The University of Canterbury

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Literature Review:

The Weddell seals and their physiological adaptation to deep diving

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1. Introduction:

Seals, sea lions and walruses; all belong to a group of marine mammals called pinnipeds, which means "fin-footed". Marine mammals are just like the mammals that live on land environment; they are warm-blooded, breathe air to stay alive and give birth to live young that fed with milk. Seals are categorized into three families: Phocidae, true seals; Otariidae, eared seals and Odobenidae, walruses.

The walrus has just one species. They are big seals with long teeth called tusks that they use to make breathing holes in ice and to help them climb out onto the ice. They can only be found in the arctic region and not in Antarctic. The eared seals include five species of sea lion and nine species of Fur seal. The most distinctive feature of this animal is their small furry earflaps or lobes to their ears. They can also turn their back flippers forward under their bodies and walk, even run on land. Some can move faster than a human. In water they swim by using their large front flippers. True seal may sometimes call "hair seal" to distinguish them from the Fur seals and they belong to the family of Phocidae. They have no ear-flaps; all you can see of their ears are tiny holes. Their back flippers cannot turn forward under their bodies so earless seals move on land or ice by wiggling like caterpillars or slithering from side to side like snakes (Castellini, 2002).

There are only five Antarctic species of true seal, they are: Crabeater Seals (Lobodon carcinophaga), Leopard Seals (Hydrurga leptonyx), Ross Seals (Ommatophoca rossii), Southern elephant seal (Mirounga leonina) and the Weddell Seals (Leptonychotes weddellii). They are well adapted for ocean life and some of them are truly ice-dwelling. To cope with the extreme conditions in which they live, they have well developed layers of blubber as insulation. Their swimming and diving ability are also unquestionably impressive among the marine animals. Records show that Weddell seals can dive into 600m deep into the ocean and hold their breath for 86.3 minutes (Castellini, 2002).

Unlike the Crabeater seals and the Leopard seals which resist intrusion very actively, the Weddell seals behave much differently. They show no fear to man's approach and are hardly aggressive when being disturbed. This phlegmatic characteristic allows human being to make investigation on this uniquely adapted marine mammal in terms of their physiological adaptation to the extreme environment as well as their social behavior. It is
the aim of this article to make a review of some scientific findings about this animal particularly to their unique physiological adaptation in diving to the deep ocean.

2. Their adaptations for cold environment and deep diving:

2.1 Their body shape
The streamline of body shape is one of the major adaptations for the Weddell Seal to live in the extreme environment. Small head and almost "spindle-shape" of their body is nearly resistance free that it has one of the lowest possible drag coefficients (Kooymans, 1981). Their short hairs also allow them to glide nearly friction-free through the water. Their limbs were modified to become flippers and fins. They may not be that useful after leaving the water, but this will enable them to "fly" in the water and make their movement much more efficient and effective (Baner, 2004). This "relaxing" swimming stroke will enable them to save a lot of energy in water and thus make their diving time much longer (Milius, 2000).

2.2 Their ears
Despite of the fact that a true seal has no ear-flaps, it will not affect their hearing ability. In the water, the Weddell Seals' hearing is even better. It is believed that they have the ability to hear noises over a 10 km area in water (Sabbatini, 2002). Its theorized that seals use a type of sonar to locate food, much like what dolphins and whales use (Kooymans, 1981). In addition to sonar for navigation and locating their preys, it is believed that seals use their whiskers as a form of radar. The whiskers detect movement in the water and allow the seal to zoom in a particular object. Through the use of their sonar and radar, seals can accurately find food in complete darkness better than in the light (Baner, 2004).

2.3 Their eyes
As for their eyes, seals don't really see colour but they are particularly sensitive to common sea water colours (greens and green-blues). Seals eyes have a silvery lining behind the retina, just like cats and other nocurnal/low-light hunters (Baner, 2004). This lining reflects the light back through the eye and increases the total amount of light absorbed by the eyes. There is also a special adaptation of high bloodflow in the membrane in the lower part of the eye which allows it to retain heat and stay warm when diving (Sabbatini, 2002)
2.4 Their circulation system

The most important adaptation to make Weddell Seals to be one of the phenomenal divers of Antarctica is their storage capacity and distribution of oxygen and their ability to cope with pressure when they perform deep dives.

Weddell seals have a high concentration of hemoglobin in their blood and the myoglobin in their muscle. Oxygen may be stored as a gas in the lung, in physical solution in the blood and tissue fluid, or bound to hemoglobin molecules in the erythrocytes or to myoglobin in the muscle tissue. In Weddell seals, the major oxygen storage is in their blood. The oxygen carrying capacity of Weddell seal blood is 1.60 times that of human blood because of the greater concentration of hemoglobin. The blood volume per unit of body weight is 150 ml/kg, or about double that of humans. The net result is that blood oxygen stores per unit of body weight in seals are 3.0 to 3.5 times more than human. Excluding bubbler which is rather inert and accounts for 30% of the body weight of seals, leads to a 5.3 times more in blood oxygen stores per unit of body weight in seals than human being. (Kooyman, 1981)

Myoglobin is found primarily in muscle, and its main function is to bind oxygen. Myoglobin is a kind of heme-protein that has an organic structure which contains iron. They have a higher affinity for oxygen than hemoglobin (Butler, 2001). When blood passes through muscle, oxygen is transferred easily from the blood to the muscle. Myoglobin, oxygen and diving ability has a strong inter-relationship with each other. More oxygen storage in muscle means more sustainable in the continuous exercises (diving) in a aerobic level.

During steady-state exercise and oxygen is abundantly supplied, metabolic substrate, normally carbohydrate and/or fat, is completely oxidized in the slow oxidative and fast oxidative glycolytic muscle fibers via the Krebs cycle and electron transport chain to produce adenosine triphosphate (ATP). During such exercise, there are no changes in blood gases or in blood pH from their resting values. In other words, the rate at which oxygen is being consumed by the tissues, especially by the active muscles, is matched by its increased rate of provision by the respiratory and cardiovascular systems. However, the reaction does not proceed to completion unless oxygen is present. In the absence of
oxygen, or inadequate to match up with the intensity of the exercise, the metabolism will take place anaerobically, with lactic acid as a waste product. Such high levels of exercise are not sustainable; the blood becomes acidic and fatigue soon sets in (Burns and Castellini, 1996).

Most mammals that do not have rich stores of oxygen in various tissues would extremely dependent on oxygen supply via their circulation system. Human being is one of the examples and that is why we cannot go for very long without breathing. Nevertheless, it is found that the myoglobin concentration in seal muscle is about 10 times greater than human which represents another substantially larger oxygen store (Butler, 2001). With this abundant supply of oxygen, Weddell seals have the ability to stay in water for a much longer time than the torrential animals. Kooymen coined the term aerobic dive limit (ADL) to describe the dive duration up to which there was no increase in post-dive blood lactate concentration (that is, the duration up to which all dives were completely aerobic). He found that there is no significant changes in the lactate level until the dive exceed 20 minutes (Kooymen, Castellini and Davis, 1981).

2.5 The distribution of blood to different organs according to their differences in oxygen requirement

To conserve a better utilization of their energy and oxygen, Weddell seals and some diving animals have adapted a unique way of distribution of oxygen when they are diving. When the Weddell seals dive, they only have the oxygen they take with them. The size and availability of these stores and the rate at which they are utilized will determine the duration for which an animal can remain submerged and metabolize aerobically. This breath-holding mechanism of diving animals has been a long time interest of physiologists since Paul Bert (Bret, 1870, cited in Kooymen, 1981) who discovered that the heart slowing (bradycardia) occurred in ducks when their heads were forced underwater. Classic experiments of Per Scholander on restrained aquatic birds and mammals in the 1930's shown that these animals can survive for long periods of breath-hold by constricting the blood vessels in tissues (vasoconstriction) that can withstand periods of oxygen lack. Oxygen can, therefore be conserved for the oxygen dependent organ such as the Central Nervous System (CNS), and heart (Butler, 2001; Kooymen, Castellini and Davis, 1981). The various organs of the body have different oxygen requirements and different abilities to function through anaerobic metabolic pathways.
During a dive, blood flow changes dramatically in some organs and only slightly in others. A seal becomes a "heart-brain-lung aerobe", in which circulating blood is limited to these organs (Kooymman, 1981). The brain is an aerobic organ as it must keep functioning at full capacity during a dive and thus there is only a little change in blood flow in this organ. However, blood flow in kidney nearly ceases during a dive and much of the kidney's filtering process stops until breathing is resumed (Burns and Castellini, 1996). It is expected that the blood flow in the skeletal muscle also decline, but owning to the fact that most of the studies were conducted with forced dive and the animals are either swimming or struggling, and thus their muscle is still continue to function. Nevertheless, it is believed that their energy comes from the aerobic pathway initially and transitioning to anaerobic pathways later (Kooymman, 1981). These changes in blood flow can occur almost immediately upon submersion. The shifts in flow are reflected in a fall in heart rate as the restricted distribution of blood decreases the output requirement of the heart. The changes are so natural that only a very little change in blood pressure occurs.

When a seal is resting, their heart rate is about 50 to 60 beat per minute (BPM). This is an average calculation as their breathing pattern is somewhat cyclical, several breaths and then an apnea sometimes of several minutes. Their heart rate will vary accordingly, fast when breathing (eupnea) and slow when stop (apnea) (Davis and Kanatous, 1999). Average heart rate of a seal was recorded as, apnea, 34 BPM, eupnea, 64 BPM, apnea. The average rate between dives was 85 BPM (Kooymman, 1981). When a seal dive, their heart rate drop dramatically to the average of 30 BPM and interestingly that the longer the dive, the lower will be their hear rate. They can reach to the minimum of 15 BPM if they were submerged into the water after 25 minutes. This interesting result suggested that seals can actually "control" or influence its heart beat according to his diving plan and duration. Kooymman concluded that this response to diving should not be considered as a "reflex" action. He also suggested that there is probably a wide range of gradations, depending upon a variety of stimuli upon and within the animal that deserve a further investigation.

2.6 Their respiratory system

The other most astonishing adaptation of the seals is their ability to cope with the enormous pressure that generated from deep diving. The Boyle's Law revealed that, for ever 10 meters you dive under water, 1 atmospheric pressure will be generated. When a
seal reaches 600m, the pressure bearing on the animal is 60 atmospheres which is equivalent to 64 kg/cm² (Kooymans, 1981). Liquids are relatively incompressible in nature; therefore these great pressures will have little or no effect on most of the internal organs except the lung and the respiratory system which is filled with air and space. As a result, the deeper the seal descends, the smaller the lungs, trachea, middle ear cavity and any other gas spaces must become (Milius, 2000). The external and internal pressure must maintain equilibrium otherwise the membranes and blood vessels lining the cavities would rupture and obliterate the space with blood and cell fluids because the body fluids will always nearly match the ambient hydrostatic pressure. When an inequality occurs, much pain would probably be experienced. This is one of the physiological hindrances that people come across when diving. However, anatomical studies have elucidated how the seal manages this problem. The middle ear is lined with a system of venous sinuses. When the seal descends, the absolute venous blood pressure begins to increase and this additional pressure expands the sinuses. This causes the middle ear membranes to bulge into the middle ear space, reduce its volume, and compress the gas in the space. The result is a close match to the ambient pressure (Kooymans and Ponganis, 1993). It is fascinating to know that this system does not need additional air to be supplied through the Eustachian tube as human divers usually do when diving. The seal can simply dive deeply even if the Eustachian tube is blocked.

The respiratory system is the largest gas space of all, and obviously it has great volume-changing properties. In terrestrial mammals there is a limited of about 25% of the total lung volume that you must keep in the lung as a residual volume. At this volume, the ribs are incapable of contracting further and the thoracic volume is fixed. Seals however have no such limitations. The thorax is more compressible because the structure is made up of their highly flexible and rubbery ribs. The high proportion of cartilage content of the rib and the sophisticated bronchioles structures makes the compression possible and allows nearly all the gas in the lungs to be exhaled. This absence of a residual volume was first noted by Scholander in 1940 (Butler, 2001) and it is proved that there are several species of marine mammals such as the whales and seals shared this common characteristics. It was also noted that the trachea of the Weddell seal is "exceptionally plain", "their lumen is nearly obliterated" when relax (Kooymans, 1981). Thus, as the hydrostatic pressure increase as the seal divers deeper and the lungs progressively collapse, air is forced into the upper airways where gas exchange cannot occur. This could allow the seal to dive to
depth where the compression is so great that even the major airways collapse (Butler, 2001).

Another problem for a diver is the decompression sickness commonly knows as "the bends" and "shallow-water blackout". People get the bends most often when they are breathing compressed air at high pressure. At these pressures, a human diver takes in additional oxygen and nitrogen gas, which remains dissolved in the blood until the person starts to ascend. By this time, most of the oxygen is used up, but not the nitrogen. As the pressure decreases, the dissolved nitrogen may form bubbles in the blood and other tissues. Nitrogen bubbling in tissues, particularly in the joints causes pain and sometimes neurological problems as well as other complications. In addition, nitrogen bubbles in the blood form emboli that may block circulation and cause physical damage to organs or tissues. The emboli may also prevent oxygenation of tissue. However, Weddell seals do not have this problem. This is because when the animals reach a relatively shallow depth of only 50-70 meters, their lungs collapse and do not become re-inflated until after the animal ascends to shallow depth. This means that over the major part of their dives, their lungs are not functioning. They do not exchange gas and much of the nitrogen in the lungs never enters the blood stream (Kooymen, Castellini and Davis, 1981).

3 Conclusion

By reading materials about the Weddell seals and their special adaptation, I become more and more amazed about the world that we are living. There is so much to learn about in the nature. They dive into the unimaginable depth of the ocean requires a highly sophisticated physiological system. Their high content of hemoglobin in their blood, myoglobin in skeletal muscles allows them to store more oxygen than other animal. Their highly flexible lung and respiratory system give ways to accommodate the enormous pressure that generated from the depth and prevent themselves from decompression sickness. Their intelligent circulation system can make full use of the resources (Oxygen) and deliver it to the organs that are mostly needed. All these work together to make the Weddell seals such successful divers of the deep Southern Ocean.

My gratitude goes to those scientists who work in the exceptionally difficult and challenging environment. Without their hard work, creativity, intelligence and endurance
all these facts of the nature cannot be revealed. My admiration also goes to the scientists
that are thinking of transferring their understanding of the physiological adaptation of
Weddell seals to human medicine. This will surely enrich our understanding on how
organs survive in low blood flow and the consequent oxygen depletion. Their finding
will surely aid in the treatment of shock, stroke and organ transplants.

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