Physiology in extreme conditions II

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High pressure: diving

also building tunnels
(high pressure against seeping water)

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Diving – 2 different situations/problems

- diving without breathing (freediving)
  - main problem: hypoxia

- diving with breathing apparatus
  - main problem: pressure

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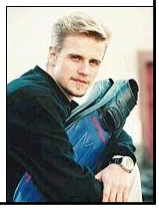
How long underwater?

- sperm whales & dolphins: 2 hr
- whales & seals: 18 min
- beaver, duck: 15 min
- rat, rabbit, cat, dog: 2-4 min

- Man: ~1 min
  - synchronized swimming: PaO_2 30-35 mmHg
  - Korean pearl divers : 2 min (20-30 m, 20x/hr)
  - free divers: 8 min. 6 sec.
    - 170 m no limits
    - own effort: Pipin Ferreras, Audrey Mestre, Martin Štěpánek, William Trubridge – over 100 m



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Free diving records

Constant Weight Apnea (CWT)	The athlete has to dive to the depth following a guide line that he is not allowed to actively use during the dive. The 'Constant Weight': the athlete is not allowed to drop any diving weights during the dive. Fins can be used	130 m 114 m	Alexey Molchanov Alenka Artnik	2018 2020
CWA Without Fins (CNF)	The same as CWT, but no fins	102 m 73 m	William Trubridge Alessia Zecchini	2016 2016
Free Immersion Apnea (FIM)	The athlete uses the vertical guiderope to pull himself down to depth and back to the surface. The athlete is still not allowed to release weights	125 m 98 m	Alexey Molchanov Alessia Zecchini	2018 2019
Variable Weight Apnea (VWT)	The athlete uses a weighted sled for descent. Athletes return to the surface by pulling themselves up along a line or swimming while using their fins	146 m 130 m	Stavros Kastrinakis Nanja van den Broek	2015 2015
No-Limits Apnea (NLT)	The athlete can use any means of breath-hold diving to depth and return to the surface, guideline used to measure the distance. Most use a weighted sled to dive down and inflatable bag to return	253 m 160 m	Herbert Nitsch Tanya Streeter	2012 2002

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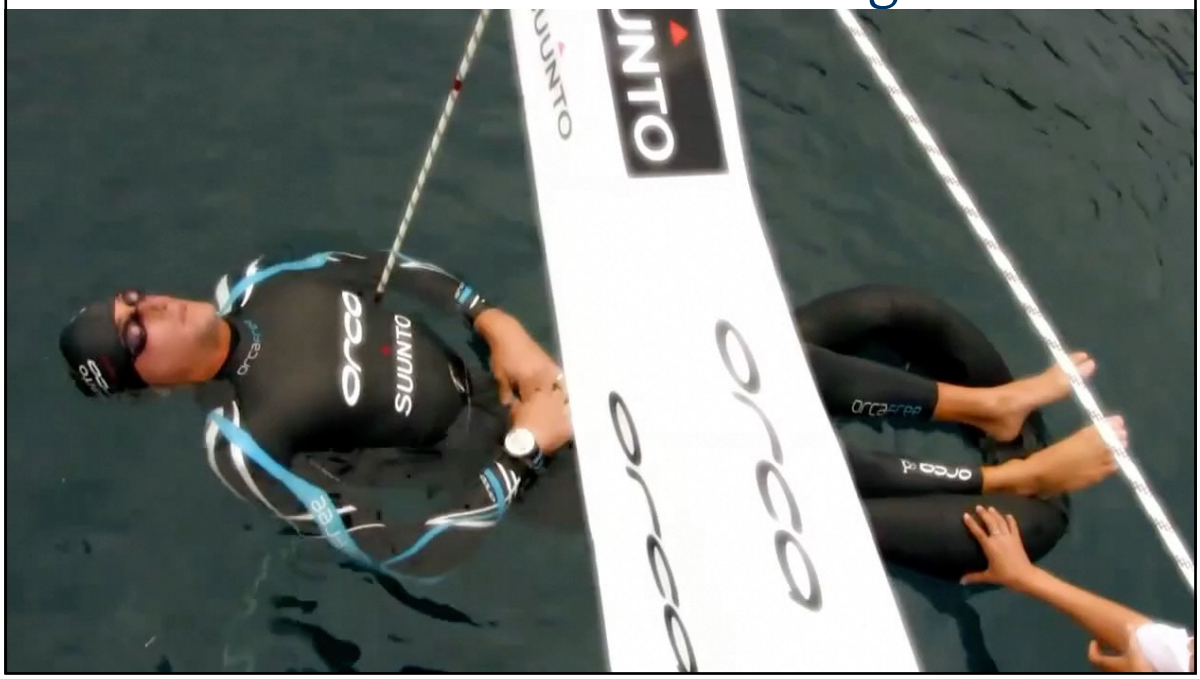
William Trubridge 101 m



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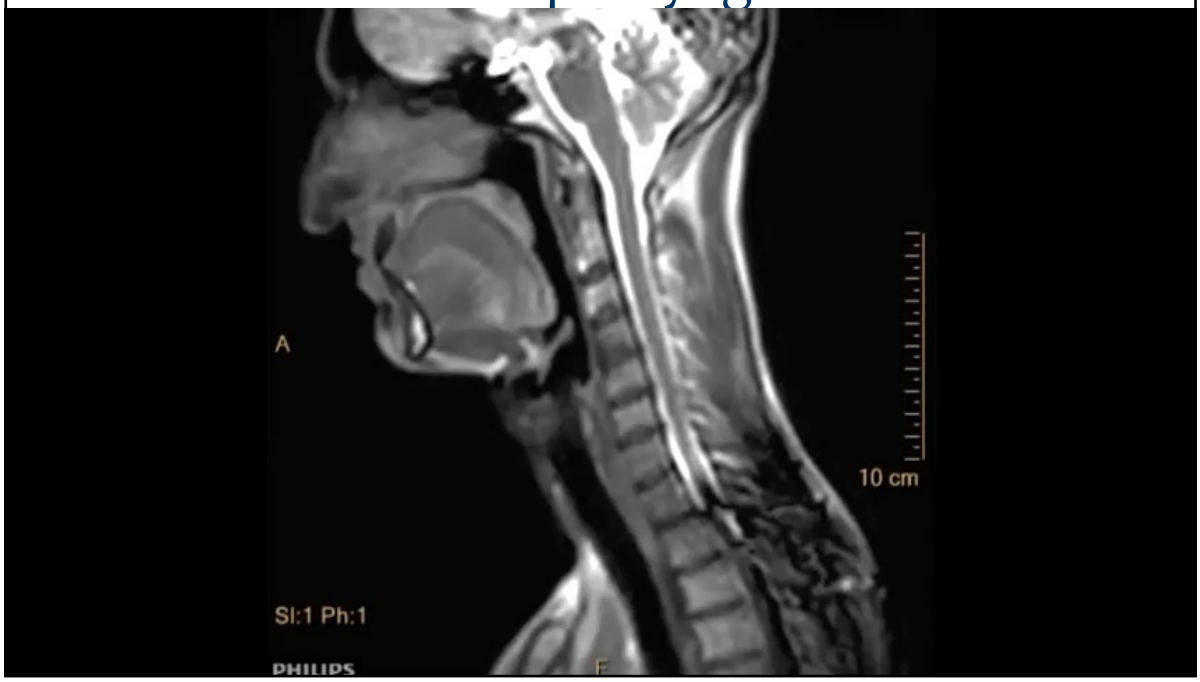
Glossopharyngeal insuflation



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Black-outs

- shallow water
  - ↑ ventilation before dive → ↓CO_2→ hypercapnic stimulus for inspiration later than PO_2 drops below brain needs
- deep water (just before re-surfacing)
  - down PO_2 OK, with ascent [O_2] in alveoli (& blood) insufficient for adequate PO_2 for brain

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Ploutvonožci

- reflex bradycardia (4/min), perfusion only of essential organs
- pressure at 30-40 m squeezes air out of lungs ⟶ fast descent (saves energy)
  - also from peripheral capillaries & veins ⟶ muscles, heart & brain
- muscle cooling (20 °C – they would not work in humans)
  - lower metabolism, less heat loss
- high blood volume, very high htc and high Hb/RBC
  - how do they resist coagulation & high viscosity?
- higher O_2 reserves in muscles (25-30% vs. 12 in humans)

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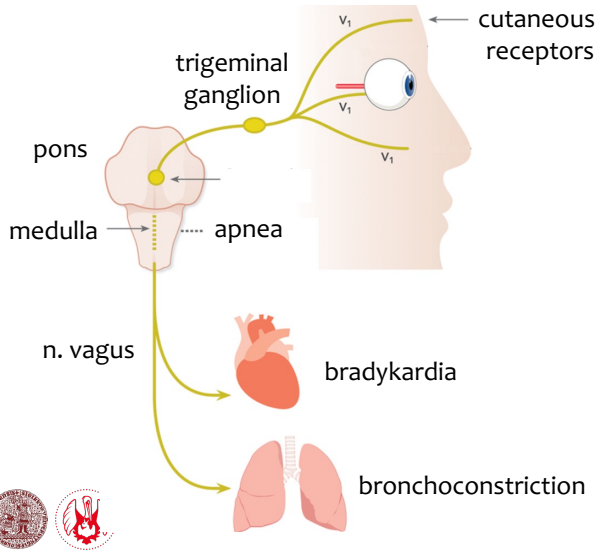
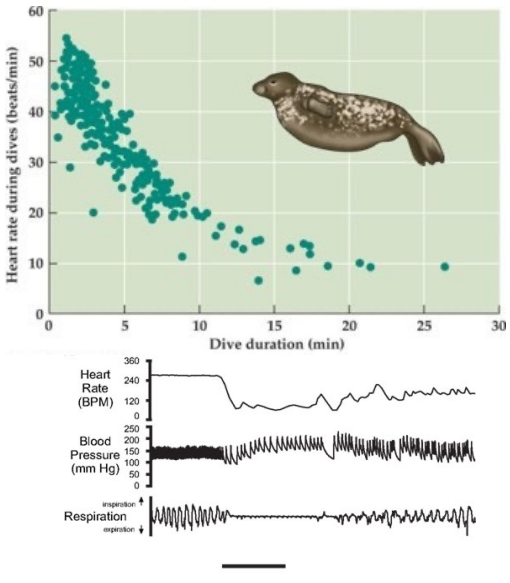
Mammalian diving reflex





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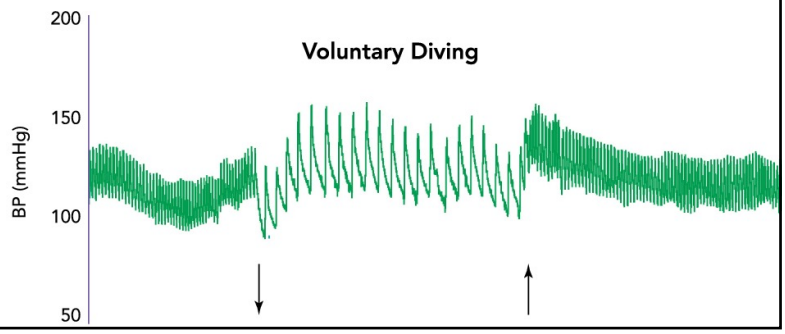
Mammalian diving reflex

- strong in aquatic mammals, weaker in other mammals (incl. humans)
- triggered specifically by cold water contacting the face
  - not water warmer than 21°C
  - not submersion of other body parts
- increases proportionally to decreasing water temperature
- apnea survival longer in cold water
- can be used to treat supraventricular tachycardia (?)



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Diving with a breathing apparatus

(SCUBA = self-contained underwater breathing apparatus)

- pressure ↑ by 1 atm per each 10 m
- to prevent lung collapse, the inhaled mixture must come under ↑ pressure

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↑ pressure → ↑ gas density

- at 4 atm: 2x ↑ work of respiratory muscles to move air through airways
- + need to move air in added dead space
- ± intentional or unconscious breath-holding
- → CO_2 retention → unconsciousness

- He density << N_2 (0.18 vs. 1.23 kg/m^3)

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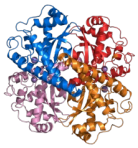
High PO_2

- e.g. PO_2 at 40 m:
  21% O_2, 5 atm ~ 100% O_2, 1 atm

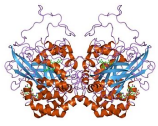
- ↑ O_2 radical production (O_2^-) overcomes cellular defenses
  - superoxide dismutase

    $2\ O_2^- + 2\ H^+ \rightarrow H_2O_2 + 2\ O_2$



  - catalase

    $2\ H_2O_2 \rightarrow 2\ H_2O + O_2$



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High PO_2

- 60% O_2 at 1 atm:
  - OK even for a long time (adults)
- $PO_2 \leq 760$ mmHg (100% O_2 at 1 atm)
  - pharyngitis, tracheitis after ~8 hr
  - then atelectasis, lung edema, ↓ mental activity
- 100% O_2 at >1.7 atm (~30 min):
  - irritation, nausea, dizziness, muscle cramps & seizures, vision problems, disorientation, unconsciousness

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Nitrogen narcosis

- Air breathing at ≥4-5 atm
- Similar to alcohol: euphoria, confusion, sleepiness, ↓ motoric coordination & strength
- By dissolving in cell membranes of neurons, N_2 reduces their excitability (similar to volatile anesthetics)

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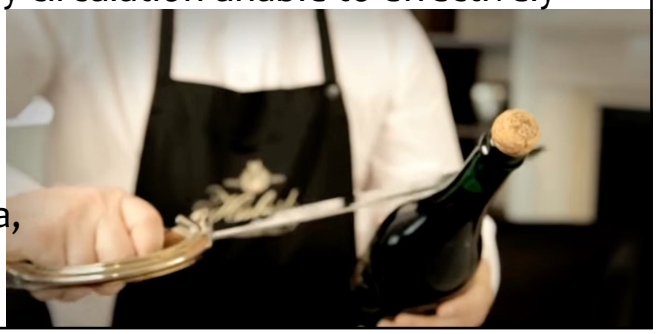
Decompression sickness

- bubble (20-700 μm) formation during surfacing in blood & tissues from supersaturated gas solution created during exposure to ↑ pressure
- surface of the bubbles is thrombogenous → generation of bubble-proteins-platelets complexes
- problems when pulmonary circulation unable to effectively filter it out
  (PAP ↑ by ~20 mmHg)
- pain in muscles, joints, paralysis, collapse, unconsciousness; dyspnea, lung edema, embolism



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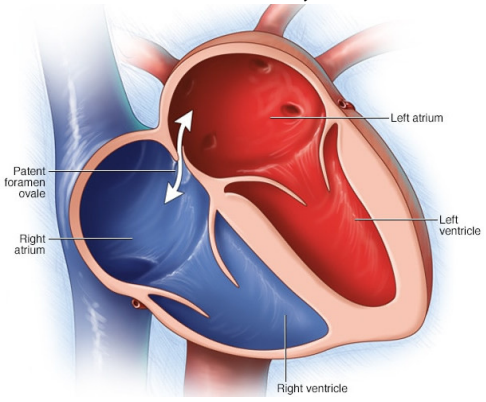
Decompression sickness

- only after a longer exposure
  - it takes time for N_2 to saturate body fluids (poor solubility)
  - esp. little vascularized fat (easiest for N_2 to dissolve in)
- worsened by activity
- He dissolves less than N_2
- cardiac shunts → ↑ risk
  (lungs cannot trap bubbles)



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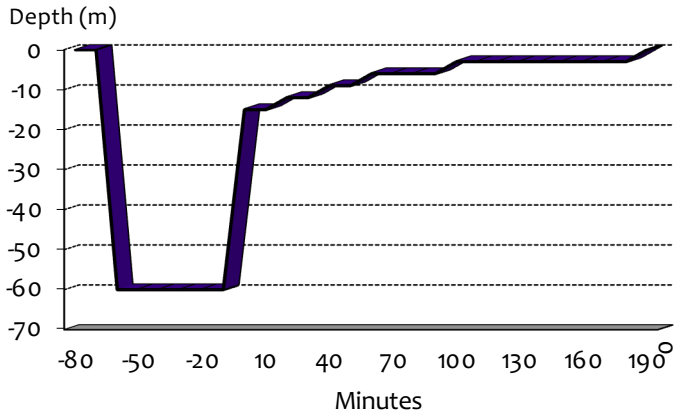
Decompression sickness: Prevention

- slow surfacing
- days/weeks in hyperbaric tanks



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Decompression sickness: Therapy

- recompression & slow decompression in hyperbaric chamber
- can be accelerated by hyperbaric O_2
  - no more N_2 is supplied
  - ↑ N_2 gradient between bubbles & their surroundings
  - ↑ O_2 diffusion into obstructed areas

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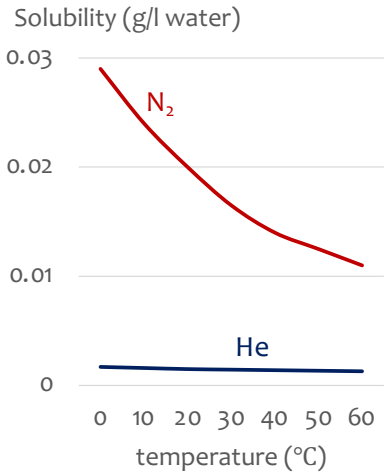
He instead of N_2

- ↓ density (0.18 vs. 1.23 kg/m³)
  - ↓ work of breathing → ↓ CO_2 retention
  - ↑ voice pitch → ↓ communication
- ↓ solubility
  (0.0015 vs. 0.02 g/l at 20°C)
  - ↓ narcotic effect
  - ↓ decompression sickness
- ↑ heat conductivity
  (0.151 vs. 0.026 $W \cdot m^{-1} \cdot K^{-1}$)
  - ↑ risk of hypothermia



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High pressure nervous syndrome (HPNS)

- below 130 m
- hyperexcitation of nerves by pressure
  - hand tremor
  - nausea, dizziness
- worse with faster descent
- reduced by blunting effects of N_2 (→ "Trimix")

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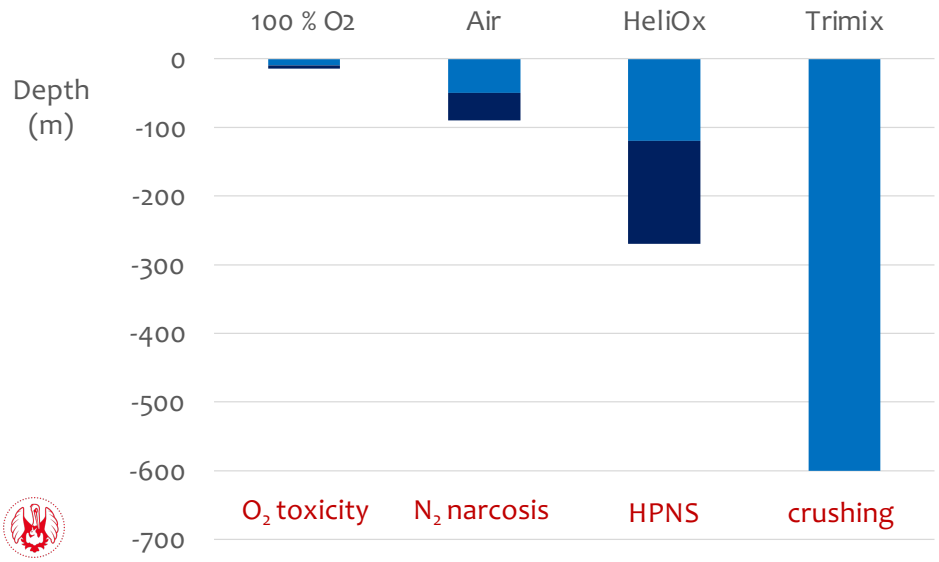
Depth of dive with various gas mixtures



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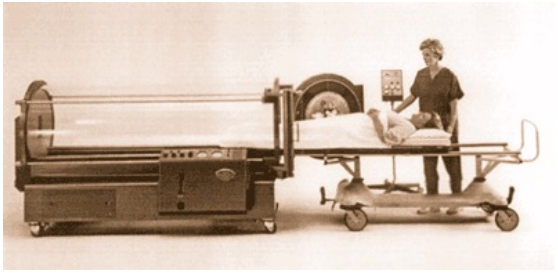
High pressure chambers



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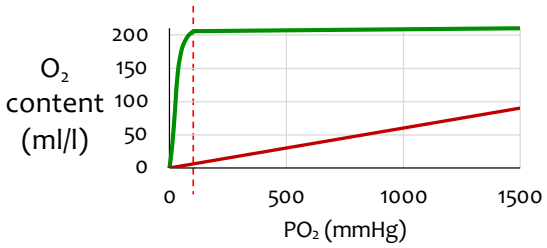
Hyperbaric oxygenotherapy



- CO intoxication
- air embolism
- anaerobic infections
- traumatic ischemia (crush syndrome)
  - after grave injury to extremity & its circulation, often with infection
- ischemic disease of the leg

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Barotrauma

due to gas pressure change where it cannot equilibrate with surroundings:

- nasal cavities
- rotten teeth
- middle ear (obliteration of Eustach's tube)
- bowel gases
- alveoli
  - excessive pressures during mechanical ventilation
  - if no exhalation during ascent

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Submarines

- Emergency escape
- Inner environment
  - (e.g. CO in cigarette smoke)

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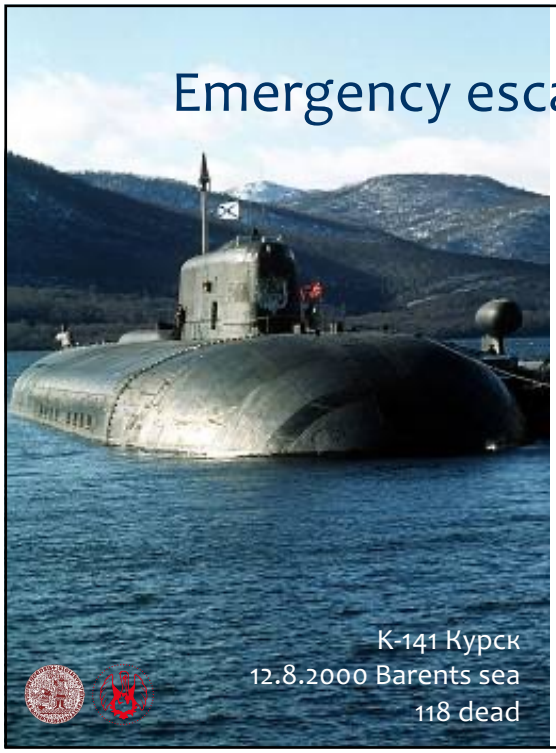
Emergency escape from submariness



- from 100 m possible without devices
- during ascent gas in lungs expands
- → constant exhalation necessary
- that also removes CO_2 → ↓ drive for inspiration

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Increased gravity

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G-force

- Rockets (3-9 G), airplanes, falls, collisions
- G = multiple of normal normal gravitational force

  \+ from head to toe

- opposite (from toe to head)

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Positive longitudinal G

- sitting humans can withstand:
  - 4 G ~40-50 sec
  - 15-20 G ~ 1 sec
    (standing less, recumbent slightly more)

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Positive longitudinal G

2 G:
- heavy, less movable limbs

3-4 G:
- problem with head upright
- keeping eyes open difficult
- breathing difficult

4-6 G:
- gray-out in several sec, then black-out

20 G:
- crush fractures of vertebrae

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"Gray-out/black-out"

+5G: pressure in leg veins 450 mmHg

- distension of veins of legs & abdomen
- downward shift of blood
- drastically ↓ venous return
- blood pressure ↓ (temporarily towards ~20 mmHg, then partly rectified by baroreceptors)
- less blood flow to brain & retina
- graying of the field of vision
- after tens of sec loss of vision, then unconsciousness

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Positive longitudinal G

- partly alleviated by anti-G suit
  - presses water or motorized cushions against legs & abdomen
  - does not prevent heart & diaphragm downward (⇒ limit ~10 G)
- training:
  - abdominal compression by forward bending & contraction of abdominal muscles
  - ↑ intrathoracic pressure

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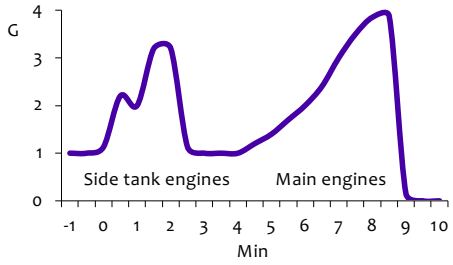

Positive transversal G

- rockert launch almost 10 G (space shuttle [1981-2011] 4G)
- the largest G tolerance: recumbent (10-17 G ≤3 min)
- the most affected: breathing
  - hypoventilation

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Negative G

- mainly air acrobatics
- more problematic than + G
- high pressures in brain vessels
  - despite opposing effect of cerebrospinal fluid
  - not true for retina ⟶ red-out
- face edema, risk of brain bleeding

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”Red-out"

- too much blood to retina
- the field of vision gets red
- loss of vision quickly follows

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Spaceflight challenges

- ↑ gravity at launch & re-entry
- microgravity
  - on orbit ~200 km the rest of gravity balanced out by centrifugal force
- radiation
  - e.g. Apollo flights < RTG check
  - worse at longer flights

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Weightlessness (microgravity)

- position sensing
- H_2O shifts
- muscles & bones
- lot more…

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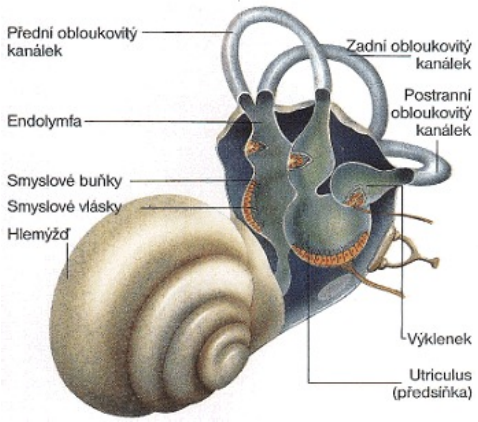
Position sensing

- mechanoreceptors in muscles & tendons
- inner ear
  - semicircular canals
  - otoliths
- tactile receptors in skin (mainly soles)
- visual cues



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Position sensing: semicircular canals

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Position sensing: otoliths

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Position sensing in microgravity

- dissociation of gravity-dependent and visual sensations
- disorders of spatial orientation
  - ”clomping with a rocket" instead of push-ups
  - sudden upward turn
  - upside down on entering weightlessness
  - eventually: down is where the feet are

- space adaptation syndrome

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Space adaptation syndrome

- ”seasickness" from the mismatch between visual, tactile and gravitational sensations
- nausea, sweating, dizziness, headache, disturbances of concentration, nausea, vomiting
- ≥ 45 % of astronauts
- resolves spontaneously (3-4 d)
- can return upon re-entry
- can be simulated by virtual reality

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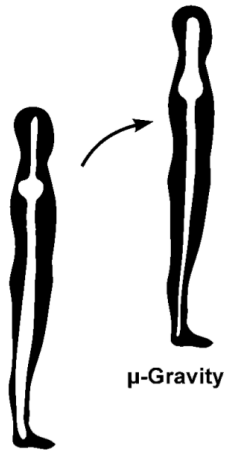
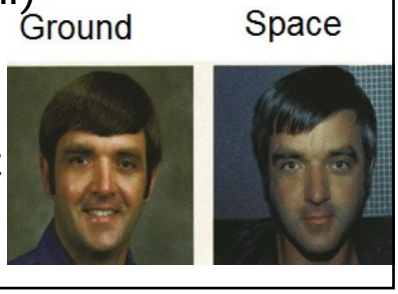
H_2O shifts



- water moves ↑ (head, chest)
- each leg loses ~1 l of fluid (10% of volume) during day 1
- this is helped by the ↑ volume of the chest (↓ weight of its wall)
- facial swelling ("puffy face"), nasal congestion, "runny nose" throughout weightlessness



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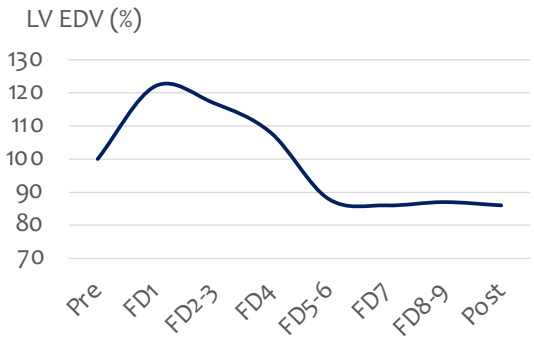
H_2O shifts

- ↑ blood volume in the chest → ↑ stroke volume and cardiac output
  - but CO ale eventually ↓ (non-active muscles need it less)
- atrial distension → ↑ ANP → ↑ diuresis "corrects" perceived hypervolemia



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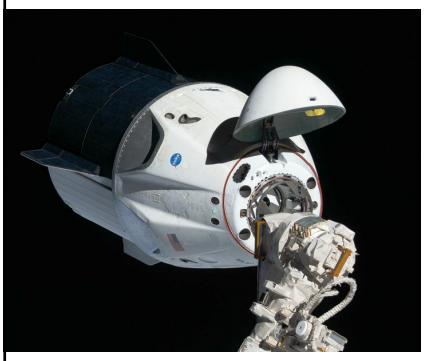
↑ H_2O in the upper half of the body



→ ↑ pressure in renal arterioles

→ ↑ GFR (up to +20%)

→ ↓ RAS

→ ↓ aldosterone → ↓ plasma volume (by 10-20%) → tissue dehydration

- normalization soon after return

  but first orthostatic intolerance (↓ stroke volume while standing because ↓ blood volume & shift to legs)

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Transient anemia

- first dehydration → ↑ relative hematocrit
- then ↓ erythropoiesis (↓ O_2 need due to ↓ muscle activity)
- blood cells even break down in an unclear way
- almost normalized after 2 months

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Heart in microgravity

↓ blood volume
↓ energy for movement and posture
→ ↓ demands on heart
→ ↓ heart size & efficiency

- normalization within a few weeks of return

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Bones & muscles

- astronauts get taller (no pressure on the spine)
- loss of ~1-1.5% bone mass (& Ca^{2+})/month for the duration of the flight
- strenuous exercise won't stop it, just slow it down (a bit)
  - most effective: running with one's feet in a vacuum chamber

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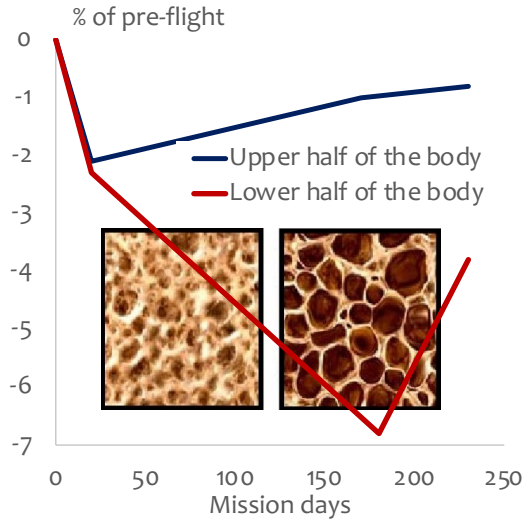
Loss of bone mass (osteopenie)

- mainly legs
- no natural vitamin D
- stops ~ 1 month after return
  - not entirely reversible?
- osteolysis: ↑ plasma Ca^{2+} → ↑ risk of kidney stones



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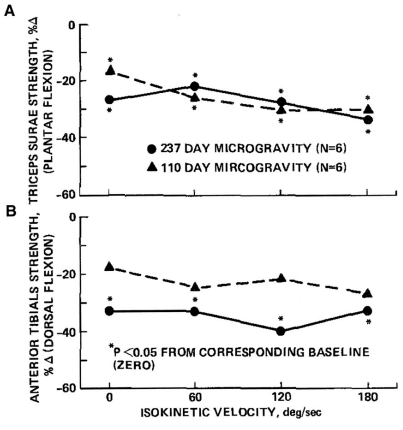
Muscles in microgravity

- atrophy
- slow (to support body weight) turn into fast
- ↓ myosin
- ↓ proteosynthesis
- ↓ number of vessels
- ↓ nerve endings
- similar to prolonged bedrest



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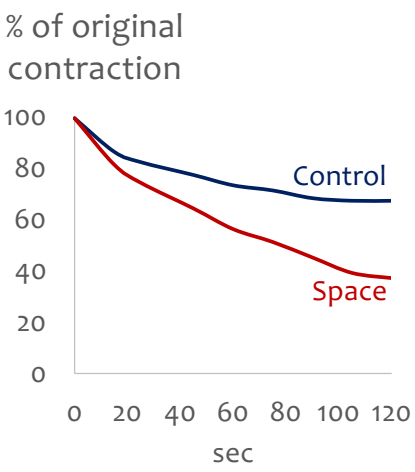
Muscles fatigue more easily in weightlessness



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Sleep

- snoring and sleep disturbances due to poor upper airway patency disappear
- circadian rhythm disturbance
- noise (ventilators)

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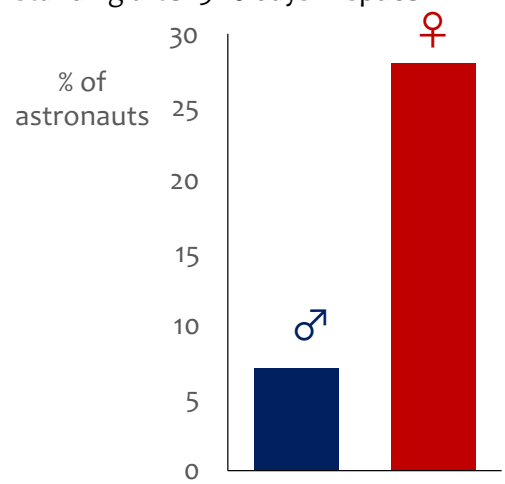
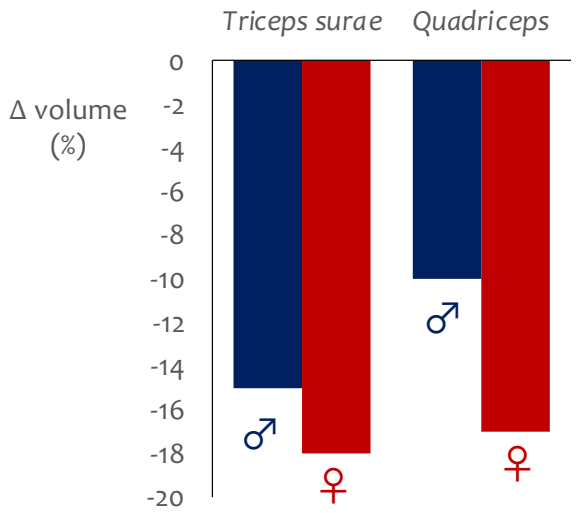
Sex differences

incidence of presyncope at 10-min standing after 5-16 days in space





retrograde intra-abdominal bleeding during menstruation → endometriosis

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Re-entry

- orthostatic intolerance
  - ↓ blood volume
  - ↓ arterial tone in legs
  - reasonable normalization within hours
  - drink ≥ 2 l of salt water before return
  - α1 agonists can help
- musculoskeletal weakness

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