From sea to land to sea

- **Short shallow divers** dive near the shore and only about 33 feet deep are the majority
  - These make up the majority of marine vertebrates (sea snakes, crocodiles, marine iguanas)
- **Deep divers** can spend longer periods underwater and can dive deeper
  - The typical dive of the emperor penguin is 400-500 feet deep and 4-5 minutes long, but can last up to 22 minutes!
- **Diving enthusiasts** spend up to 90% of their life at sea, diving for most of that time
  - The elephant seal can spend 2-8 months at a time at sea, only coming up for air for ~3 minutes every 20 minutes
OVERVIEW

All air-breathing marine mammals face the same problems:

1. Effects of pressure at depth
2. The need to actively forage while breathholding

There are two kinds of adaptations to resolve these problems:

1. Adaptations to pressure
   - Deals with mechanical effects of pressure and increased solubility of gas (N2 and O2) at depth
2. Adaptations to breath holding
   - Deals with modifications in metabolism, blood flow, and increased oxygen storage capacity
Adaptations To Pressure

- Air breathing vertebrates must deal with the effect of pressure involved with changes in volume in their air filled spaces.

- The first 10m of the water column has the most dramatic changes in air volume.

  - this is relevant to all diving vertebrates

- Pressure on cellular processes (organs and membranes) is only an issue for deep depths of 500-1000m.
Boyle’s Law

- Changes in volume dealing with diving depth follows Boyle’s Law.

\[ P_1 V_1 = P_2 V_2 \]

- This law states that within a closed system, as the pressure increases, the volume declines proportionally.
- Example: An animal with a 10-L lung at the water’s surface has a pressure of 1 atm. At a depth of 10m the pressure has increased to 2 atm. The lung is now at 5L, or half of its original volume.
Lung Collapse

- When diving, the air volume becomes so small that the lung collapses.
- To solve these problems, special adaptations arose in the thoracic cavity.
- Most marine animals have flexible chest walls that allow for complete lung collapse and have structures in their lungs to allow for the alveoli to collapse first and then the terminal airways.
- Recent studies show that marine mammals have specialized surfactants in their lungs that help in post-dive reinflation of the lungs.
Middle Ear Squeeze

- A similar problem to lung collapse occurs in the middle ear, called Middle Ear Squeeze
- Adaptations came about in the middle ear to solve this
- Marine mammals developed cavernous sinuses in the middle ear that presumably engorges with blood as they dive, therefore filling the air space so it does not “squeeze”
HPNS

- Pressure affects the tissues themselves—specifically the nervous system
  - In humans, this manifests itself as tremors and convulsions
- Majority of marine mammals do not dive deep enough to experience this
DISEASES ASSOCIATED WITH GASES AT PRESSURE

- At high partial pressures, $\text{N}_2$ and $\text{O}_2$ are toxic
  - Severe consequences in humans
- The problem with increased pressure is that body tissues absorb greater amounts of gas at higher pressures
  - Decompression sickness
Solution to Decompression Sickness

- Some marine mammals have the advantage of lung collapse...however, not all mammals can avoid this condition.

A spherical lesion in a sperm whale rib caused by nitrogen bubbles in the blood.
Diving Metabolism

- Diving animals have reduced metabolism
- There is also an increased reliance on anaerobic metabolism
  - Advantage: no need for oxygen
  - Disadvantage: produce 2 ATP instead of 38 ATP. Lactic acid is also toxic.
- Some diving animals have greater buffering capacities in their muscles to deal with lactic acid, have higher concentrations of glycolytic enzymes, and a greater tolerance to hypoxia.
Bradycardia is the reduction of heart rate and therefore cardiac output of blood
- Periphery resists blood so that it is localized in the heart, lung, and brain
- Result is reduced metabolism and conservation of energy
- Highly elastic aortas is a key adaptation of diving mammals
  - Stores energy from each heartbeat and uses the energy to pump blood out from time to time when peripheral tissues need it
Microspheres Study

- The redistribution of blood flow to the heart, lung and brain was confirmed in a study that used microspheres
  - The small, radiolabeled microspheres accumulate in tissues that have the greatest blood flow
- Microspheres were injected into the blood of a seal breathing at the surface and compared to a seal which had microspheres injected while it was in a forced dive
  - In the forced dive, the labeled particles were mostly found in the heart, lung, and brain (duh)
The percentage of red blood cells for a given volume of blood is called the haematocrit.

A high haematocrit means more red blood cells and thus more oxygen. The initial confusing observation was that the haematocrit increased during a dive. But where were these red blood cells coming from?

- Possibly were released by the spleen.
- Possible came from the hepatic sinus.

In a study with seals, the spleen volume decreased as the hepatic sinus volume increased, indicating that while breathing at the surface a seal sequesters red blood cells in the spleen, however, when the seal dives the spleen contracts, pushing the red blood cells into circulation.
Oxygen Stores

- To stay submerged, diving animals increase the oxygen stored in their internal tissues (lungs, muscles, and blood)
- The muscles of these animals have greater concentrations of oxygen-carrying pigments of hemoglobin and myoglobin.
  - Myoglobin carries oxygen into muscles and helps stores it.
  - Hemoglobin carries oxygen in red blood cells
- Diving animals have 10-30 times more myoglobin and about 10-20% more hemoglobin and even greater blood volume.
Forced-dived animals heart rates dropped from 140 to less than 10 beats per minute, showing profound bradycardia.

But when the same seal was asked to voluntarily dive, the heart rate dropped from 140 to only 40 beats per minute.

This shows that dive response is graded and can be managed to the circumstances in which the animal finds itself.
Weddell Seals

- Further studies were done with diving Weddell seals, *Leptonychotes weddelli*
- Confirmed that animals have considerable control over their heart rate and can modify it as appropriate to the needs of a specific dive
- Additionally, blood lactic acid levels were measured
- This work showed that lactic acid levels remained constant for dives up to 20 minutes and increased rapidly with increased dive durations
ADL Calculation

- This work defined the maximum time an animal could remain submerged without utilizing anaerobic metabolism.
- Thus, the Aerobic dive limit (ADL) was calculated.
- ADL (min) = total oxygen store (mLO2)/diving metabolic rate (mLO2/min).
- Disadvantage to using anaerobic metabolism:
  - Total accumulated time spent under water is less, because the animal spends proportionately more time at the surface clearing lactic acid.
Other Determinants of Diving Behavior

- Large body size also confers greater diving ability
- Still need to move through water to capture food
  - Most accomplished divers are also very efficient swimmers and have a very hydrodynamic body that allows efficient underwater locomotion
- No reason to go deeper than prey
Wrap-Up

- All air-breathing marine mammals face the two key problems:
  1. Effects of pressure at depth
  2. The need to actively forage whole breathholding
- To cope with these problems, air-breathing marine mammals have adapted:
  1. Adaptations to pressure
     - Deals with mechanical effects of pressure and increased solubility of gas (N2 and O2) at depth
  2. Adaptations to breath holding
     - Deals with modifications in metabolism, blood flow, and increased oxygen storage capacity