

Acknowledgments

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VISION, DARWIN AND THE DEEP BLUE SEA The visual sense and adaptations for terrestrial and aquatic sight.

Malcolm Le May

Key Words

Physiology.

Introduction

When we learn to dive we are told that the ocean is a “hostile environment” and that we are wholly adapted for life on the land. This is only partly true. Man has shown a liking and a fascination for immersing himself in water which is unlike that of many of our fellow apes. Our closest relative, the chimpanzee, has such an aversion for water that a narrow moat is sufficient to confine captive apes. With the exception of a Japanese relative with a penchant for volcanic springs, other monkeys tend to avoid immersion.

In spite of our seeming adaptation to the land, we continue to carry with us reminders of our life in the sea. Our internal environment is isolated from the hostile dry outside by a space suit of waterproof skin, and when that is damaged, we leak. If we damage enough of our skin, for example by burning, we die. Our internal osmolarity, equal to 0.9% saline, is a reminder of the salinity of the primordial sea. The process of reproduction remains a function conducted in a moist environment and we spend the first nine months of our life immersed. During the process of birth we mimic the change from an ocean dweller to a land mammal, repeating the invasion of the land in microcosm over and over again as each child is born.

In spite of a long history of living on the land, our eyes remain an aquatic based sense. In changing from vertebrate life underwater to life above, gills and swim bladders have become lungs, fins have become limbs, but eyes still remain essentially the organ that evolved in the sea. The continued function of our vision requires an adequate supply of tears and our eyelids ensure that our eyes are kept moist, returning briefly to the aquatic environment twenty times every minute as we blink to maintain the pre-corneal tear film.

We do not see well underwater without the aid of a mask.

Land animals rely on the interface between the air and the cornea for most of their refractive correction and in water man is hyperopic by some +43 Dioptres. Vision evolved in the sea and an interest in how the eye was adapted to different environments led me to a search for the origins of the eye as we know it.

Evolution

It is said that embryology mimics evolution. We begin our gestation as a unicellular creature and build our organs and our systems in the early part of our development, looking like any other embryo in the early stages and passing through stages that resemble our simple vertebrate ancestors. In our early embryonic development we resemble all other *Chordata*, equipped with gills and tails, and developing eyes like all others. Later we develop eyelids, lose our gills and develop other features necessary for life on land.

Charles Darwin wrote, "To suppose that the eye with all its inimitable contrivances for adjusting the focus to different distances, for admitting different amounts of light, and for the correction of spherical and chromatic aberration, could have been formed by natural selection, seems, I freely confess, absurd in the highest degree." This statement has been used by the opponents of evolution to support their beliefs, but Darwin followed this statement with one of the best supportive arguments of his monograph in favour of evolutionary theory. The idea of progressive development of one creature from an earlier predecessor was not new when Darwin published *The Origin of Species* in 1859.¹ The ancient Greek philosophers, Empedocles and Aristotle, hinted of a belief of one species developing from another. In the years preceding Darwin's famous publication, Jean Baptiste de Lamarck, and Darwin's own grandfather, Erasmus Darwin, had written on the same subject. Darwin returned from the voyage of HMS BEAGLE in 1836, and worked on the eventual contents of *The Origin* for some years. He read *Malthus on Population* (1798) in 1838, which reportedly stimulated his own ideas. Publication of *The Origin of Species* was precipitated some twenty-two years after the *Beagle* when the biologist Alfred Russell Wallace foreshadowed publication of his own independent conclusions on "survival of the fittest" in 1858. It is difficult for us now to imagine the revolutionary nature of Darwin's publication which was to become the bestseller of 1859. At a time when the Bible was taken literally by many, the age of the Earth was by them believed to be less than 6,000 years, and even scientists like Lord Kelvin believed the age of the Earth to be only 100 million years, too short for Darwinian evolution.

Life on Earth is some four billion years old.² Four billion is a very large number and most of us find it difficult to comprehend. Australians know that Sydney and Perth are some four thousand kilometres apart. There are four billion millimetres in 4,000 km. Continuing this analogy, for someone living in one of these cities, the Cambrian era began 570 km from home, the dinosaurs ruled from 220 to 65 km away and hominids first appeared about four kilometres from the front door. The biblical teaching in Darwin's time put the creation at the year 4,004 BC, a few metres away, rather than the entire width of the country.

For the first three billion years life was unicellular and for the first billion anaerobic organisms dominated. It is estimated that 99% of all species that ever lived have become extinct, either as part of numerous sporadic mass extinctions or as part of a continuing "background extinction".³ For some three billion years, aerobic stromatolite producing cyanobacteria dominated, eventually declining due to predation by more complex oxygen breathing animals. Stromatolites still exist at sites in Western Australia and in The Bahamas. Animal life as we know it began at the start of the Cambrian period, around 570 million years ago. During an explosion of life in the Cambrian sea nearly all known phyla appeared, including the first chordates.⁴

The early unicellular organisms were equipped with a light sense. Today, light sensitive organelles are present in some unicellular organisms and can include a directional or focussing mechanism or primitive "lens". Multicellular eyes are found in segmented worms, including lenses to concentrate the light and to increase directional accuracy. The compound eye of the *arthropoda* is an alternate design not seen in other phyla. The compound eye offers good directional sense, an ability to perceive the direction of polarised light, and colour vision, but with much lower resolution than the optical based systems. Other invertebrates have a variety of designs of eyes, ranging from a simple pit to the complex eye of the octopus. The eye of the octopus, a *cephalopod*, is structurally similar to the vertebrate eye, with a retina on the rear of a spherical eye and a similar lens, iris, cornea and accommodative mechanism. This in spite of the separate evolution of vertebrates since the Cambrian era and confirms that good designs will appear repeatedly due to convergent evolution. Another *cephalopod*, the nautilus, retains a more rudimentary eye like a pinhole camera, with a 2 mm pupil and the cavity of the eye filled with seawater. The vertebrate eye differs only from the eyes of some invertebrates in its origin.⁵

Vertebrate eyes are derived from neuroectoderm. The invertebrate eye forms wholly from the surface ectodermal layers and, although the vertebrate neuroectoderm also originates from surface ectoderm, the slightly different origin of the vertebrate eye has the advantage of closer integration of vision with the eventual nervous system. An early Cambrian chordate, *Pikaia*, had the basic design of the evolved vertebrate eye, not dissimilar to the eyes of modern *Agnatha* like the lamprey. The fossil records of the *Agnatha* are sparse. The lamprey, like its predecessors, has a sub-epithelial eye which was originally possible due to the small size and transparency of the organism. As size and opacity increased, the eye migrated to the surface, but has remained essentially similar in all vertebrates up to the present day. The lens and cornea form from surface ectoderm, their differentiation stimulated by the presence of the underlying embryonic optic vesicle.

Vision above and below water

The aquatic eye does not use the cornea as a refractive surface. The eyes of fish therefore have a large spherical lens and a relatively flat cornea. Fish are myopic in the unaccommodated state. A constant relationship exists between the radius of the lens and the radius of the eye in all fish and is described as Matthiessen's ratio. A spherical lens resists deformation and the accommodative mechanism found in most fish consists of a displacement of the lens within the eye by a small internal muscle, rather than deformation of the lens itself. In the *Agnatha*, the muscle moves and flattens the cornea as well. Some fish need good vision both in and out of the water and achieve this either with an increased range of accommodation or by means of a dual optical system found in the sloping retina of rays, or the twin pupils of the curious South American fish, *Anableps*. Colour vision is relatively rare in nature, being present in some arthropods (insects and crustaceans), fish, birds and in higher apes, including man. Sharks do not have colour vision, and uniquely amongst fish have a lower eyelid which protects the eye during close quarter encounters. Benthic fish have relatively huge lenses, an adaptation to make use of sparse available light. Only in the extreme depths and in permanent cave dwellers do eyes become rudimentary.

The *Sauropsida*, reptiles and birds, have structurally similar eyes. The lens, although spherical, is equipped with an equatorial annular pad which enables the lens to be squeezed strongly by a powerful ciliary muscle. The eyes of the *Sauropsida* are not spherical and various structural modifications are present, which enable the eye to retain its non-spherical shape in spite of the positive intraocular pressure and accommodative forces. Typically, a ring of bony plates is present anteriorly, forming a firm base for the action of the ciliary muscle. This ring of scleral ossicles can also be seen in the fossils of many Ichthyosaurs (Figure 1) and exists in present day *Chelonians*, the tortoises and turtles. Scleral ossicles are also found in the Coelacanth, *Latimera*. The *Chelonians* are considered more primitive than the *Sauropsida* and have additionally a powerful iris sphincter which compresses the anterior lens, assisting underwater vision. The kingfisher, *Alcedo*, has two maculae, an egg-shaped lens with both a short and a longer diameter and has adopted the strategy of the dual optical system to enable vision both above and below the water. Diving ducks and loons are primarily focussed in air but use the third eyelid, the nictitating membrane, underwater. The nictitating membrane is transparent and contains an area of high refractive index, providing a powerful accessory lens.

Mammals evolved from common ancestors present throughout the long rule of the dinosaurs. It was not until after the great Cretaceous/Tertiary extinction of the dinosaurs that modern species evolved. The history of the mammalian common ancestor means that the mammalian eye has evolved from an ancestor that was not only nocturnal, but had lost colour vision as well. The basic mammalian eye is poorly equipped for accommodation and has a thin sclera.

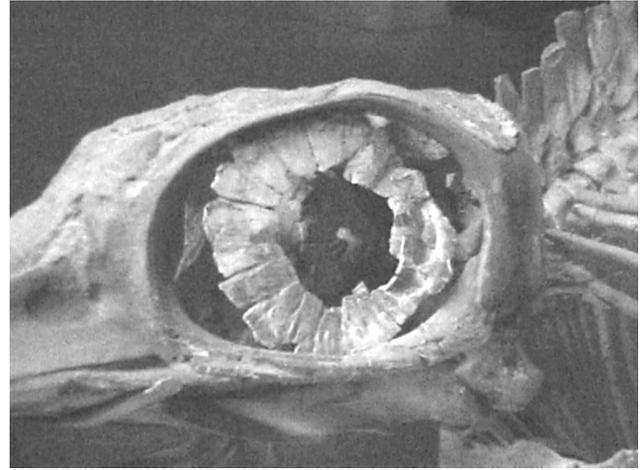


Figure 1. The scleral ossicles preserved in a fossil Ichthyosaur. Photo: Malcolm Le May.

Nocturnal mammals have a *Tapetum*, a reflective layer in the upper retina, which increases the light sensitivity in the lower field of vision by reflecting light a second time through the retina. The mammalian eye has subsequently evolved to suit all habitats, including a return to the water by several different groups. The *Cetaceans*, dolphins and whales, have a spherical lens similar to fish. Whales have extremely small eyes relative to their great size and the eyes of the larger whales have an enormously thick sclera posteriorly, a feature shared with large land mammals like the elephant. These eyes are relatively immobile. The otter has a mechanism not unlike the turtle for clear underwater vision. It needs to have good vision both above and below the water and has a deformable lens assisted by a powerful iris sphincter. *Pinnipeds* such as seals are myopic on land and have clear vision underwater. Their terrestrial vision is assisted by a very small vertical slit pupil when on land, producing a pinhole or stenopeic effect, a mechanism also found in the sea-snake.

Conclusion

The same design of eye exists with minor differences in all vertebrates. The early fossil record is incomplete, but the organ appears to have emerged in its present form following the initial evolution of the *Chordata* during the Cambrian era.

The eye evolved for vision in a shallow sea, but has adapted to suit all environments including the land, the air and a return to the sea by several groups.

Some animals require vision both above and below water and a number of different strategies have developed to ensure clarity of sight in media with markedly different refractive indices.

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LONG TERM HEALTH EFFECTS OF DIVING

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Key Words

Diving safety, investigations, medical conditions and problems, treatment sequelae.

Introduction

With the improvement in prevention and treatment of diving accidents over the last few decades, attention has now been focussed on the possible undesirable long-term health effects of diving. Much of the investigative efforts in this field have centred on the professional diver, however, for large numbers of recreational divers these concerns are very real. If we, as medical practitioners, are going to assess our patients' fitness to dive, we must also be able to provide advice as to how diving may affect their health.

Long term effects

A long term effect of diving can be defined as an effect outside the range of normal for an appropriately matched population. This effect must be causally related to diving and must persist beyond the acute and rehabilitation phase of a diving accident. There must be no non-diving pathology to explain the effect and it must produce a reduction in the performance or the quality of life of the diver.

There is no dispute that diving accidents can result in permanent sequelae such as dysbaric osteonecrosis, decompression illness (DCI) and pulmonary barotrauma with cerebral arterial gas embolism. A diver who suffers hypoxia from any cause with resultant brain injury may have permanent damage. Other diving related injuries, such as barotraumas, can result in hearing loss and vestibular damage. Gas toxicities and marine animal injuries may also result in permanent sequelae.

A more difficult question to address is, do long-term health effects occur in divers who have not suffered an overt injury or a specific diving accident?

A variety of physiological and pathological changes have been postulated to produce a great variety of long-term health effects, not related to a specific diving accident. This non-exclusive list includes increased environmental pressure, increased gas partial pressure, oxygen toxicity, gas induced osmosis, asymptomatic bubble development with local tissue effects, blood bubble interaction and blood brain barrier disruption, barotrauma damage to surrounding tissues, asymptomatic lipid emboli and adaptive effects of diving. I will specifically discuss dysbaric osteonecrosis (DON), barotrauma, decompression illness (DCI), ⁹⁹Tc-HMPAO-SPECT scanning (which is an investigation that has been in and out of favour), ophthalmological effects, ear nose and throat problems, pulmonary effects, subclinical pathological deficits (which from their very nature are hard to detect and quantify), neuropsychology, behavioural factors, and finally mention some miscellaneous findings.

Dysbaric osteonecrosis

Dysbaric osteonecrosis is usually assumed to be the direct or indirect result of gas bubbles that form during decompression interfering with the blood supply to vulnerable areas of bone. Juxta-articular, or A, lesions are found near articular joint surfaces and may eventually result in the collapse of the joint. Medullary, or B, lesions are found away from the articular surface, are usually asymptomatic but occasionally result in the development of sarcomata.

DON is often thought of as a consequence of deep diving, although it was first observed in caisson and tunnel workers. It became a problem in the commercial diving world as exploration went deeper.

DON is rare in recreational and military divers who have not been involved in experimental diving. It has been generally assumed that there was no risk of DON in divers who did not descend below 30 m. However, tunnel workers, who work long shifts under pressure, have had a significant incidence of DON, although they were typically working at pressures less than 12 m.