Comparative Respiratory Physiology of Diving in Man and Dolphin

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Marine mammals in general, but specifically the dolphin, because of his intelligence and his friendship with man, have always spurred an interest, if not a fascination, with their freedom and their obvious enjoyment of their marine habitat. Perhaps it was this fascination that first led man to try entering the ocean and swimming in its depths. It did not take long for man to realize his limitations as a diver, and to see the effects of pressure on his body, a body that is adapted to a terrestial existence.

What is it that allows the dolphin, a warm blooded, air breathing mammal, like ourselves, to dive to depths of 300 meters, or to stay submerged for fifteen minutes, while most of us, as breath-holding divers, are limited to a maximum of 30 metres for a few brief moments?

Ever since the dolphin returned to the sea, time and nature have worked to provide him with several anatomical and physiological adaptations to facilitate his existence in his marine environment. Many changes have been made but we will concern ourselves here with only those changes which have helped the dolphin to become a better diver.

Dolphin Respiration

Let's begin by looking at the way in which the dolphin breathes. Breathing is done through the nose as in man, but the external nares or nostrils of the dolphin have migrated to the top of the head, to a position directly above the internal nares, thus he has a built in snorkel, known as the blowhole. The blowhole is closed by a dense fibrous mass called the plug, with a relaxation of surrounding musculature. During normal swimming, the dolphin surfaces about two to three times every minute to "blow". The blow consists of a complete exhalation and inhalation taking about 0.3 seconds. During this time, the dolphin exchanges about 80% of his air volume at a flow rate of 30 to 70 litres per second. This is compared with man who exchanges only about 20% of his air volume on the average of fifteen times a minute. Thus, though the pulmonary capacity of man and dolphin are not appreciatively different, the dolphin has a much greater tidal volume. Between each blow is a 20 to 30 second apneustic plateau where the breath is held.

Breathing is not an unconscious activity in the dolphin, as it is in man, but in fact, when anaesthetized, the breathing reflex is one of the first to disappear, even before adequate surgical anaesthesia is reached. Respiration must be assisted in the anaesthetized animal or death will result.

Inhalation is an active process while exhalation is a passive one; that is, it takes an expenditure of energy to inhale but exhalation requires little or none. This is due to a large amount of elastic tissue present in the lungs and diaphragm, giving them an elastic recoil when inflated, much like that of a stretched rubber band. The dolphin is however capable of forced expiration.

This style of breathing accomplishes several things. With the greater volume of air exchanged, more oxygen is obtained more rapidly. Also, water and body heat which are lost through respiration are conserved by the fewer number of exchanges per minute. In fact, heat lost through respiration, is cut to 10 to 30% that lost in terrestial animals.

Diver Respiration Problems

These are several problems which confront us as breath-holding divers, which do not appear to affect the dolphin. These include thoracic, middle ear, and sinus squeeze, as well as anoxia seen with prolonged submersion, and the possibility of the bends with repeated deep breath-hold diving. Let's look at each one of these problems individually and see what happens in man, and then how it is that the dolphin is not similarly affected.

First, the squeezes. According to Boyle's Law, as we descend, pressure increases and volume decreases proportionately. Since fluid portions of our bodies are relatively incompressible it is mainly the air spaces with which we must be concerned. These include the lungs, sinuses and middle ear primarily. At depths of around 30 meters, the air volume in our lungs, assuming a full inspiration before descent, is usually equal to the residual volume, or that point at which no more air can be consciously forced out of the lungs. The remaining air is just enough to fill up the dead air space. Descent beyond this point means that with the increasing pressure the air volume, and the remaining space must be filled with something. This something usually begins in the form of engorgement of thoracic blood vessels as much as possible, and is continued by a leakage of fluid and blood from the vessels into the alveoli of the lungs. This fluid in the alveolar spaces is called pulmonary oedema, and reduces the efficiency of the lungs by decreasing the functional area. If severe, this can result in dyspnoea, or difficult breathing, and even in respiratory failure due to anoxia.

Why is it that the dolphin is not bothered by thoracic squeeze during dives to depths of 300 metres, when his lung capacity is not significantly larger than that of terrestial mammals. In fact, it has been shown that the volume of air in his respiratory passages at 300 metres is only about 200 to 300 ml, much less than his calculated residual volume. Actually, several factors contribute to this ability. The thoracic structure of the dolphin allows for much greater pulmonary collapse than that of man. The dolphin has four pair of floating ribs where man has only two pair. These ribs are not attached to the sternum and so allow for greater thoracic flexibility. The trachea and bronchi of the dolphin are equipped with an extensive system of cartilaginous support, but they are arranged to allow for flexibility.

BLAST THAT FISH!

Alf Leggatt, who was awarded the NBE for his services to fishing, asked the army to blow a perch out of his pond because i had eaten 2000 goldfish there. The army obliged and exploded two charges. But the perch stayed put. Nicknamed "Jaws" to commemorate his appetite, he remained an unwelcome victor. His reign only closed when the Southern Electricity Board sent two men to shock him. They used an electrified fishnet, 20 minutes and 240 volts to complete the assignment. As Alf said when his enemy floated stunned to the surface, "I knew I'd get him in the end - I wouldn't let a thing like this beat me. But I must admit I've developed a grudging respect for him". So he put Jaws, all of 31 cms long, into a separate pond in front of his house. Jaws quickly recovered and swam strongly round the pond.

"He looks hungry," said Al.

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The trachea has been shown to be capable of dorso-ventral collapse when exposed to increasing pressure. The diaphragm is also well developed and capable of a great deal of flexibility. The lungs contain a large amount of elastic tissue which allows extreme collapse without trauma. The lungs are actually capable of almost complete atelectasis, or collapse, without being torn away from the thoracic wall. With collapse of the trachea, bronchi, and other respiratory passages to the full possible extent, only the bony portions of the nasal passages remain fully inflated, with a volume of 50ml, much less than the 200 to 300 required for the 300 metre dive.

The lungs are provided with a rich supply of large distensible veins which are seen to engorge with increased pressure of diving, and thus assist in filling some of the dead air space. Extensive thoracic and vertebral vascular networks called retia are present and capable of engorgement to prevent complete collapse of the trachea.

Middle ear squeeze in man is seen on descent when, again according to Boyle’s Law, the volume of air in the middle ear is reduced and the remaining space requires filling up with something. In this case, the space may be filled with water, when the flexible tympanic membrane is stretched beyond its limit and it ruptures. Middle ear squeeze and rupture of the tympanic membrane is prevented in man by allowing air to pass up the Eustachian tube to equalize the pressure on both sides of the tympanic membrane, in the dolphin, Eustachian tubes exist for this purpose and it is believed that he uses a modified Valsava technique for equalizing his ears on descent. Numerous venous plexuses also exist in both the middle ear and the air sinuses of the head which can engorge to prevent ear and sinus squeeze.

Anoxia, or lack of sufficient oxygen to maintain consciousness, is a problem encountered as man attempts to stay underwater for any extended amount of time on one breath of air. Anything in excess of a few minutes, and most individuals will become unconscious. The dolphin, on the other hand, makes routine dives for five minutes at a time and can stay under for fifteen minutes and sometimes more without suffering any ill effects. How? It’s not a simple matter of, “He can hold his breath longer”, or “He doesn’t need as much oxygen,” but is instead, a complicated mixture of anatomical and physiological adaptations of the cardiovascular and respiratory systems.

Cardiovascular adaptations are numerous. The blood itself has undergone certain changes. The volume of blood has increased, as well as the haemoglobin concentration, and the packed cell volume, or percentage of red blood cells to serum. This allows for a greater oxygen carrying capacity of the blood. The mean corpuscular volume has also been increased, thus the surface area of the red cells has been increased 1.5 to 2 times that in terrestial mammals. This permits rapid absorption and release of oxygen, allowing for rapid oxygen transport to the tissues. Another cardiovascular adjustment involves a widespread peripheral vasoconstriction which is seen during diving. This vasoconstriction is not confined to the capillaries alone, but effectively results in a shunting of blood away from the peripheral circulation and to the more vital organs of the heart, liver, and brain. Thus oxygen is conserved for essential life-preserving processes. Shunting of blood away from the outside of the body and appendages also assists in the preservation of body heat, a constant struggle for the warm blooded dolphin.

A diving bradycardia, or slowing of the heart rate is seen in the dolphin as well as other diving mammals. Man, and even non-diving mammals show a similar bradycardia upon submersion. The slowed rate is more evident in the deeper diving mammals such as the seals, and deep diving whales. The exact mechanism which initiates this reflex is not known. It is primarily the result of an extension of diastole, or the resting phase of the cardiac cycle. Though the heart rate slows, the blood pressure remains about the same. A similar bradycardia can be seen in the anaesthetized dolphin which is suffering from anoxia, but is not seen if the animal is properly ventilated. A normal respiratory arrhythmia has been noted, with the heart rate increasing to 70 to 120 just after inspiration and dropping to 30 - 60 quickly thereafter; maintaining that rate until the next breath is taken.

A so called “natural aneurism” or bulbous dilatation of the ascending aorta has been noted just distal to the left ventricle. It has been postulated that this dilatation, with its extensive supply of elastic fibres, may serve as an assist to the coronary blood flow and maintenance of arterial pressure during the long diastole seen with diving bradycardia.

The value of the lung air as far as increasing blood oxygen levels during diving is, at best, of little value, in fact, in deeper dives, alveolar collapse precludes any pulmonary gas exchange. What this means is that reserves must exist elsewhere, or that anaerobic respiration must take place, especially in those tissues which are essentially cut off from the main circulatory system by the widespread vasoconstriction seen with diving. As it turns out, the dolphin can store a great deal of oxygen in the muscle tissue bound to the muscle form of haemoglobin., or myoglobin. Myoglobin can be responsible for up to 50% of the total oxygen stores. In addition, the muscle tissue can function anaerobically, when its oxygen stores are exhausted. This builds up a so called oxygen debt which must be repaid upon surfacing. After a period of prolonged submersion, the dolphin must surface and by means of several exchanges of air, repay any oxygen debt he has accumulated. The vasoconstriction is relieved on surfacing and the oxygen rich blood is carried to the muscle tissue to complete the required aerobic portion of sue **respirati**on.

In addition to these cardiovascular changes, several respiratory adaptations have been made. The dolphin has higher tolerances for both oxygen debt and carbon dioxide excess. In man, one of the more sensitive signalling devices of the brain to initiate breathing is an increase in the partial pressure of carbon dioxide in the blood. This effect can be lessened somewhat by hyperventilation, where carbon dioxide is blown off to such a low level that the decreased level of oxygen in the blood takes over as a secondary signalling device. Hyperventilation has also been noted in the dolphin, but is not the sole method for suppressing the carbon dioxide signal. There is actually a naturally decreased sensitivity of the brain to carbon dioxide, so the urge to breathe is not as strong, and in fact the need to breathe is not as immediate as in man with similar blood carbon dioxide levels.

Dolphins and Bends

Why don’t dolphins get the bends? The bends, or decompression sickness, is in general thought to be associated with compressed air or SCUBA diving, but it has been shown to occasionally result from repeated, deep, breath holding dives. In this case, continued repeated compression of the alveolar air with resulting high partial pressure of nitrogen in the blood. Upon ascent this nitrogen in solution comes out of solution and bubbles into the tissues, especially the joints, causing pain and other associated signs of the bends. This disease has not been reported in dolphins even following as many as ten dives to 260 feet within a one hour period.

The reason why dolphins don’t suffer from the bends is related to the anatomy of the lungs. From eight to ten discrete circular myoelastic bundles are present in the terminal bronchioles, or the small air passages leading into the alveolar sacs. These act as sphincters to compartmentalise the bronchiole. They serve as valves between the high pressure air in the trachea and the low pressure maintained in the alveoli during diving. They break up this large pressure differential into several small pressure differentials. These sphincters do not trap air in the alveolus, but instead actually trap air away from the alveolus, and this away from the area of gas exchange. By maintaining low air pressure in the alveolus, the partial pressure of nitrogen is not driven into solution in the blood in significant quantities to result in the bends.

Thus we can see that nature has provided the dolphin with many and varied adaptations to facilitate his marine existence, just a few of which are mentioned in this article.

Summary

Nature has marvellously adapted the dolphin to his environment. These adaptations include many anatomical and physiological changes. The thoracic structure can collapse without permanent damage, almost to the point of complete atelectasis. This is due to a large supply of distensible veins, elastic pulmonary tissue, and flexible bronchi, trachea and rib cage. The blood has a greater oxygen carrying capacity than that found in land mammals. The muscles are capable of storing up to 50% of the oxygen in the body, to make possible continued muscular activity in spite of widespread peripheral vasoconstriction and a reflex bradycardia. The muscle tissue is also capable of functioning anaerobically and accumulating a large oxygen debt without tissue damage. The brain has a higher tolerance to carbon dioxide and is less sensitive to its signal to initiate breathing. A series of muscular sphincters in the bronchioles permits a low air pressure in the alveolus even while diving to great depths, and thus a low partial pressure of nitrogen exists. This prevents adequate amounts of nitrogen to be dissolved in the blood to result in the bends. All this has been done for the dolphin while man has been adapted for an existence on dry land. Thus what is natural for the dolphin, we must supplement our bodies with machinery to do. So the fascination remains with the beautiful, graceful, diving dolphin .....

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What about the deliveries? What about the babies? These are the questions we all ask. All the babies were “normal” according to their mothers. Only one baby was under weight, at birth. The male babies outnumbered the females 61% to 39%. The complications that occurred during pregnancy included one premature birth, one septic abortion, and two miscarriages. (One of the women had two miscarriages before learning to dive and two more since diving). The normal rate of spontaneous abortions is 20%, for the general public, the rate among the respondees was less than 3%. There were seven Caesarean sections (12%). This procedure is becoming increasingly popular and the average rate is between 10-15% for the general public. All but one woman continued to dive after delivery.

From this survey, it seems that many women discontinued diving as soon as pregnancy was established, and the reason given was the lack of information on the safety or danger to the foetes. However, most women dived at least during the first trimester, at a time when the foetus is very vulnerable. Those who continued to dive as long as possible did not run into any apparent problems. Even the women who made deep dives reported no mishaps. I believe in good prenatal care and I recommend that pregnant divers limit their maximum depth to 33 feet, take it easy (make the easy dives), avoid overextending oneself, and use common sense.