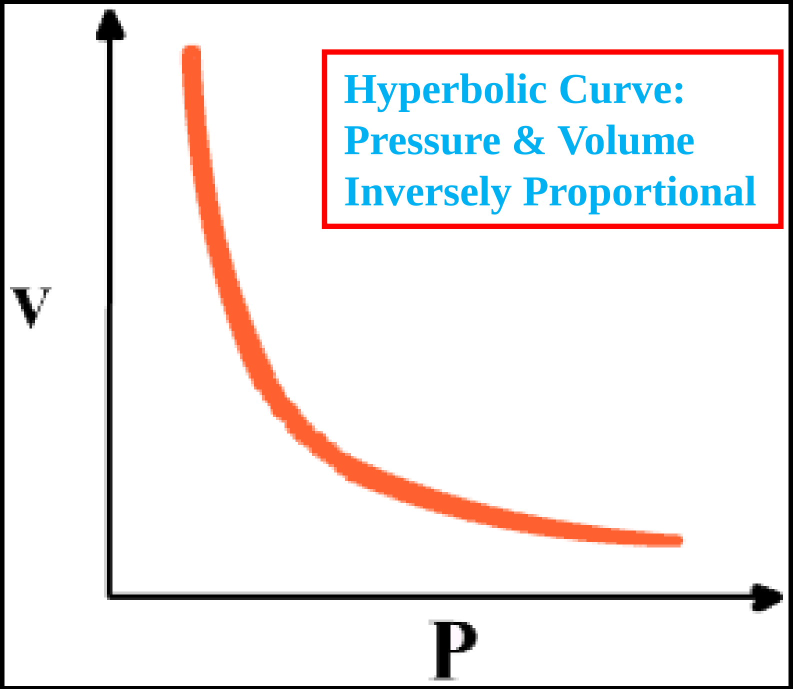
Remember Boyles's Law



Greatest volume change: where pressure is less

Means greatest risk to tissue: shallow water

Do NOT need "panic ascent" to develop overpressure
~ 20-25 % of injuries "undeserved"
Its Your body chemistry on the day you dive:
internal air trapping, asthma, cysts, fibrosis, inflammation tumors, blebs, wave height, diseases, inadequate exhalation

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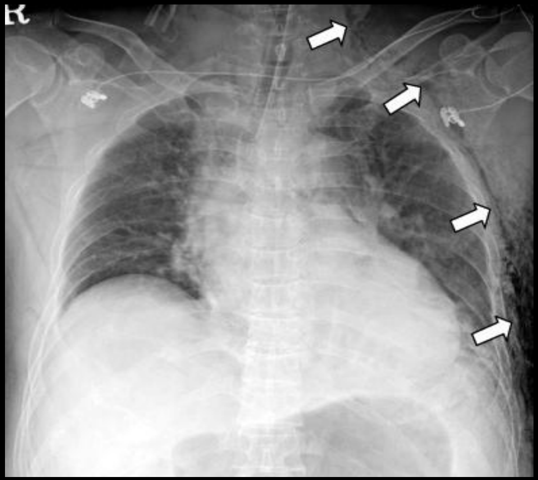
Pulmonary Barotrauma of Ascent

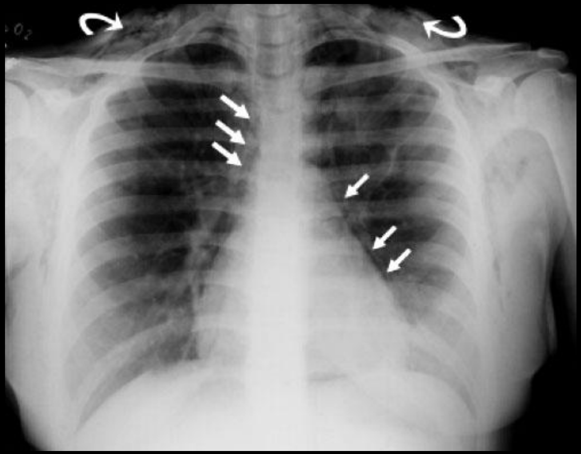
The Emphysemas: Signs & Symptoms

Under Skin: Subcutaneous
Chest Cavity: Mediastinal

May be asymptomatic
Crepitus (Noisy gas)
Voice change
  (if gas moves into throat)
Cardiovascular Issues:
  Tachycardia
  Cyanosis
  Hypotension
X-rays may show trapped air



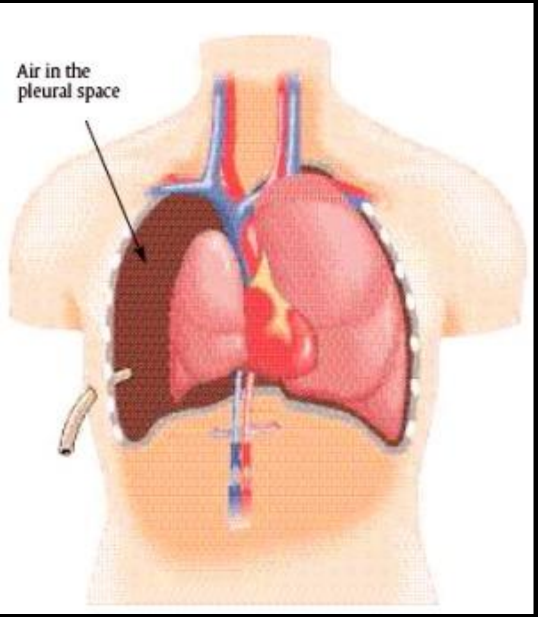
Subcutaneous

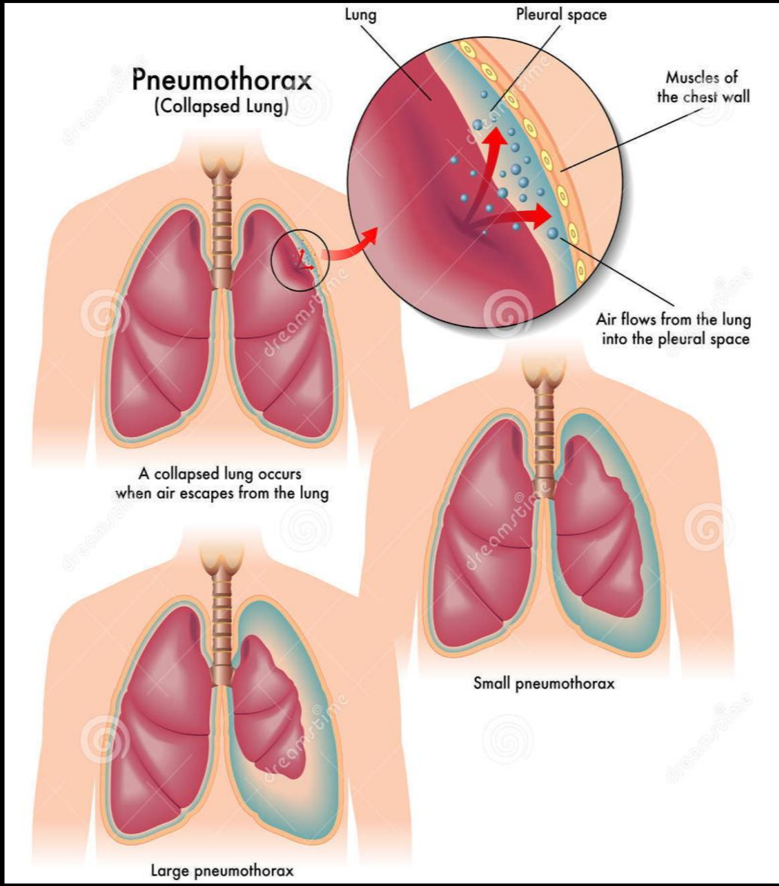

Mediastinal

Pulmonary Barotrauma of Ascent

Pneumothorax: Mechanism of Injury

Visceral pleura (tissue surrounding the lungs) ruptures
Gas enters into pleural space
Expanding gas compresses lung
Lung function diminishes





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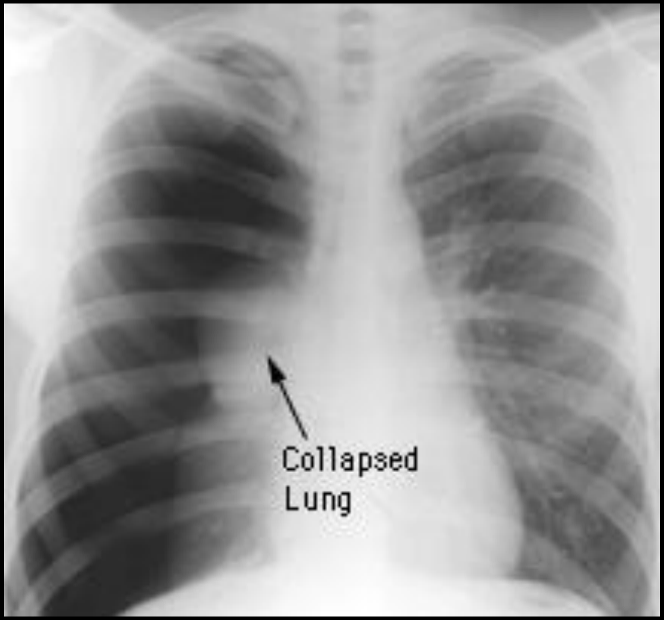
Pulmonary Barotrauma of Ascent

Pneumothorax: Signs & Symptoms

- Sudden, intense, unilateral chest pain
- Difficulty breathing
- Rapid breathing
- Chest rises less on affected side
- Diminished Breath sounds
- X-ray may show air



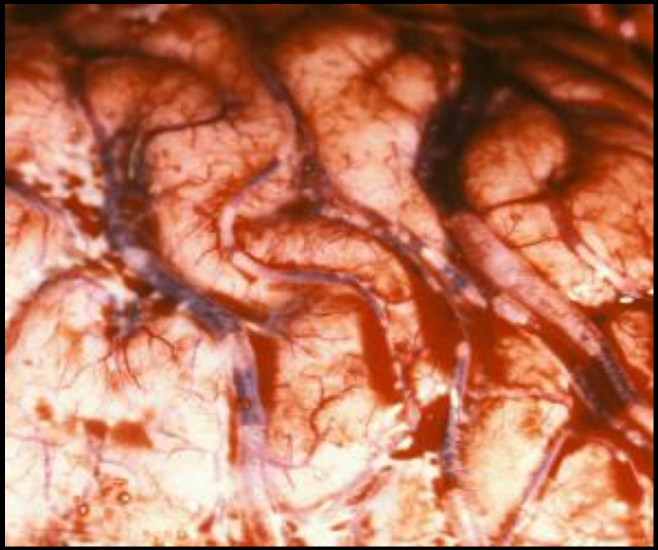
Medical staff will check for this malady prior to recompression

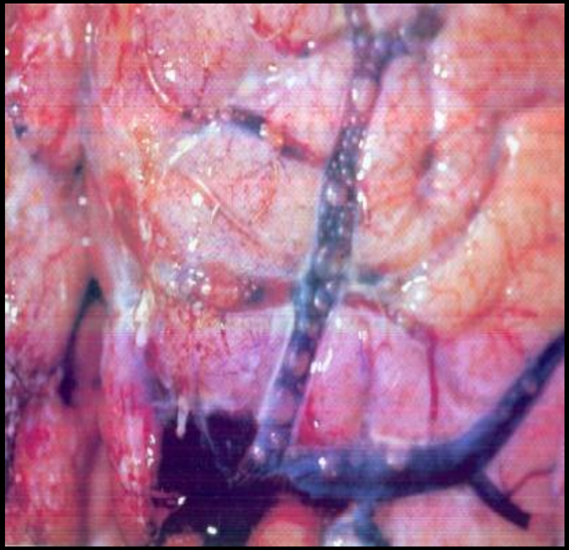
Pulmonary Barotrauma of Ascent

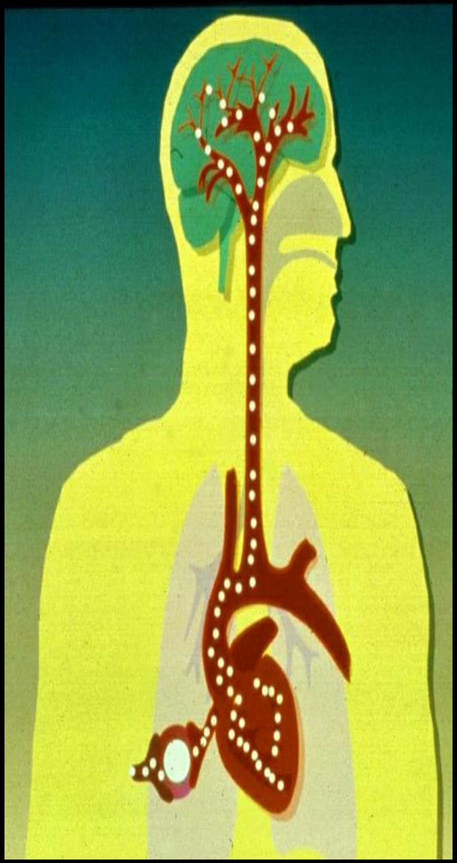
Arterial Gas Embolism (AGE)

Gas enters pulmonary vein
Gas moves into heart
Gas enters arterial circulation
Gas follows carotid artery to brain

Worst case scenario







Autopsy bubbles in brain

Pulmonary Barotrauma of Ascent: Signs & Symptoms

Bubbles in Brain ("stroke"): Damage depends on where bubbles lodge

Major clue: CNS involvement; may see

- Unconsciousness
- Cognitive Impairment
- Aphasia (can't talk)
- Auditory dysfunction
- Visual Disturbances (tunnel vision; unequal pupil sizes)
- Partial Paralysis (usually unilateral)
- Parathesis (unilateral numbness)
- Vertigo
- Convulsions
- Chest pain
- Skin marbling
- Personality change

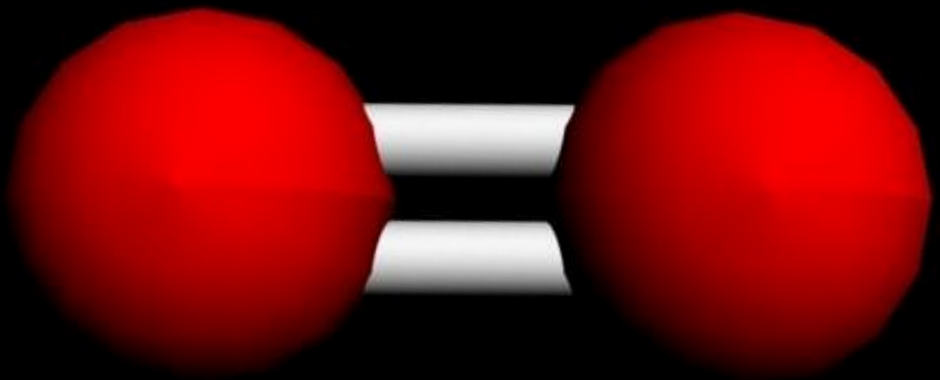
Rapid Onset:
Before surfacing
< 10 minutes after dive

Libermeister's Sign (white triangle on tongue)

Gas bubbles visible in retina of eye

Abnormal EKG

Red froth at the mouth



OXYGEN

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Oxygen Toxicity

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Oxygen Necessary For Life

Metabolism: narrow oxygen partial pressure window

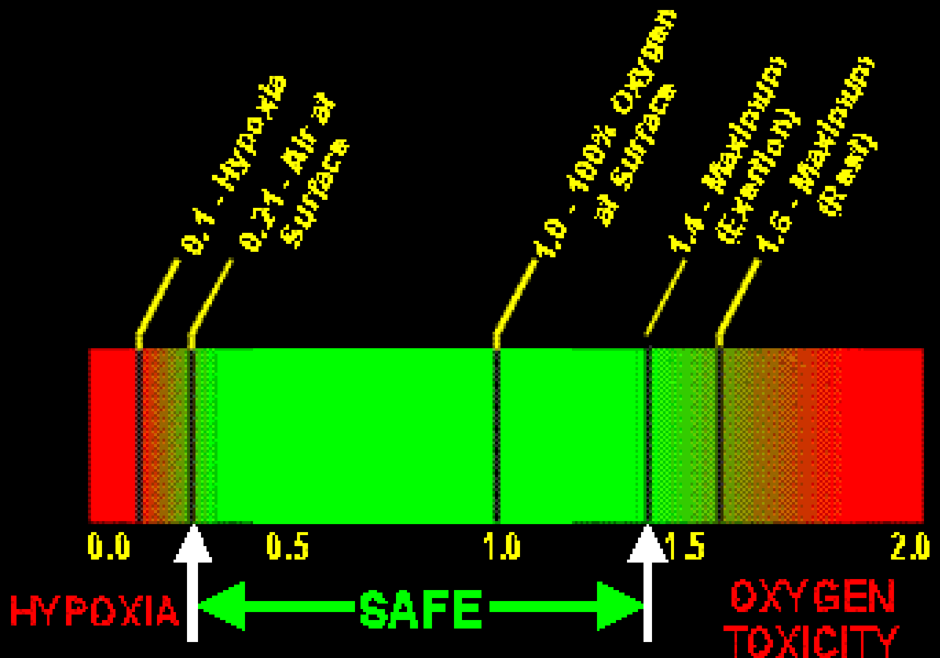
Too little oxygen (hypoxic) ➔ no life

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

Too much oxygen (hyperoxic) ➔ toxic reaction

Cellular components + O_2 ➔ "Bad stuff" (ROS)

Hypoxia
pO_2 < 0.16 ata



Hyperoxia
pO_2 > 1.6 ata

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Hypoxia (too little oxygen)

Simplistic View of Body Chemistry:

Fuel (sugar, fat, protein) + O_2 ➔ Energy

Brain can only use sugar supplied by blood flow

Any trauma (shock) reduces blood flow / sugar / O_2

Brain among first tissue to be compromised

Brain uses ~ 20% of total metabolic O_2 consumed

Low O_2 reduces / stops above energy reaction:

Normal cell function compromised

Blood vessels swell to increase blood supply

Skull impairs brain tissue expansion

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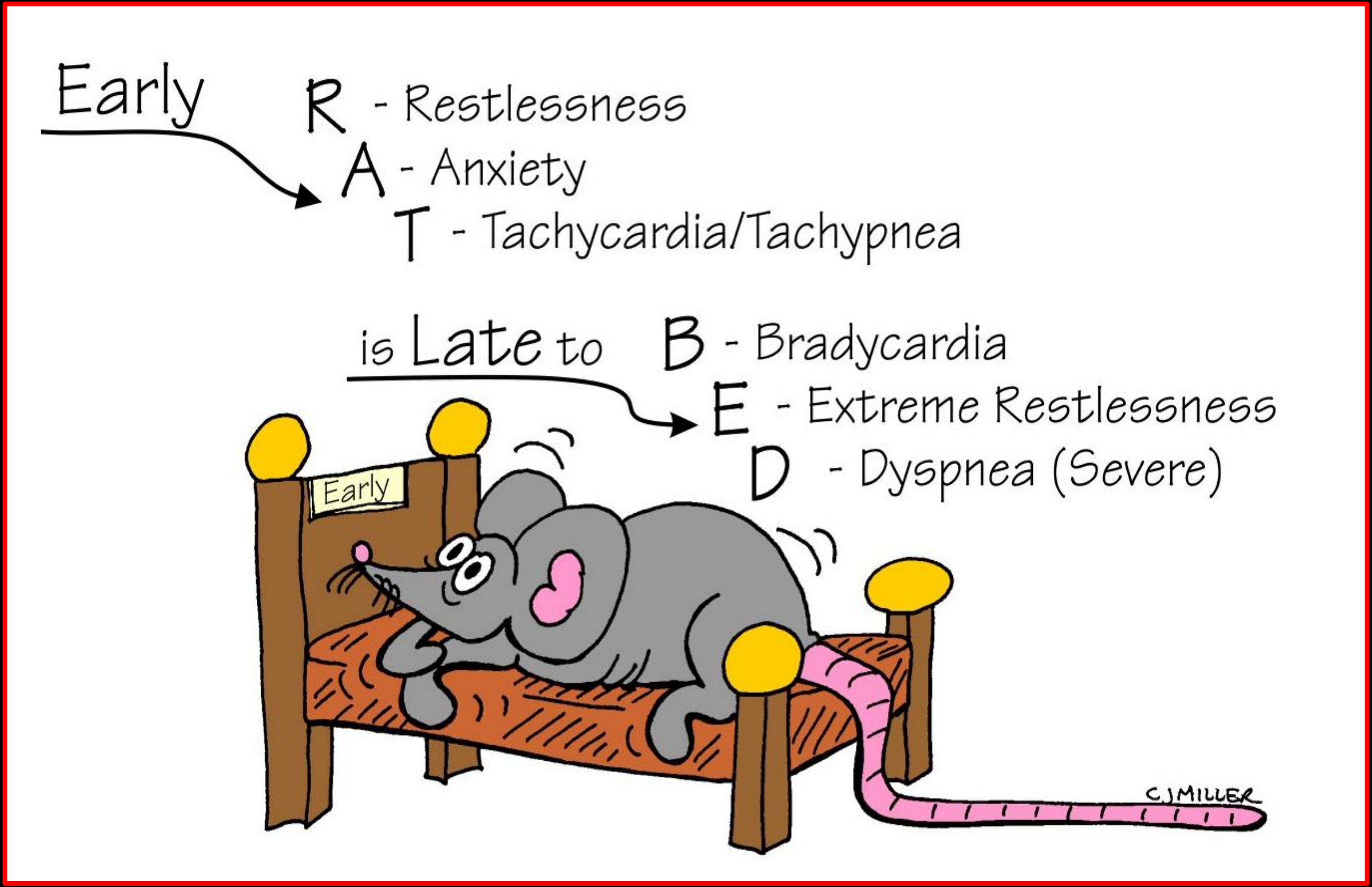
Hypoxia Symptoms



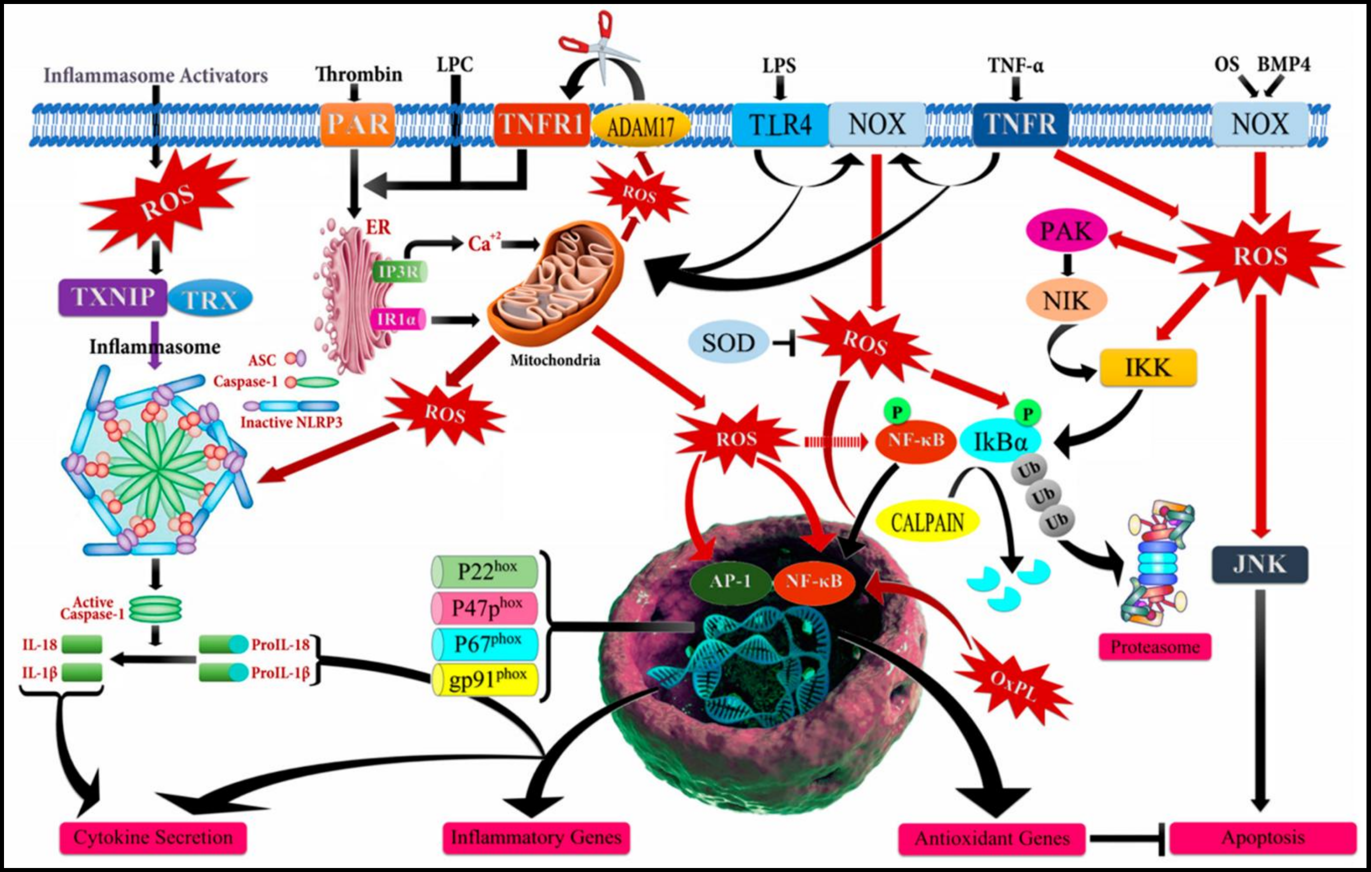
Ultimately: No oxygen → no life

Hyperxia (Too Much Oxygen)

Oxygen is a highly reactive element

Cellular components + O_2 ➔ "Bad stuff" (ROS)

ROS: Reactive Oxygen Species (Cellular Saboteur)



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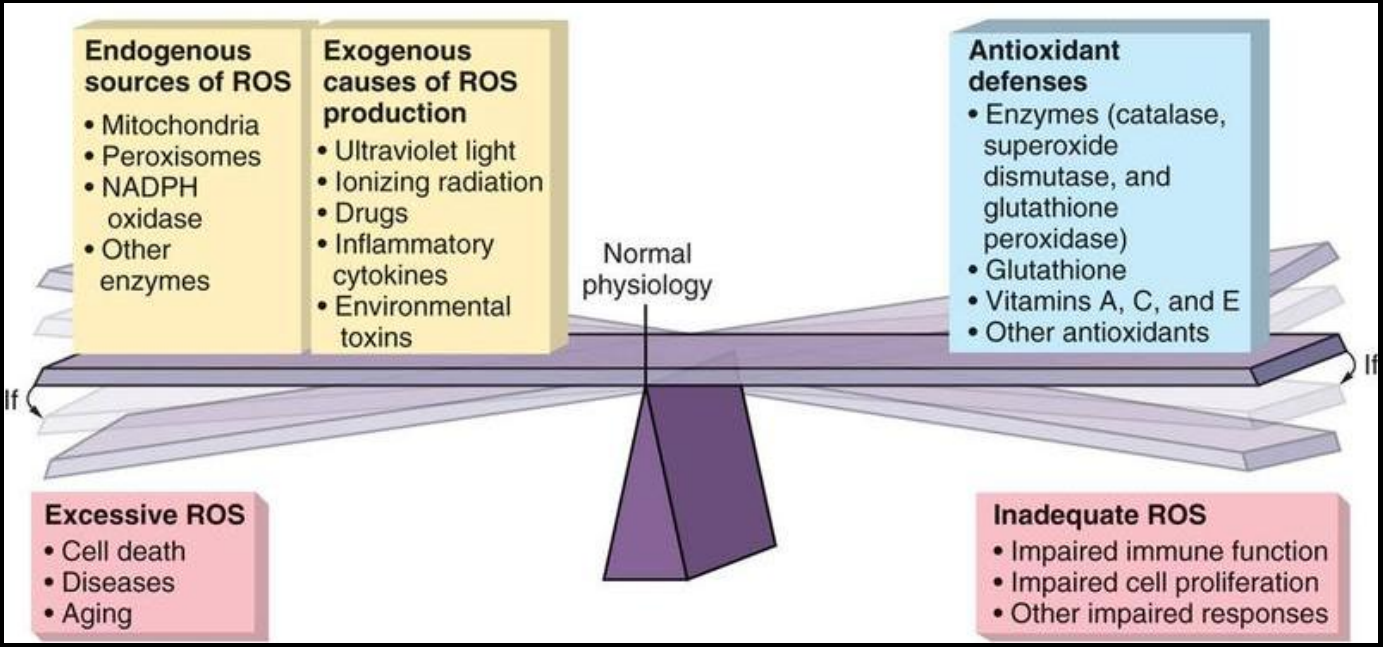
Hyperoxia

Reactive Oxygen Species (ROS) Constantly Produced

Direct result of oxygen molecule's chemical reactivity



ROS are biologically very destructive

Numerous biological defenses against ROS

SOD Superoxide Dismutase

GTP Glutathione Peroxidase

Lots of anti-oxidant molecules

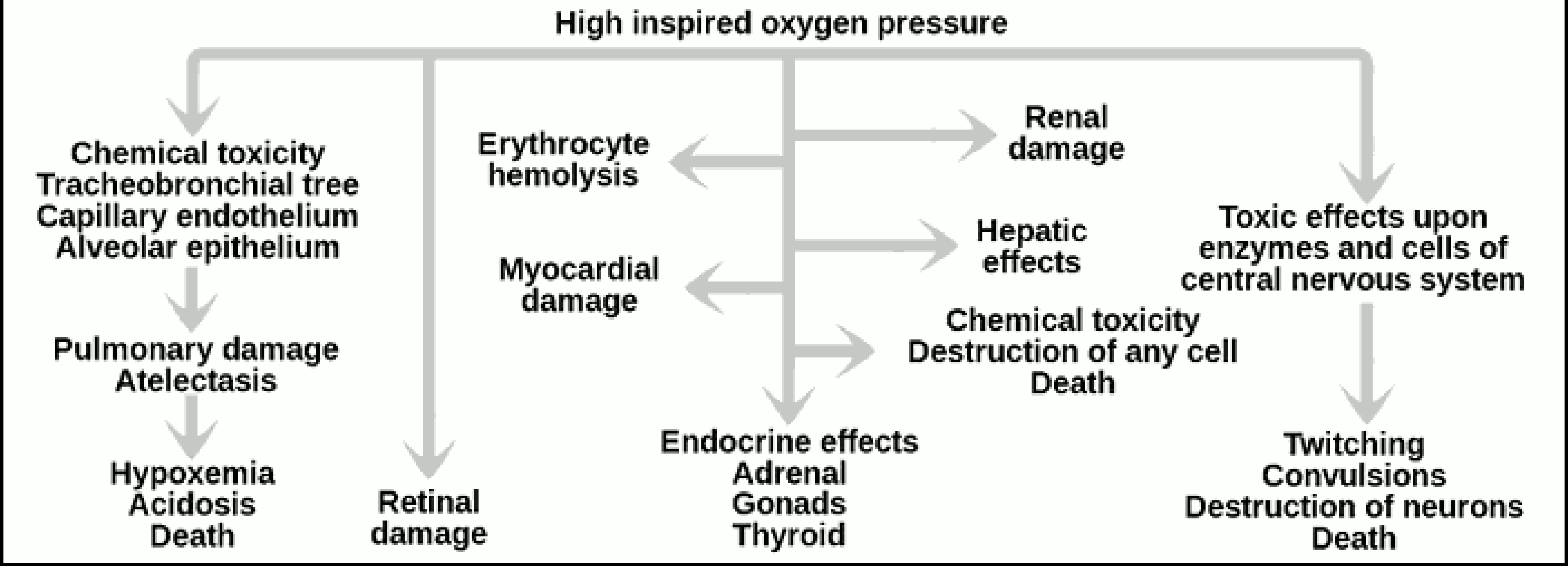
Hyperoxia Effects

Higher pO_2 increases ROS concentrations

Le Châtelier's Principle

Increase partial pressure: drive reaction to the right

Cellular components + O_2 ➔ "Bad stuff" (ROS)



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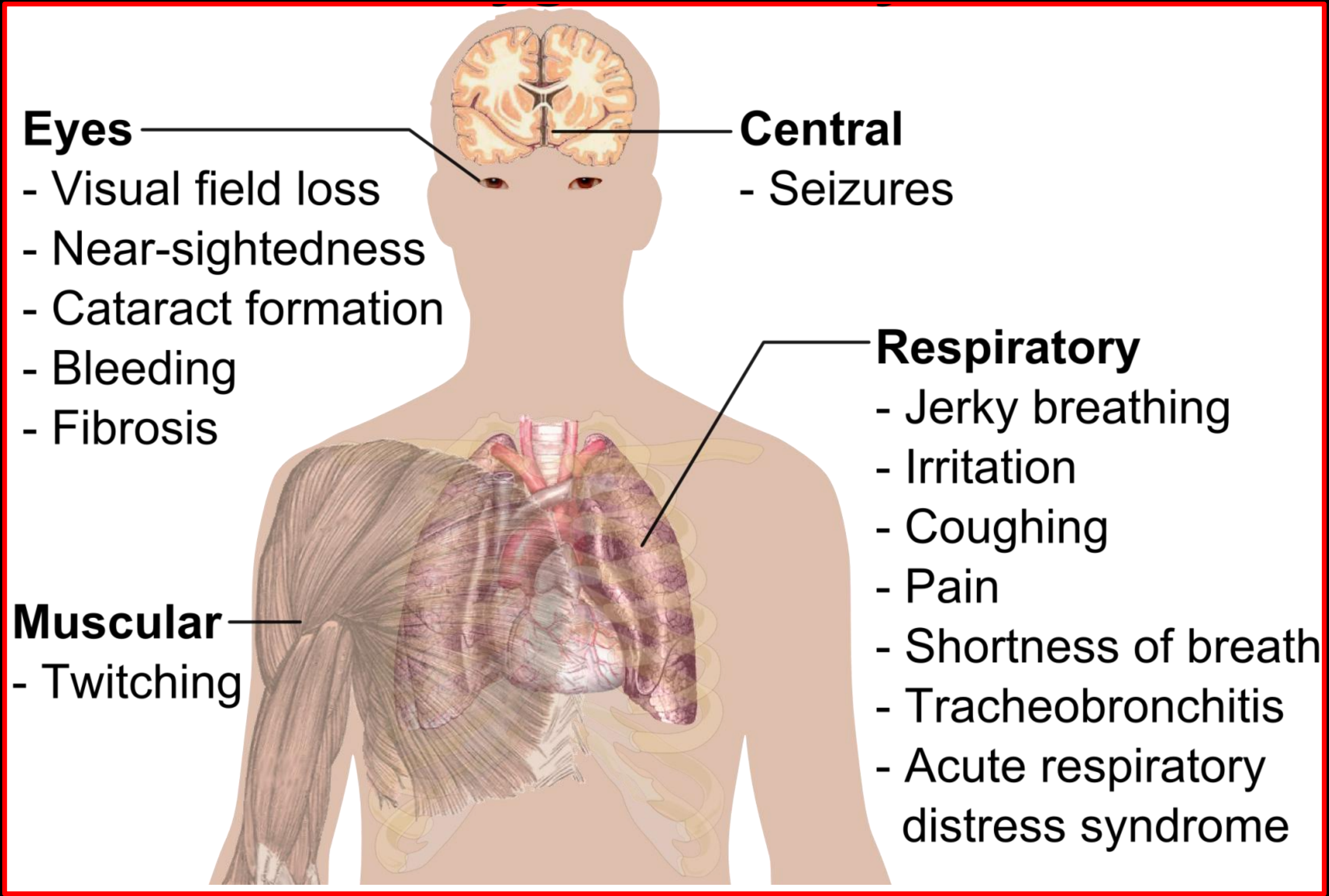
Hyperoxia Effects



Symptoms depend on pO_2 and exposure time

Hyperoxia Effects on CNS

VENTID – C

V	Vision
E	Ears
N	Nausea
T	Twitching
I	Irritability
D	Dizziness
C	Convulsions

ConVENTID

Not a progression … maybe no warning
May start with convulsions

Twitching usually starts at lower lip

Common causes:
Exceeding the oxygen exposure limits
Using an incorrect mix for the depth
Using wrong deco gas at depth

Recognition of ANY Symptom ➔ immediately ascend (reduce pO_2)

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Hyperoxia Effects on CNS

Oxygen toxicity effects may be enhanced by:
- Heavy exercise
- Breathing dense gas
- Breathing against resistance
- Increased CO_2 buildup
- Chilling or hypothermia
- Water immersion (as opposed to "chamber diving")

Individual tolerance to oxygen toxicity varies over time
Tolerance varies from individual to individual

Oxygen tolerance tests no longer considered valid

Hyperoxia Effects on CNS

Seizure in sport diving equipment is usually fatal

Spit out regulator (reflex inhale) and breathe water

Panic and "escape to surface" (embolize)

Diving EAN_x requires monitoring oxygen exposure

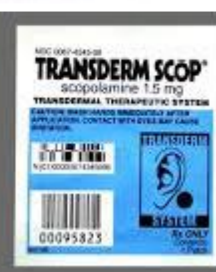
Surviving convulsions: reason to use full face mask

Hyperoxia Effects on CNS

Anecdotal suggestion that Sudafed increases seizure risk
(seizures are a side effect in children)

Other concerns:
anti-motion drugs (especially transderm (scopolamine))
aspirin, caffeine, viagra, nitro heart medication

Never rigorously studied
Best to avoid diving with any drugs



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Biological Defenses Occasionally Sold to Divers

No evidence that ingestion of unprotected SOD has any physiological effects

Ingested SOD is broken down into amino acids before being absorbed

SOD bound to wheat proteins MIGHT improve its ROS protection

Nitrox Therapy is a power workout Nitric Oxide promoter

An absolute contraindication for diving

(Nitric oxide implicated in oxygen toxicity convulsions)

Recent Findings suggest eating dark chocolate bar
~ 30 minutes pre-dive offers some protection from oxidative cell damage

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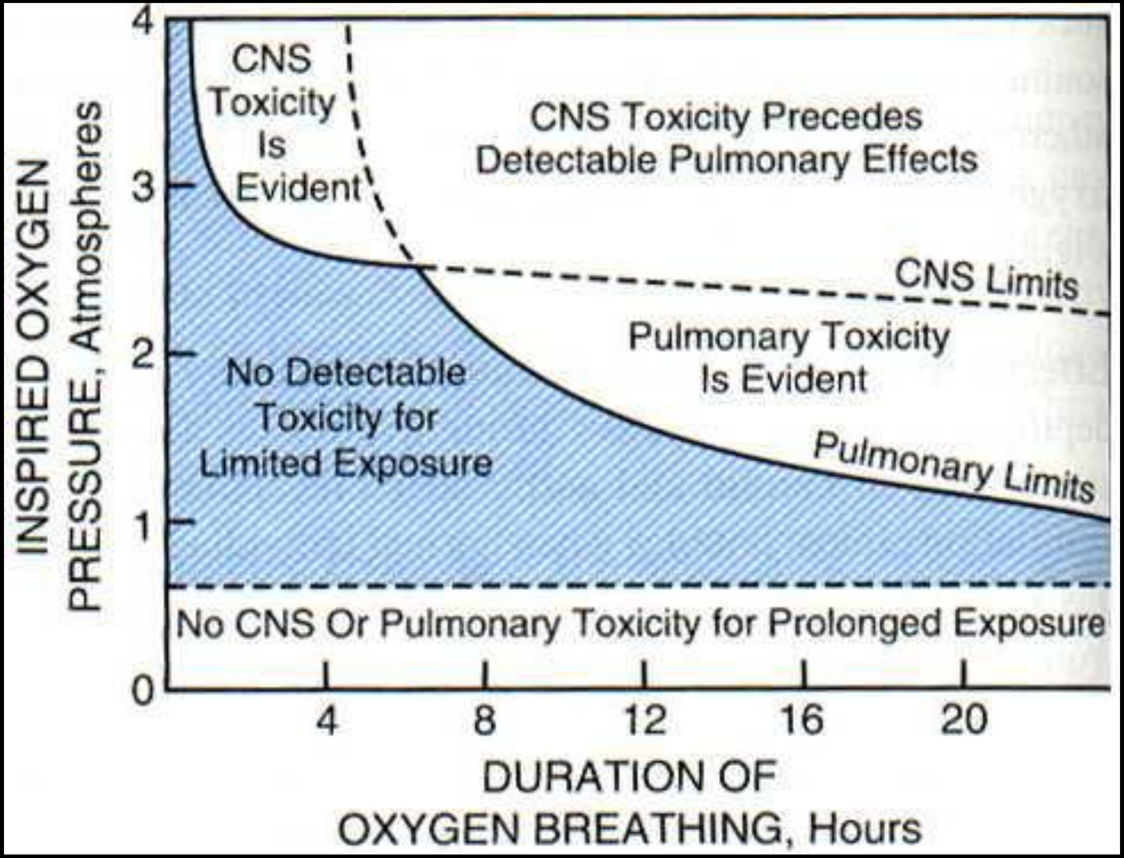
Whole Body Oxygen Toxicity

Formerly Pulmonary Toxicity (Lorrain Smith Effect)

Contrasted to CNS Toxicity (Paul Bert Effect)



CNS:
Rapid Onset

Whole Body
Slow Onset

Whole Body Oxygen Toxicity

No-deco stop diving concerned primarily with CNS toxicity

Whole Body a concern for:

- **Extended range**
- **Deco diving**
- **Intensive, multiple dive operations**
- **Mixes with high O_2 concentration**

Onset: breathing high pO_2 (> 0.5 ata) for hours

Relief: breathing pO_2 < 0.5 ata

Primarily effects the lungs

Typically, not a concern in standard range diving

Whole Body Oxygen Toxicity

Symptoms

Pulmonary
- Chest pain or discomfort
- Coughing
- Chest tightness
- Fluid in the lungs
- Reduction in vital capacity

Non-pulmonary
- Skin numbness and itching
- Headache
- Dizziness
- Nausea
- Visual disturbances
- Diminished aerobic capacity

Body optimized for 21% O_2

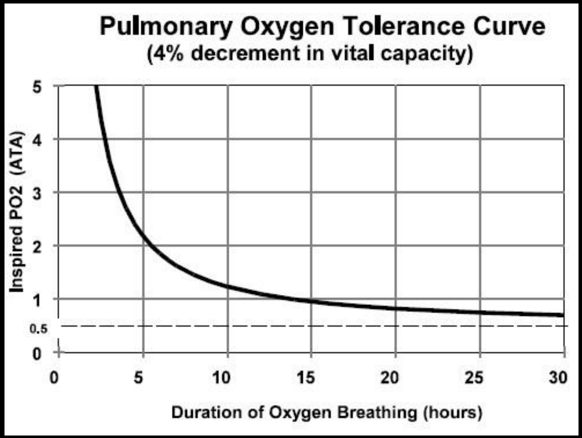
High pO_2 alters tissue structure

Lung tissue
- Thickens
- Becomes less pliable
- Reduces vital capacity

Oxygen Toxicity Units (OTU)

Based on decreased lung vital capacity while breathing 100 % O_2

1 OTU = Breathing 100% O_2 for 1 minute



At constant depth:

$$OTU = t\,[\,(pO_2 - 0.5) / 0.5\,]^{-0.83}$$

Ascending and descending:

$$OTU = \frac{0.27\, t}{pO_{2f} - pO_{2i}}\,[\,\{(pO_{2f} - 0.5) / 0.5\,)\}^{1.83} - \{(pO_{2i} - 0.5) / 0.5\,\}^{1.83}]$$

time (t) in minutes

pO_2 at constant depth in absolute atmospheres

pO_{2f} at final condition in absolute atmospheres

pO_{2I} at initial condition in absolute atmospheres

Solving involves integration of pressure over time ➔ best done by computer

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Oxygen Toxicity Units (OTU)

EAN_x diving below OTU threshold, so typically not tracked

OTU Daily (24 hours) Limits

Allowed Daily Exposure: 1440

Typical DCS Treatments:

- Table 5: 297
- Table 6: 607
- Table 6A: 820

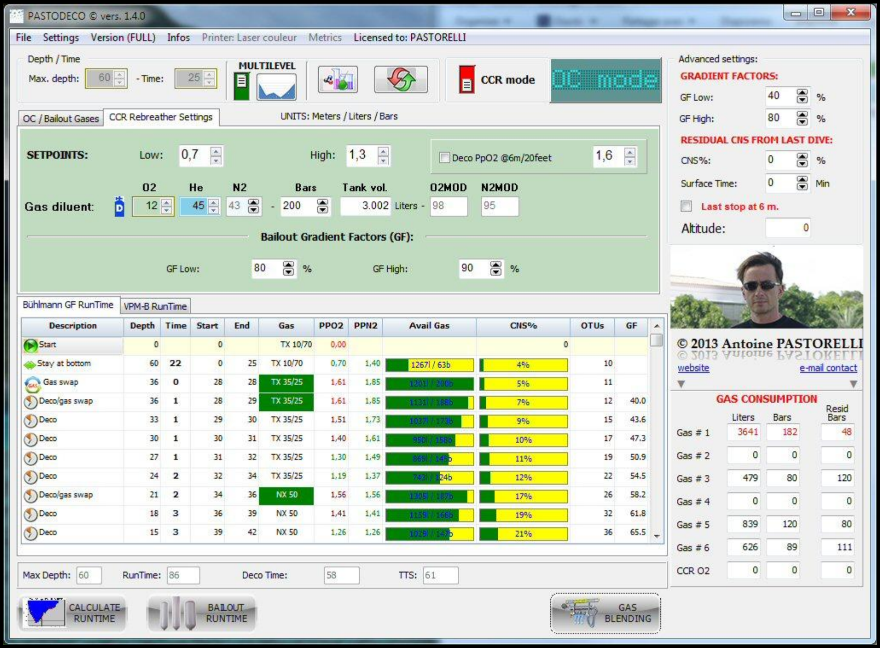
EAN_X Diving: ~40 - 300

Extended Range Diving: ~850

Typical Technical: ~300 - 400

Divers Track OTU's By

- Computer Planning Software
- In-water Dive Computers
- OTU Tables
- OTU Spreadsheets



NOAA Oxygen Exposure Limits

Example:

EAN_{32} mix at 130 fsw

Determine pO_2 at depth

% O_2 Depth to Pressure

pO_2 = 0.32[(130 fsw /33 fsw/atm) +1 atm]
pO_2 = 1.58 ata

NOAA Oxygen Exposure Limits		
PO_2 (atm)	Maximum Single Exposure (minutes)	Maximum per 24 hr (minutes)
1.60	45	150
1.55	83	165

Single Dive limit of 45 minutes

Example:

EAN_{40} mix at 130 fsw

Determine pO_2 at depth

% O_2 Depth to Pressure

pO_2 = 0.40[(130 fsw /33 fsw/atm) +1 atm]
pO_2 = 1.98 ata

pO_2 exceeds oxygen exposure limits

pO_2 too high for 130 fsw
Unacceptable oxygen toxicity risk

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NOAA Oxygen Exposure Limits

Example:

Using EAN_{32}

Reduce allowed pO_2 to 1.40 ata

1.45	135	180
→ 1.40	150	180
1.35	165	195

Single Dive limit of 150 minutes

Decreased allowed pO_2
Lowers maximum depth (MOD)

$$MOD = \left[\frac{(1.4\ ata)}{0.32} - 1\ atm \right] \frac{33\ fsw}{atm}$$

MOD = 111 fsw

Need to determine time and max depth for all EAN_x dives

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Percent CNS Oxygen Exposure

% Daily O_2 Allowance = [Dive Time / 24 hour Allowed] x 100

NOAA Summary for Common Dives

Max. PO2 Exposure (atm)	Dive Time (minutes)	:5	:10	:15	:20	:25	:30	:35	:40	:45	:50	:55	:60
1.2	210 Max.	2%	5%	7%	10%	12%	14%	17%	19%	21%	24%	26%	29%
1.25	195 Max.	3%	5%	8%	10%	13%	15%	18%	21%	23%	26%	28%	31%
1.3	180 Max.	3%	6%	7%	11%	14%	17%	19%	22%	25%	28%	31%	33%
1.35	165 Max.	3%	6%	9%	12%	15%	18%	21%	24%	27%	30%	33%	36%
1.4	150 Max.	3%	7%	10%	13%	17%	20%	23%	27%	30%	33%	37%	40%
1.45	135 Max.	4%	7%	11%	15%	19%	22%	26%	30%	33%	37%	41%	44%
1.5	120 Max.	4%	8%	13%	17%	21%	25%	29%	33%	38%	42%	46%	50%
1.55	82 Max.	6%	12%	18%	24%	30%	36%	42%	48%	55%	61%	67%	73%
1.6	45 Max.	11%	22%	33%	44%	56%	67%	78%	89%	100%			

For repetitive Dives:

Treat Residual O_2 Like Residual N_2

Use Surface Credit Table (Next Slide)

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CNS% Oxygen Exposure Surface Interval Credit Table

	Surface Interval							
Start	30 MINS	60 MINS	90 MINS	120 MINS	180 MINS	240 MINS	300 MINS	360 MINS
100%	83%	66%	49%	41%	24%	16%	11%	7%
95%	79%	63%	46%	38%	22%	15%	10%	7%
90%	75%	59%	44%	37%	22%	15%	10%	7%
85%	71%	56%	42%	35%	21%	14%	9%	6%
80%	66%	53%	39%	32%	19%	13%	9%	6%
75%	62%	49%	37%	31%	18%	12%	8%	5%
70%	58%	46%	34%	28%	17%	11%	7%	5%
65%	54%	43%	32%	27%	16%	11%	7%	5%
60%	50%	40%	29%	24%	14%	9%	6%	4%
55%	46%	36%	27%	22%	13%	9%	6%	4%
50%	41%	33%	24%	20%	12%	8%	5%	3%
45%	37%	30%	22%	18%	11%	7%	5%	3%
40%	33%	26%	20%	17%	10%	7%	5%	3%
35%	29%	23%	17%	14%	8%	5%	3%	2%
30%	25%	20%	15%	12%	7%	5%	3%	2%
25%	21%	16%	12%	10%	6%	4%	3%	2%
20%	17%	13%	10%	8%	5%	3%	2%	1%
15%	12%	10%	7%	6%	3%	2%	1%	1%
10%	8%	7%	5%	4%	2%	1%	1%	1%
Start	30 MINS	60 MINS	90 MINS	120 MINS	180 MINS	240 MINS	300 MINS	360 MINS

Cumulative % CNS Oxygen Exposure

Example:

First Dive: 40 minutes at pO_2 of 1.60 ata

% CNS Oxygen Exposure: (40 min / 45 min x 100) = 89%

Surface Interval: 120 minutes

New (Residual) % CNS Oxygen Exposure: 37 %

Second Dive: 30 minutes at pO_2 of 1.2 ata

Dive % CNS Oxygen Exposure: (30 min / 210 min x 100 = 14 %

Total CNS Exposure = (14 + 37) % = 51 %

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Per Minute % CNS Oxygen Exposure

PO2	CNS%/min	PO2	CNS%/min	PO2	CNS%/min
0.6	0.14	1.02	0.35	1.42	0.68
0.62	0.14	1.04	0.36	1.44	0.71
0.64	0.15	1.06	0.38	1.46	0.74
0.66	0.16	1.08	0.4	1.48	0.78
0.68	0.17	1.1	0.42	1.5	0.83
0.7	0.18	1.12	0.43	1.52	0.93
0.72	0.18	1.14	0.43	1.54	1.04
0.74	0.9	1.16	0.44	1.56	1.19
0.76	0.2	1.18	0.46	1.58	1.47
0.78	0.21	1.2	0.47	1.6	2.22
0.8	0.22	1.22	0.48	1.62	5
0.82	0.23	1.24	0.51	1.65	6.25
0.84	0.24	1.26	0.52	1.67	7.69
0.86	0.25	1.28	0.54	1.7	10
0.88	0.26	1.3	0.56	1.72	12.5
0.9	0.28	1.32	0.57	1.74	20
0.92	0.29	1.34	0.6	1.77	25
0.94	0.3	1.36	0.62	1.78	31.25
0.96	0.31	1.38	0.63	1.8	50
0.98	0.32	1.4	0.65	1.82	100
1	0.33				

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Maximum Operating Depth (MOD)

MOD – the maximum depth that should be dived with a given EAN_x mixture

$$MOD = \left(\frac{(PO_2\ limit,\ ata)}{(FO_2\ mix)} - 1\,\text{atm} \right) 33\,\text{fsw / atm}$$

Example: Determine MOD for a 36% mix with a pO_2 1.60 ata:

$$MOD = \left(\frac{(1.60\,\text{ata})}{(0.36)} - 1\,\text{atm} \right) 33\,\text{fsw / atm} = 114\,\text{fsw}$$

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Maximum Operating Depth (MOD)

For NOAA I (32% O_2)

pO_2 1.60

$$MOD = \left(\frac{(1.60\ \text{ata})}{(0.32)} - 1\ \text{atm} \right) 33\ \text{fsw/atm} = 132\ \text{fsw}$$

pO_2 1.50

$$MOD = \left(\frac{(1.50\ \text{ata})}{(0.32)} - 1\ \text{atm} \right) 33\ \text{fsw/atm} = 122\ \text{fsw}$$

pO_2 1.40

$$MOD = \left(\frac{(1.40\ \text{ata})}{(0.32)} - 1\ \text{atm} \right) 33\ \text{fsw/atm} = 111\ \text{fsw}$$

Maximum Operating Depth (MOD)

For NOAA II (36% O_2)

pO_2 1.60

$$MOD = \left(\frac{(1.60\ \text{ata})}{(0.36)} - 1\ \text{atm} \right) 33\ \text{fsw/atm} = 114\ \text{fsw}$$

pO_2 1.50

$$MOD = \left(\frac{(1.50\ \text{ata})}{(0.36)} - 1\ \text{atm} \right) 33\ \text{fsw/atm} = 105\ \text{fsw}$$

pO_2 1.40

$$MOD = \left(\frac{(1.40\ \text{ata})}{(0.36)} - 1\ \text{atm} \right) 33\ \text{fsw/atm} = 95\ \text{fsw}$$

EAN_x has shallower onset of CNS toxicity than air (Has more O_2)

For 1.4 ata limit

Air	187 fsw
NOAA I	111 fsw
NOAA II	95 fsw

For 1.6 ata limit

Air	218 fsw
NOAA I	132 fsw
NOAA II	114 fsw

Higher the pO_2
Shallower the MOD

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Using Dalton's Law (Determine Partial Pressures)

Dalton's law (based on fraction of component gas)

$$P_g = F_g \times P_t$$

P_g = partial pressure of the component gas
F_g = fraction of the component gas
P_t = total pressure of gas mixture (determined from depth)

For air (21 % O_2) being breathed at 90 fsw:

$P_g = F_g \times P$ where P = [(D fsw /33 fsw/atm) +1 atm]

pO_2 = 0.21 [(90 fsw / 33 fsw/atm) + 1 atm)

pO_2 = 0.78 ata

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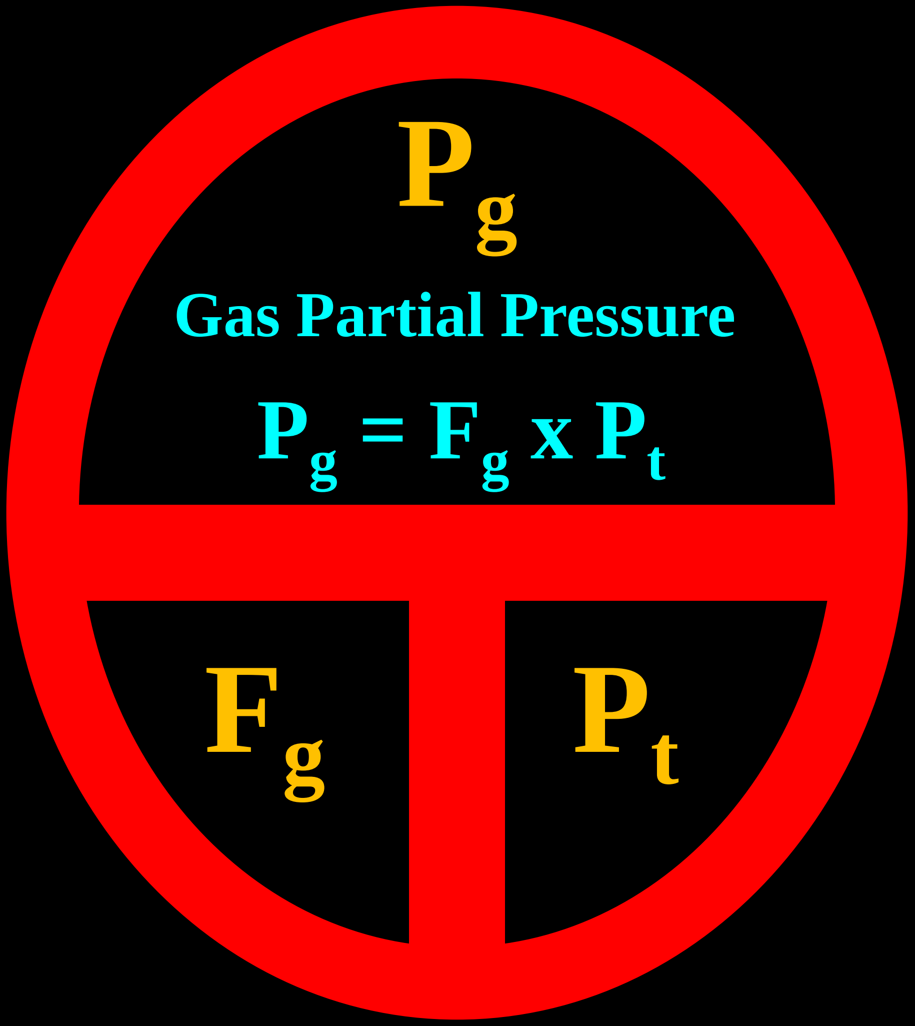
Classic Recreational Diving Dalton's "Pie"

Hide wanted segment: Result Solves for hidden segment

Also called:
"T"
Diamond



Fraction
Of a Gas

$$F_g = \frac{P_g}{P_t}$$

Total
Pressure

$$P_t = \frac{P_g}{F_g}$$

NOAA pO_2 for Depth vs. Fraction of Oxygen in the Breathing Mix

Depth (fsw)	Depth (msw)	atm abs	21%	28%	30%	31%	32%	33%	34%	35%	36%	37%	38%	39%	40%
0	*0*	1.00	0.21	0.28	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40
35	*11*	2.05	0.43	0.57	0.62	0.66	0.66	0.68	0.70	0.72	0.74	0.76	0.78	0.80	0.82
40	*12*	2.21	0.46	0.62	0.66	0.69	0.71	0.73	0.75	0.77	0.80	0.82	0.84	0.86	0.88
50	*15*	2.52	0.53	0.71	0.76	0.78	0.81	0.83	0.86	0.88	0.91	0.93	0.96	0.98	1.01
60	*18*	2.82	0.59	0.79	0.85	0.87	0.90	0.93	0.96	0.99	1.02	1.04	1.07	1.10	1.13
70	*22*	3.12	0.66	0.87	0.94	0.97	1.00	1.03	1.06	1.09	1.12	1.15	1.19	1.22	1.25
80	*25*	3.42	0.72	0.96	1.03	1.06	1.09	1.13	1.16	1.20	1.23	1.27	1.30	1.33	1.37
90	*28*	4.73	0.78	1.04	1.12	1.16	1.19	1.23	1.27	1.31	1.34	1.38	1.42	1.45	1.49
100	*31*	4.03	0.85	1.13	1.21	1.25	1.29	1.33	1.37	1.41	1.45	1.49	1.53	1.57	1.61
110	*34*	4.33	0.91	1.21	1.30	1.34	1.39	1.43	1.47	1.52	1.56	1.60	1.65	1.69	1.73
120	*37*	4.64	0.97	1.30	1.39	1.44	1.48	1.43	1.58	1.62	1.67	1.72	1.76	1.81	1.86
130	*40*	4.94	1.04	1.38	1.48	1.53	1.58	1.63	1.68	1.73	1.78	1.83	1.88	1.93	1.98
140	*43*	5.24	1.10	1.47	1.57	1.62	1.68	1.73	1.78	1.83	1.89	1.94	1.99		
150	*46*	5.55	1.17	1.55	1.67	1.72	1.78	1.83	1.89	1.94	2.00				
160	*49*	5.85	1.23	1.64	1.76	1.81	1.87	1.93	1.99						
170	*52*	6.15	1.29	1.72	1.85	1.91	1.97								

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Using the NOAA pO_2 Chart

Determine pO_2 of a 32% mix being breathed at 110 fsw

Depth (fsw)	Depth (msw)	atm abs	21%	28%	30%	31%	32%	33%	34%	35%	36%	37%	38%	39%	40%
0	*0*	1.00	0.21	0.28	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40
35	*11*	2.05	0.43	0.57	0.62	0.66	0.66	0.68	0.70	0.72	0.74	0.76	0.78	0.80	0.82
40	*12*	2.21	0.46	0.62	0.66	0.69	0.71	0.73	0.75	0.77	0.80	0.82	0.84	0.86	0.88
50	*15*	2.52	0.53	0.71	0.76	0.78	0.81	0.83	0.86	0.88	0.91	0.93	0.96	0.98	1.01
60	*18*	2.82	0.59	0.79	0.85	0.87	0.90	0.93	0.96	0.99	1.02	1.04	1.07	1.10	1.13
70	*22*	3.12	0.66	0.87	0.94	0.97	1.00	1.03	1.06	1.09	1.12	1.15	1.19	1.22	1.25
80	*25*	3.42	0.72	0.96	1.03	1.06	1.09	1.13	1.16	1.20	1.23	1.27	1.30	1.33	1.37
90	*28*	4.73	0.78	1.04	1.12	1.16	1.19	1.23	1.27	1.31	1.34	1.38	1.42	1.45	1.49
100	*31*	4.03	0.85	1.13	1.21	1.25	1.29	1.33	1.37	1.41	1.45	1.49	1.53	1.57	1.61
110	*34*	4.33	0.91	1.21	1.30	1.34	1.39	1.43	1.47	1.52	1.56	1.60	1.65	1.69	1.73
120	*37*	4.64	0.97	1.30	1.39	1.44	1.48	1.43	1.58	1.62	1.67	1.72	1.76	1.81	1.86
130	*40*	4.94	1.04	1.38	1.48	1.53	1.58	1.63	1.68	1.73	1.78	1.83	1.88	1.93	1.98
140	*43*	5.24	1.10	1.47	1.57	1.62	1.68	1.73	1.78	1.83	1.89	1.94	1.99		
150	*46*	5.55	1.17	1.55	1.67	1.72	1.78	1.83	1.89	1.94	2.00				
160	*49*	5.85	1.23	1.64	1.76	1.81	1.87	1.93	1.99						
170	*52*	6.15	1.29	1.72	1.85	1.91	1.97								

pO_2
1.39 ata

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"That's all Folks!"


Woo Hoo!
All done!


End of Class This Is


Dive long and prosper

LPT