# MAMMALIAN BREATHOLD DIVING

John Knight

I am going to talk about air breathing mammals, of which one has two legs, two arms, a head and is called man or woman and compare that mammal with the other mammals that go underwater.

## DIVING RESPONSES IN ALL MAMMALS

All mammals when they dive develop a bradycardia. There is vaso-constriction to all areas except the heart and brain. As a result they develop a lactic acidosis and more than usual anaerobic metabolism. That applies to all mammals, but some have these responses more developed than others.

There are certain advantages from these diving responses. They shut down the circulation to the unnecessary parts of the body. As an anaesthetist, I reckon that the heart and the brain are necessary for survival. By shutting down the peripheral circulation, these responses reduce the oxygen need. Again, by shutting down the peripheral circulation, there is increased oxygen extraction from the blood, because the blood-tissue partial pressure differential is higher. The production of energy without oxygen is increased. By shutting down the circulation to the periphery the core temperature is maintained. Anyone who gets into the water in Victoria shuts down the peripheral circulation very smartly. In a wet-suit I can last for about three-quarters of an hour before my core temperature has dropped to the point where I start to shiver.

There are certain disadvantages. There is an increased oxygen debt because of the anaerobic metabolism. The oxygen has to be supplied later. There is tissue anoxia from the shut-down. No matter how efficient the peripheral vasoconstriction is, one still loses heat and gets cold.

## IMMERSION RESPONSES IN MAN

The effect of getting into water in the vertical position is that hydrostatic pressure compresses the legs and abdomen and forces blood from the periphery up into the chest. This results in a number of physiological reflexes. There are receptors which monitor the size of the great veins in the chest. If they get stretched, the brain reckons that there is too much blood and takes steps to get rid of fluid. As a result there is a diuresis. That is why about half an hour after one gets into the water there is an overpowering urge to dampen your wet suit even more. It is a very comfortable dampness because it is warmer than the water.

### Lung Changes

Vertical immersion puts blood into the chest and even with the diuresis it leaves more blood in the chest than before. As blood is transferred to the thorax, lung mechanics change. If there is more blood in the lungs, the lungs become stiffer. This results in an increase in airway resistance of the order of 58%. This results in an increase of 60% in the work of breathing. This is with immersion to the neck. Underwater the work of breathing is further increased by the inefficiencies of the diver's breathing apparatus.

The increase in pulmonary blood volume increases the size of the closing volume. With expiration an equal pressure point develops at which the small airways collapse and trap the air beyond it. During immersion the pressure is higher and the trapped volume, the closing volume, larger. As a result of the increased pulmonary blood volume areas which are normally poorly perfused, are better perfused but they are not better ventilated. So there are changes in ventilation-perfusion ratios. These changes occur because normally the apices of the lungs are perfused less than the bases. Also the apices are better ventilated than the bases. But when we get in the water the blood flow is redistributed and the whole lung is more or less uniformly perfused, but ventilation continues to be preferential.

Lung compliance decreases. Our lungs become stiffer so it is more difficult to take a breath. The vital capacity goes down, depending on whose work you quote by 3% to 10%. The residual volume decreases by 4% to 17%. The expiratory reserve volume decreases by 50% to 74%. That is the part of your lung contents you could breathe out if you tried to but is not used in normal breathing. The maximum voluntary ventilation, (MVV) decreases by 15%. This is because the lungs are stiffer and cannot accommodate to rapid change. When underwater one breathes denser gas than at the surface, so the MVV goes down further due to the increased density.

There are two theories why the vital capacity goes down. Recently it has been claimed that the increased thoracic blood volume would completely explain the decrease. Earlier workers attributed 60% of the decrease to extra intrathoracic blood and 40% to the changes in chest mechanics, ie. the upward elevation of the diaphragm and the resistance of the surrounding water to chest expansion. I am not sure that either side convince me that they are right. I think that the earlier workers are probably right. When one has water around the chest one has to push the water out of the way to expand the chest, which must be a drawback to taking a full breath of air.

This displacement of blood into the thorax allows humans to breathhold dive to depths at which their total lung capacity has been reduced to less than their residual volume. Humans can go as deep as 100 metres, if you happen to be Jacques Mayol. I can not do it, but if you have got the right physique and the right amount of blood shunted into your lungs, you can do it.

### Gastro-oesophageal Pressure Changes

Another consequence of immersion is gastro-oesophageal pressure changes. If you weigh divers during a dive as the

Swedes have done, you find that they get lighter towards the end of a dive. In other words, they are displacing more water. The reason that they are displacing more water, is that every time they equalize, they swallow a little bit of air. It goes down into the stomach much more easily than in air because the pressure differentials are much reduced in water.

We normally have a quite reasonable pressure gradient between gastric pressure and oesophageal pressure. If we stay upright underwater that increases, but if we invert ourselves, as most of us do at some stage in a dive, that pressure difference decreases tremendously. Upside down in the water the pressure to keep gas out of the stomach is not there. People who come out of the water feeling slightly bloated have every reason to feel that way, if they have been swimming upside down.

Cardiovascular Changes

The cardiovascular changes apply to humans, dogs, beavers, hippopotamuses, or any other mammals that you like to put in water. There is a heart size increase. In humans it is 150 ml, 50% increase compared with out of the water. The stroke volume increases by 35%. In thermoneutral water the peripheral resistance is decreased by 30%. As a result of the decrease in the peripheral resistance, peripheral circulation increases. This has been shown by radioactive xenon elimination from muscles which increases by 130%. Also by measuring the rate at which nitrogen came out of the immersed body compared with the out-of-water body. In 35°C water, nitrogen excretion rate was increased by 40% in the first 30 minutes and by 27% over 7 hours. There was a greater increase in excretive rate in 37°C water.

In cold water there is an increase in peripheral resistance due to the effects of cold on the skin and heat loss.

So perhaps one could say that the sensible thing for the diver to do while decompressing is to sit in a bath of warm water. This is based on the idea that you get rid of the inert gases better if you are warm and immersed to the neck. What happens when you warm a cooled body during decompression is a gamble. I am not volunteering to be the first experimental subject.

There is not all that much work that tells one about what happens when someone gets into the water feet first and then swims horizontally or head down. As far as I can make out, many of the changes of vertical immersion are reversed. But I have not read any evidence to show that the changes that occur on immersion are completely reversed. One must always remember that any diver who has been in the water for any length of time is going to dehydrate just from the physiological results of pushing blood from his periphery into his chest, stimulating the great vessel reflexes and excreting more urine.

RESPONSES ACQUIRED WITH DIVING PRACTICE

Any mammal which is subjected to diving improves his or her diving ability with practice. There is evidence that groups of humans that breathhold dive for their living, had higher haemoglobins, bigger lungs and a better efficiency of ventilation; that is they exchange more gas per breath, than those who do not. Incidentally, Robin Cox told me some eight years ago that the only positive research finding that he had got out of all the diving medicals that had been done in Yarmouth, was that the eighteen year olds had developed a bigger vital capacity by the time they were twenty. People who breathhold dive for a living can hold their breath for longer so can tolerate a larger oxygen debt. They can tolerate a raised $PaC0_2$. Also they can tolerate cold better. They start to shiver after a longer than usual heat loss. If they have got enough food, they increase their insulation.

These responses have certain advantages. If one has a bigger vital capacity, one can go deeper before getting a thoracic squeeze. With a higher haemoglobin there is an increase in body oxygen stores. increased tolerance to a raised $PCO_2$ allows the person to hold his or her breath longer. The two together allow a longer dive. Tolerance to cold can be acquired. Whether all humans can develop this tolerance is a subject that can be debated for many days. It is accepted that many ethnic groups are tolerant to cold. I believe that western Europeans can be made tolerant to cold otherwise they could not have done the exploratory voyages that they did in unheated sailing ships.

AQUATIC MAMMALS

The specialised aquatic mammals are better at diving than we are. They are especially adapted to life in the water. A human has problems when he gets underwater. If he wants to dive for more than a couple of minutes he has to have an air supply. He has to have a tank on his back, a regulator in his mouth, a compensator on his chest, and so is not a streamlined shape. The specialised aquatic mammals, whether they be beavers, or sea otters, or seals or whales, have a nice rounded body contour for efficient swimming. They also have various anatomical changes that help. Their chest walls are easily compressed. They have lungs that collapse and expand again easily. They have adaptations in their blood vessels which allow blood to be shunted, not to the lungs, but into the blood vessels in the thorax, so that the lung does not get stiffer. When they dive, they shut down the renal circulation and become anuric.

They also have certain modifications in their anatomy for avoiding barotrauma. The lining of the middle ear is distensible, unlike that of humans. As they go down blood is shunted into that lining. It is like a great big velvet rug, which swells out and surrounds the ossicles and completely displaces any air in the middle ear. They also have an adaptation to avoid decompression sickness and nitrogen narcosis. As they go down their lungs collapse and gas is pushed into the non-respiratory airways. Here it has no exchange with the blood so the $PN_2$ does not rise. So they do not get nitrogen narcosis. Neither do they take up any extra gas. They also have high haemoglobin and so carry a lot more oxygen. They can use the venous oxygen stores.

The circulatory shutdown shunts the blood to the heart and brain. Because they are streamlined they have increased swimming power. Because they shut down the peripheral circulation they are tolerant to cold. A whale is not impervious to cold. It survives in the Antarctic because it has about a foot and a half of blubber all around. He has got heat producing organs inside and the insulation keeps the heat in.

TABLE I

BREATHHOLD DIVING TIMES (IN MINUTES)

| | |
|---|---|
| Man | 3.5 |
| Dog | 4 |
| Beaver | 15 |
| Porpoise | 6 |
| Killer Whale | 12 |
| Manatee | 30 |
| Grey Seal | 20 |
| Harbour Seal | 23 |
| Weddell Seal | 43 |
| Blue Whale | 50 |
| Sperm Whale | 75 |
| Bottlenose | 120 |

Now to compare the times that mammals can hold their breath. Dogs can do it better than humans. The beaver can last longer than with dog or man. The porpoise, a very specialised aquatic mammal, can breathhold only twice as long as a human. A porpoise is about the same size or perhaps a bit bigger than a human. It is really quite interesting that his breathhold is so much less than that of the sperm whale, which is vast compared to the porpoise. Yet the sperm whale has a breathhold of over an hour.

If we compare the actual dive times with those predicted on the basis of oxygen carried in the blood, even man exceeds the predictions. The various diving reflexes increase the dive time beyond the theoretical limit.

TABLE II

PREDICTED AND ATTAINED DIVE TIMES (IN MINUTES)

| SPECIES | PREDICTED | OBSERVED |
|---|---|---|
| Man | 2.5 | 3.5 |
| Porpoise | 2.5 | 6 |
| Seal | 6 | 18 |
| Fin Whale | 17 | 30 |
| Bottlenose | 36 | 120 |

Man is a poor performer in the depth stakes. The 100 m record was attained after a long work up with special equipment to get Jacques Mayol down quickly. He reached it in a very spectacular series of dives. It was a lot further than anyone had been before and a lot further than the physiologists predicted was possible a mere five years before he did it. We know that sperm whales dive to 1,000 metres because some have died at that depth entangled in submarine cables and been found when the cable was lifted for repair.

TABLE III

DEPTH OF DIVES (IN METRES)

| | |
|---|---|
| Man | 100 |
| Grey Seal | 134 |
| Harbour Seal | 250 |
| Porpoise | 305 |
| Weddell Seal | 550 |
| Bottlenose Whale | 825 |
| Sperm Whale | 1000 |

One of the major modifications in aquatic mammals is their remarkably slow respiratory rate at rest. A human sitting on the beach sunning himself breathes fifteen times a minute. A Californian sea lion sitting on the beach sunning himself breathes six times a minute. The dolphin needs to take three or four breaths a minute. The killer whale breathes 0.8 times a minute when he gets to the surface. This is probably the most spectacular change in aquatic mammals - their incredible efficiency at inflating their lungs.

Besides the slow respiratory rate the diving mammals have, relative to man, a very much reduced ventilation. This is not surprising as their relative lung capacity is also reduced. We are pretty inefficient. We require to change 12 litres of air per minute per 100 kg. Porpoises only need 6 litres per minute, per 100 kg. The bottle nosed whale, which can dive for two hours, only needs 3 litres per minute per 100 kg.

We have a tidal volume of about 500 ml or so which works out at approximately 0.8 of a litre per 100 kg. While the porpoise has a very much higher tidal volume than we do, he does not fit into the scheme of things properly. The bottle nosed whale has a tidal volume which is three times ours per 100 kg.

Comparing vital capacity with weight, porpoises are not as good as we are. Seals are about the same as we are. But the really deep divers, the ones who can really last, are very much better equipped with what one might call a power to weight ratio. They have got relatively smaller lungs for their bodies than we have, yet they use a greater percentage of the inhaled oxygen than we do.

Humans have got about 900 ml of oxygen available in their lungs or 7 ml per kg. We use 4 ml/kg/min. So two and a quarter minutes is quite a reasonable estimate of when one should start to breathe again. The fin whale has a whopping great oxygen storage. But when you translate it into mgm per kg, it is really quite small and his usage is quite high,

## TABLE IV

## RELATIVE VENTILATION

| | BREATHS PER MINUTE | RELATIVE VENTILATION (1/min/100 kg) | RELATIVE LUNG CAPACITY (1/100 kg) | RELATIVE TIDAL VOLUME (1/100 kg) | OXYGEN UTILIZATION (%) | DIVE TIME (min) |
|---|---|---|---|---|---|---|
| Man | 15 | 12 | 5.0 | 0.8 | 4.5 | 3.5 |
| Porpoise | 1 | 6 | 6.6 | 5.9 | 8 to 10 | 6 |
| Seal | 3.4 | 14 | 5.0 | 1.8 | 5.7 | 18 |
| Fin Whale | 1.2 | 3 | 2.9 | 2.5 | 8 to 10 | 30 |
| Bottlenose | 1.2 | 3 | 2.5 | 2.2 | 8 to 10 | 120 |

which explains why he is not at the bottom of the list. The bottle nosed whale, which has a much smaller storage, and uses slightly less in ml/kg, uses so much less that he is able to take those very long breathhold dives.

## TABLE V

## PULMONARY OXYGEN STORES

| | OXYGEN AVAILABLE (ml) | LUNG VOLUME (ml/kg) | RESTING OXYGEN USAGE (ml/min) |
|---|---|---|---|
| Man | 900 | 7.0 | 400 |
| Porpoise | 1,000 | 6.9 | 450 |
| Seal | 1,520 | 5.0 | 250 |
| Fin Whale | 3,350,000 | 2.9 | 200,000 |
| Bottle | 109,000 | 2.5 | 3,500 |

The bottlenose whale uses a lot more oxygen than we do per kg, nearly three times as much. Yet he can dive an awful lot longer. He can do this because of the various anatomical and physiological adaptations. His high haemoglobin level allows him to take up a lot of oxygen. He has a lung which collapses when he dives, and so prevents him developing nitrogen narcosis, decompression sickness, or barotrauma, and still provides enough oxygen for him to do long, long dives.

When an animal puts its face into water it develops bradycardia. The vital spot is the snout area, the beak. If you push a duck's beak into water its pulse rate goes down. If you push a human's nose into water, his pulse rate goes down. If he has a tachycardia, in a large proportion of people, the tachycardia stops. If a human puts his face into water his pulse rate drops to 40 or 50. The porpoise, when his face is out of water, has a pulse rate of 60. He puts his face under water and it drops to 30. The hippopotamus divides his pulse rate by nearly 10 when he puts his face under water. The beaver by approximately 10. The seal divides his by 10. The whale very nearly divides it by 10. The penguin goes from 200 to 20 with immersion. If the heart rate goes down like that the oxygen should last longer, because it is not going to be pumped around the body so quickly.

## TABLE VI

## BRADYCARDIA WITH IMMERSION

| | RESTING PULSE RATE | IMMERSED PULSE RATE |
|---|---|---|
| Man | 75 | 40 to 50 |
| Porpoise | 60 | 30 |
| Penguin | 200 | 20 |
| Sea Lion | 95 | 20 |
| Whale | 100 | 12 to 24 |
| Hippopotamus | 100 | 10 to 20 |
| Beaver | 75 to 90 | 10 |
| Seal | 70 to I40 | 7 to 14 |

The scuba diver with a mask on does not develop as slow a bradycardia as he would with his mask off. Covering the beak area does not cancel the reflex. The bradycardia is greater in cold water than in warm water. Humans do not really rate as bradycardic mammals, which probably explains some of the problems that Chris Lourey was talking about in Singapore. *(This paper was published in the 1981 Supplement to the Journal).*

## CONCLUSIONS

So humans are not really suited to be breathholding diving mammals.

Neither are they suited to being scuba diving mammals unless they have adequate insulation to prevent them getting cold. They are not suited to being scuba diving mammals unless they stay within the limits of experimentally determined safe diving habits, ie. the diving tables. We are all sticking our necks out to get into the water and go down to look at beautiful things underwater. There is an awful lot not known about humans' reaction to being in the water. But we do knew that what is known to be relatively safe exposure has been determined by trial and error over many, many years. We would be stupid to go outside those trial and error guidelines, especially those of us who are older. Even Navy divers, who are usually 19 to 30, should keep inside the limits set down for Navy divers, which have been proved on Navy divers. We should keep in practice, so keeping our diving adaptation. We need to be confident in the water, so that we may enjoy our holidays, enjoy our diving, pick up large scallops and keep our heads down when a motor boat goes overhead.