CARDIOVASCULAR AND METABOLIC ADAPTATIONS TO DIVING

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We Thrive Under Pressure

Introduction

At the 2006 UHMS we presented an overview, in a poster format, of mammalian adaptations to diving and their counterparts in human divers. The adaptations were divided into six organ systems as follows:

Systems Adaptations

Cardiovascular
- Dive reflex
  - -Bradycardia
  - -Shunting
  - -Anaerobic metabolism
- Maintain perfusion of critical organs

Respiratory
- Lung function
  - -Dive on exhalation
  - -↓breathing rate } ↑O_2 Extraction
  - -↑TV/TLC ratio }
- Altered sensitivities
  - -Low O_2's
  - - High CO_2's

Orientation
- Ecolocation
- Visual changes
  - -Low light (↑rods)
  - -Accommodation ("U" shaped iris)

Hematological
- ↑Blood volume
- ↑Hematocrit
- Muscle myoglobin
- ↑O_2 extraction

Thermal
- Surface area mass ratio
- SQ Fat
- Metabolism
- Dive reflex
- Heat exchange

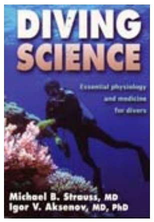
Propulsion
- Hydrodynamics & body shape
- SQ Fat
- Kinesiology
- Heat exchange

This presentation is a sequel to the 2006 overview and focuses on the cardiovascular (CV) and metabolic adaptations of the diving mammals. The goals of this presentation are as follows:

- To explain the anatomy and physiology of the cardiovascular (CV) and metabolic adaptations of the diving mammals
- To describe how these adaptations contribute to other organ system adaptations to diving
- To consider the counterparts of these adaptations observed in human divers

Materials & Methods

In researching material for Part II *(Physiological Responses to the Underwater Environment)* for our text, ***Diving Science—Essential physiology and medicine for divers,*** we discovered a wealth of information about mammalian adaptations to diving.



The primary role of cardiovascular and metabolic adaptations to diving is to extend the apneic dive time, that is the time spent underwater while breath-holding. Three adaptations explain how diving mammals perform apneic dives for as long as two hour durations: 1) The diving reflex, 2) Anatomical modifications to ensure continuous perfusion of critical organs and 3) The ability to utilize oxygen from blood reservoirs.

Like the other mammalian adaptations to diving, the cardiovascular and metabolic adaptations have secondary roles which contribute to the aquatic abilities of these animals.

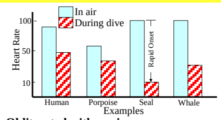
Features of the CV/Metabolic Adaptations

Diving Reflex

- **Initiated by H_20 contact with the ophthalmic branch of the Trigeminal (5th cranial) nerve**
- **More effective in cold water**

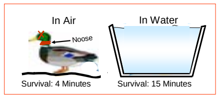
Bradycardia

Rapid, marked slowing of heart rate



1. **Obliterated with panic—**Observations in seals similar to humans; best responses in seals with "good dispositions"
2. **Heart rates increase as the dive progresses**
3. **Arrhythmias common—cease upon surfacing**
   - Prolonged diastoles
   - ↑ QT intervals
   - ↑ PR intervals (to loss of P wave)
   - AV blocks & peaked T waves observed in humans

Observed in 75% of human apneic divers



Andersen's classical experiment demonstrating the diving reflex in a non-mammalian diving animal

Shunting

Shifting of blood to the core

1. **Profound peripheral vasoconstriction and movement of blood to the core**
   - Extremities
   - Kidneys
   - Splanchnic bed
   - Skin/subcutaneous tissue

   There is almost total cessation of blood flow in these areas

2. **Oxygen stores in the core blood** (plus extraction from blood reservoirs—see below) **provide adequate O_2 to meet the brain and heart's metabolic needs during the dive**

- **In air** — Seal resting O_2 consumption = 300 ml/min; Seal blood O_2 stores = 1000 ml — **3 1/3 min**
- **Dive** — Brain O_2 consumption = 40 ml/min — **25 min**

Anaerobic Metabolism

Energy producion without O_2

1. **Sustains viability of non-critical tissues**
2. **About 1/19th the energy production as aerobic metabolism**
3. **Lactic acid does not escape into the core circulation (secondary to shunting)**

   Manatee:
   - Dive — Core serum lactic acid = 10 mg%
   - Surface — After Surfacing = 100-150 mg%

4. **Metabolism of non-critical tissues slows almost to hibernation levels**
5. **O_2 depletion (debt) is "repaid" during the surface interval**

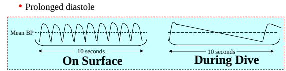
Japanese (Ama) women divers heart rates decrease by an additional 20% during the winter (cold water) diving season

Extend the Time Underwater

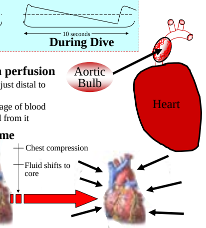
Organ Perfusion

Uninterrupted brain & heart oxygenation

1. **Maintenance of perfusion**
   - Elasticity of arterial walls
   - Prolonged diastole



2. **Aortic "bulb" to sustain perfusion**
   - Bulbous dilatation of the aorta just distal to its exit from the heart (seals)
   - Continuous perfusion from storage of blood in the bulb and the elastic recoil from it
3. **Reduction in heart volume**
   - ↓ Stroke volume
   - ↓ Cardiac output
   - Reduction in cardiac metabolic demands while maintaining perfusion to the brain



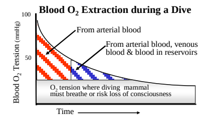
4. **Splenic contraction**
   - Movement of blood to the core
   - Increases in hematocrit

Blood Reservoirs

Maximal utilization of blood O_2 stores

1. **As part of the mammalian dive response, blood moves into reservoirs in the core from the periphery.**
   - Enormous storage capacity—perhaps 20 times that of the blood volume
   - Reservoirs include the vena cava, liver & spleen sinusoids, artery & venous plexuses, arterial-venous shunts, vasodilation and middle ear mucosa (elephant seal)
   - Abdominal vessels and organs move into the chest cavity to help displace the reduced lung volume as the diving mammal descends
2. **The sub-diaphragmatic inferior vena cava sphincter prevents blood from the engorged splanchnic organs from leaving the core**
3. **Once O_2 tensions in the arterial blood decrease to the levels in the venous blood and blood in the reservoirs, O_2 extraction begins to occur from the latter 2 sites**

Blood O_2 Extraction during a Dive



Secondary Effects

Many of the CV/Metabolic adaptations have secondary effects which compliment the adaptations observed in the other organ systems. Consider the following:

1. Vasoconstriction **reduces heat loss** since cool blood from the extremities is "isolated" from the warm core blood
2. Engorgement of blood reservoirs help fill the void in the lung cavity to compensate for collapse of the alveoli. This offers **protection from thoracic squeeze**
3. Bradycardia slows blood flow, which, in turn, improves efficiency of shunting to compliment counter current heat exchange resulting in **increased thermal protection**
4. Anaerobic metabolism in the muscle allows muscle activity to continue, thereby allowing **continuation of propulsion efforts** while underwater
5. Tolerance for lowered O_2 tensions promote the use of O_2 stores in the myoglobin. This compliments metabolic activity from anaerobic metabolism and **allows muscles to function for propulsion**
6. Shifting of blood to the core adds additional warm blood (with a heat capacity about equivalent to water) to this region thereby providing a heat reservoir and additional **protection from hypothermia**

Human Counterparts

1. Elements of the diving reflex are observed in humans
   - Bradycardia secondary to hypoxia in the fetal distress syndrome
   - Bradycardia in experienced apneic divers
   - Peripheral vasoconstriction (and shunting) enhancing cold water tolerance (and survival) in the cold-water immersion victim
   - Shifting of blood to the core (thoracic squeeze and thermal protection) with immersion
2. Splanchnic organs move into thoracic cavity to displace the void created by reduction of the lung volume with descent
3. Improved tolerance to hypoxemia and hypercapnea in trained apneic divers—whether blood oxygen levels reach levels low enough to utilize oxygen from the venous reservoirs, as apparently occurs in diving mammals, is not know at this time

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