Propulsion Adaptations of Mammalian Divers

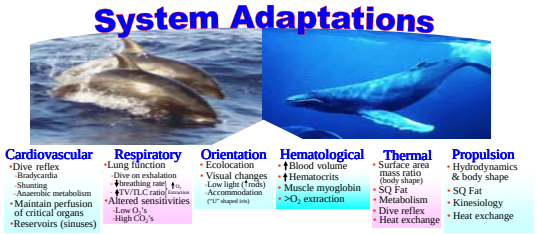
Strauss MB[1], Miller SS[1], Lewis AJ[1], Bozanic JE[1], Samson RL[1], and Aksenov IV[2]

[1]Department of Hyperbaric Medicine, Long Beach Memorial Medical Center Long Beach, CA USA

[2]University of Florida and VA Medical Center, Gainesville, FL USA

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 systems as follows:

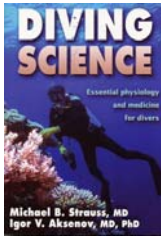


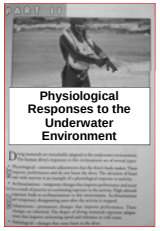
This presentation is a sequel to the 2006 overview. It focuses on the adaptations in diving mammals that help them move through the aquatic environment

Compared to the other system adaptations, the adaptations that improve propulsion in diving mammals have few counterparts in humans. Even with equipment to improve swimming performance, propulsive efforts of human divers in the water can hardly be compared to that of the diving mammals

Materials & Methods

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





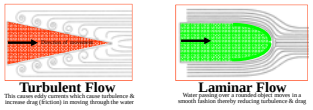
Our efforts found a wealth of information about mammalian diving adaptations and the anatomic and physiological adaptations that make it possible for diving mammals to propel themselves at amazing speeds and with great efficiencies in the aquatic environment

Like the other mammalian adaptations to diving, the propulsive adaptations have secondary roles which contribute to the overall aquatic performances of these animals

Propulsion Adaptations of Diving Mammals

Body Morphology

The rounded body shape reduces turbulence & drag



Turbulence slows the movement of objects through the water according to the following hydrodynamic principles

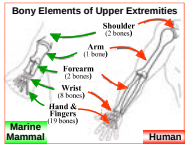
- The greater the turbulence, the more drag it places on an object moving through water
- The greater the turbulence, the more slowly an object moves through water per unit of propulsive power
- The faster an object moves through a fluid, the more turbulence it develops
- The more turbulence an object produces while moving through water, the less efficient is the use of its propulsive force

Lessons learned

- The body shapes of the diving mammals are ideal for reducing turbulence when moving through the water at fast speeds
- Hull configurations of submarines have radically changed; now they are cigar shaped with very blunt bows
- Large surface ships have made analogous changes with massive bubble-shaped hull projections attached to their bows just below the water line

Kinesiology Changes

Fins & flukes have become paddles, the muscles reside in the axial skeleton

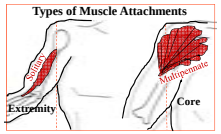


Fins, flippers & flukes are relatively avascular structures

- The perfusion requirements of fins, flippers & flukes of diving mammals is minimal.
- These structures are composed of relatively avascular cartilage, bone, fibrous tissue & skin
- Consequently, with blood shunting from the extremities, metabolic activity is almost non-existent in these structures during a dive

The multipennate muscles of the axial skeleton give mechanical advantages for swimming

- A large force multiplier effect occurs from the multiple origins of muscle groups combining to pull on single tendon insertions on the extremity
- Over 30 muscle groups act across the axial skeleton in anterior and posterior groups to stabilize the trunk and move fins and flukes



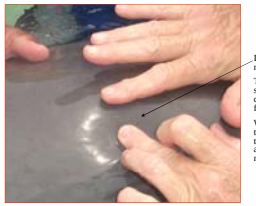
Lessons learned

- While the muscle work activity is in the core, the site of action is transmitted to the fins and flukes; this conserves core temperature (no muscle work/heat radiation from the extremities) & facilitates shunting
- The muscles of the axial skeleton are able to function for sustained periods through aerobic metabolism of slow twitch fibers to allow 10,000 mile migrations. In contrast, human mobility is largely a function of the solitary muscle groups in the extremities; the axial skeleton muscles are stabilizers for the extremities

Highly Pliable SQ Fat

Subcutaneous fat of diving mammals has an oily consistency

- The skin & SQ contour to the turbulent flow patterns that arise as the diving mammal rapidly moves through the water
- Contouring reduces drag and increases swimming efficiency and speed without increasing effort. The more turbulence an object produces while moving through water, the less efficient is the use of its propulsive force
- This compliments the body morphology changes that also improve propulsion



Lessons learned

- Although these principles are not fully applied to ship construction, the use of fiberglass and low friction paints for ships hulls reduce turbulence & drag through the water
- Conversely, world class competitive swimmers have utilized these principles by shaving and wearing swimming caps to reduce drag—and more recently rubber-silicon body suits to reduce friction (drag) when moving rapidly through the water

Heat Transfer

Heat transfer is an intriguing method of improving speed of objects that rapidly move through the water

- The heating of a fluid reduces its viscosity. The reduction in viscosity is due to the increased distance between molecules & the decrease of the cohesive forces of internal friction that occur as the temperature of the liquid increases
- Turbulence from swimming rapidly increases as the shape of the diving mammal tapers from its blunt rounded rostral aspect (conducive to laminar flow) to its flukes
- Increased vascularity of subcutaneous tissues is present in the transition zone between the main body mass and the flukes
- The increased vascularity not only provides a method for dispersion of heat produced by metabolic activity as a consequence of swimming rapidly, but it may also assist in producing a more laminar flow pattern in this body-fluke transition region through heat transfer

Lessons learned

- Hot water from surface ships and submarines that is generated from engine (and reactor heat) is discharged adjacent to the propellers. The propellers are the largest source of turbulence for ships moving through water
- Discharge of hot water adjacent to the propellers is probably done because it is nearest to the source of heat generation.
- It is interesting to speculate that, heat exchange ala the anatomy and physiology of the diving mammals may help reduce turbulence from hot water discharge when rapidly moving through water and is "factored-in" when designing new, highly efficient ships and submarines

Tolerance to Cold Water

A secondary benefit of the diving mammals' adaptations to propulsion is the protection it provides to tolerate cold water

- Their round/cigar-shape body habitus (approaching that of a sphere) is optimal for preservation of core temperature
- Axial skeletal muscles attached to tendons coursing to flippers and flukes allows these structures to be used for propulsion without obliterating the diving reflex
- Metabolic heat production from moving the flippers and flukes remains in the core
- The layer of subcutaneous fat with its oily consistency adds insulation to the core
- The relatively avascular contents of the flippers and flukes with their large surface area to mass can cool to the ambient water temperature during the diving reflex without detrimental effects to the diving mammal's core temperature
- The heat exchange system proximal to the flukes efficiently dissipates metabolically generated heat during fast surface swimming, but is auto-regulated to conserve heat during the dive

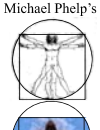
Protection from Medical Problems

A tertiary benefit of diving mammals' propulsion adaptations is their help in preventing medical problems of diving

- The cigar shape of diving mammals offers protection from **thoracic squeeze** by symmetrical compression of the thoracic cavity as pressure increases with descent. The compressibility of subcutaneous fat also contributes to this mechanism
- Shunting of blood from the appendages preserves O_2 availability for the critical core tissues—the brain and heart to prevent **hypoxic blackout**
- The relative avascular structure of the fins and flukes plus shunting prevents nitrogen deposition in these structures and **limb bends** from developing with ascent

Human Propulsion in the Aquatic Environment

- World class human swimmers' are about 28% (~ 4 ½ MPH) as fast as dolphins (~16 MPH). The most efficient underwater swimming rates range from 0.7 to 0.9 MPH
- Swim fins increase the efficiency of moving through the water from 2% to 8% which approximates the efficiency of the arm stroke. Swimming with fins is only 20% as efficient as walking or running
- Michael Phelp's domination of the competitive swimming world is due to anatomical, physiological and equipment components that have counterparts in the propulsive abilities of diving mammals
  - -His arm span is 4 inches > his height; compared to da Vinci's "Vituvian Man"
  - -His torso tapers to a narrow waist that resembles the shape of a diving mammal; this may help with surface buoyancy and reduce turbulence
  - -His lower extremities are shorter than the length of his trunk
  - -He has size 14 feet and extremely flexible ankles (similar to flippers)
  - -His flexibility is so great that concerns are raised that he may have a variant of Ehlers-Danlos or Marfan's Syndromes
  - -He uses a body silicon-rubber body suit to reduce drag in the water
  - -Shaving of body hair and use of a swimming cap are other techniques he and other swimmers use to reduce drag while swimming



References

Strauss MB, Aksenov, IV. ***Diving Science*** Human Kinetics, Champaign, IL 2004 pp149-165

Capelli C, Pendergast DR, Termin B. Energetics of swimming at maximal speeds in humans. ***Eur J Appl Physiol Occup Physiol*** 1998; 78 (5, Oct): 385-393

Zamparo P, Pendergast DR, Termin B, et al. How fins affect the economy and efficiency of human swimming. ***J Exp Biol*** 2002; 205 (Pt 17, Sept): 2665-2676

Sumich JL. Swimming velocities, breathing patterns and estimated costs of locomotion in migrating gray whales, *Eschrictius robustus*. ***Can Jour Zool*** 1983; 61:647-652