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Bionics of the Fish Gill

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Abstract

The physiological functions of the fish gill include gas exchange, ion regulation, water and acid-base balances, hormone excretion, circulating metabolite activation and deactivation, and immune defense. Inspired by these functions of the fish gill, several facilities, such as artificial membrane, "robot fish", shark gill cooling hole, "artificial gill", and "breathing wall", *etc*., have been invented and facilitated people's daily work and everyday life. Nevertheless, there not been any comprehensive reports concerning the bionic products in terms of the structural and functional properties of the fish gill. The aim of this article is to give a brief review of the bionic inventions of the fish gill.

Keywords: Artificial membrane; Bionics; Fish; Gill; Respiration.

Introduction

Bionics, also known as bionical creativity engineering, is a science of the application of biological nature in the study and design of engineering systems and modern technologies (Weissburg*et al*., 2010). The fish gill, highly advantageous as of its unparalleled structural and functional properties, drawn much attention of the scientists of the bionic engineering. In particular, the functions of gas exchange and water and electrolyte balances of the fish gill bring about assumptions of respiratory and metabolic therapies, which now have come to true. Based on the anatomical and physiological studies of the fish gill, several bionic products have been invented, satisfying people's needs of daily work and life. However, there have not been any complementary reports concerning the bionic products of the fish gill published so far. The aim of this article is to give a brief review on this aspect.

Fish Gill

The gills are carried right behind the head, bordering the posterior margins of a series of openings from the esophagus to the exterior (Hickman *et al*., 2012; Mulhauser, 2016). A complete gill consists of bony or cartilaginous arches on each side of the pharynx (Jha, 2016). Most species enhance the diffusion of substances in and out of the gill by employing a countercurrent exchange system, with blood and water flowing in opposite directions to each other (Eckert *et al*., 1988).

Most fish exchange gases by using gills (Hughes & Morgan, 1973). The gills are composed of gill arches, which are curved bony structures, on which two rows of gill filaments are distributed (Strzyzewska*et al*., 2016). Respiration is carried out by means of gills located under the gill covers. The walls of the pharynx is perforated by five slit-like openings. The tissues between the slits are the gill arches. When a fish breathes, it draws in a mouthful of water at regular intervals. Fish exchange gases by pulling oxygen-rich water through their mouths and pumping it over their gills. The bony fish have three pairs of arches, cartilaginous fish have five to seven pairs, and the primitive jawless fish have seven. The vertebrate ancestor no doubt more arches, and some of their chordate relatives have more than 50 pairs of gills. In some fish, capillary blood flows in the opposite direction to the water, causing countercurrent exchange. Some fish, like sharks and lampreys, possess multiple gill openings. However, bony fish have a single gill opening on each side.

The physiological functions of the gills include not only gas exchange, but also ion regulation, water and acid-base balances, hormone excretion, circulating metabolite activation and deactivation, and immune defense (Braunera & Romboughb, 2012). The comb-shaped filaments, densely covered by the capillaries, are aligned densely in the gill pieces. Each filament contains a capillary network that provides a large surface area for exchanging oxygen and carbon dioxide. When the water flows through the gills, the capillaries absorb oxygen dissolved in the water, meanwhile dispel

carbon dioxide into water (Ma, 2016). These regulation functions are closely related to the Cl^- in the epithelium of the gill filaments (Zhu *et al*., 2002). The changes of Cl^- depend on the living circumstances in either the sea water or in the fresh water. The change from fresh water to sea water, the number and volume of the Cl^- increase and the number of the mitochondria remarkably increases, which activates the activity of Na^+-K^+-ATPase, whereas backing into the fresh water, the function of the release of Cl^- decreases to the lowest level, but the permeability to Na^+ and Cl^- decreases in spite of the number of the Cl^- is not reduced (Zhu *et al*., 2002).

Although both the lungs of the higher vertebrates and fish gills are vital as gas exchanging surfaces and responsible for respiratory functions, there are still some distinctions between these organs, such as animal species, organ locations, and physiological properties (Naveen, 2011). These points are shown in Table 1.

Table 1. Distinctions between the lungs and gills

Properties	Lungs	Gills
Animal species	Terrestrial animals (amphibians, reptiles, birds, and mammals) and some fish species	Aquatic animals (fish)
Functional structure	Alveoli	Gill arches
Oxygen extraction	To extract atmospheric oxygen	To extract water-dissolved oxygen
Diffusion of the excretory products	No	Yes
Organ location	Only interior	Interior or exterior

Bionics of the Fish Gill

The terrestrial animals living in the land have lungs, which separate the oxygen from the air, while fish rely on gills, for gas exchange. At present, people are developing functional materials with reference to animal lungs and gills (Ge, 2000). By imitating these characteristics, people successfully manufactured the thin film materials for the purpose of high concentration oxygen production and ultrapure water separation. As a result, a high separation rate is achieved and energy is saved. The selectivity and permeability of the biological membranes endorse itself with many special features. For example, the artificial membrane structure is made by imitating the fish gill, and it can directly uptake water-dissolved oxygen like the fish gill does. The "artificial" device can be used as a breathing facility when a person is working in deep water. The artificial organs and desalination devices could be manufactured by using modern artificial membrane technologies and are widely used in the military services (Wang, 2010). Modifications of the intravascular oxygenator, the apparatus in the imitation of the bird lung and fish gill, by implementing a tip gas chamber, redirect the oxygen entering into the gas chamber via the dual-chamber inner cores of the intravascular oxygenator. The oxygen outflow by vacuum suction, which is in a contrary direction to the blood flowing through the vena cava, enhances the oxygenation effect in a fashion of reverse flow like what is seen in the fish gill (Xie & Jin, 2001).

In 2010, inspired by silver carp feeding, a scientist in Nanjing, China developed a "robot fish", which was composed of a carrier platform, a separation, a filter, and a shovel cheek shaking concentrating screen, as well as a power device. When the "robot fish" was driven, just as a ship was traveling on the water. The front-end device, a 10-meter long platform,was the "silver carp mouth", containing 10 pumps, which could take the algae on water surface simultaneously. When the machine was working and the cyanobacteria water was flowing through the gill-type filter, the cyanobacteria could be retained on the gill surface by the 200 layers of overlapping sieves on it. Moreover, the "cheek-type filter" was able to provide with a shaking sieve concentrate. Its screen was to squeeze water with the concentrated algae slurry. Then, the algae slurry was screened with a special floating bag. In this way, the "robot fish" swallowed the dirty cyanobacteria water and "spits" clear water. Nevertheless, the "robot fish" could deal with not only the cyanobacteria, but also the green algae, diatoms, and other impurities larger than 3 microns. It was energy efficient with a maximum speed of 10 km/hour. A 50 kW generator with full power provided with enough movement, and the processing speed of cyanobacteria disposal was 1,000 m^3/hour (Wang *et al*., 2016).

With the bionic design of the filter for centrifugal dust, the dust and gas separation could be realized with the use of a bionic production vacuum cleaner. The dustless bag and transparent dust cup design with the unique double-HEPA filter configuration facilitated the deep sterilization of the mites and avoided the second pollution (No authors listed, 2013).

It is well-known that sharks lack a swim bladder to control snorkeling. It maintains survival in the living circumstances by swimming constantly. Therefore, sharks need a lot of oxygen to replenish the great consumption of energy. The design of the shark gill cooling holes of Benz SLR was converging. The Mercedes Benz SLR McLaren was hailed as the

"Highway F_1". It was equipped with a 5.5-L V_8 turbocharged engine. The designers had great originality to design the shark gill cooling hole in order to obtain the best running performance (One-Cat Car Information, 2015).

The "artificial gills" by fish imitation is now in the process for resolving the breathing problem in the deep sea. The American scientists are imitating gill functions, creating an underwater "artificial gill" that can help people respire freely under water. The "artificial gill" extracts oxygen from the water in virtue of the fish gill function, for human breathing. Scientists hope that the "artificial gill" is with a greatly reduced size, so that it can be tied to the diver's chest. If the diver wears the new "artificial gill", he can swim in water with ease like fish with no worrying about running out of oxygen (Ma, 2006). The South Korean inventor Jeabyun Yeon designed a Triton artificial fish gill mask. As long as the user wears it, he doesn't need to carry the heavy diving cylinders as the mask is helpful in filtering oxygen from water for use. Through the micro battery, Triton extends out pipelines with the inside holes. When the water flows through the pipelines, Triton can work like the fish gill does, separating oxygen from the water while discharging the water. Users just have to bite it and breathe underwater without the need of carrying the heavy oxygen cylinder. In addition, the inside compressor compresses and stores air for an urgent need (Sistare, 2014).

Jeabyun Yeon also invented a "breathing wall", which was developed from the gills inspiration. It was a wall-integrated air cleaning concept for people living in the urban areas and want to relax and rest in a home with fresh air (Electrolux Design Lab, 2013).

Conclusion

The functions of the fish gill have brought about revolutions in the bionic engineering with regard to several inventions, including artificial membrane, "robot fish", shark gill cooling hole, "artificial gills", and "breathing wall", *etc*. These designs have greatly facilitated the daily work and everyday life of people. It is believed that more inventions would come to true in the future.

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