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Research Article

Squid as a Model Organism - Part 1: Exploring Defense System, Digestion, Respiration, Blood Circulation, Reproduction, and Skin

Mahsa Jalilinejad, Ahmad Berimipour, and Leila Satarian*

Department of Stem Cells and Developmental Biology, Cell Science Research Center, Royan Institute for Stem Cell Biology and Technology, ACECR, Tehran, Iran

ORCID:
Mahsa Jalilinejad: https://orcid.org/0000-0002-5981-2543
Ahmad Berimipour: https://orcid.org/0000-0002-6758-9599
Leila Satarian: https://orcid.org/0000-0002-5068-5031

Corresponding Author: Leila Satarian; email: l.satarian@royan-rc.ac.ir

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Abstract

The giant squid is an exceptionally intriguing organism with unique features, residing in the depths of the ocean at a depth of 1.5 km. To survive in these dark, high-pressure conditions and evade predators, this giant creature requires specific adaptations in its anatomy and way of life. The anatomy and physiology of the giant squid have inspired engineering and medical topics in human life. In this study, we will explore the potential applications of its defense system, digestion, nervous system, respiration, blood circulation, reproduction, and especially its skin in solving biotechnological challenges.

Keywords: giant squid, defense system, digestion, nervous system, blood circulation, respiration, reproduction, skin, nature-inspired, biotechnology

1. Introduction

The depths of the ocean constitute an exceptionally unique and distinct biome on Earth, harboring a multitude of known and unknown organisms. Oceans cover three-fourths of the Earth's surface, and intriguingly, the deepest points on Earth lie within these very oceans. The highest peak on Earth is Mount Everest, with an approximate height of 8,882 m[1]. In contrast, the Mariana Trench in the Pacific Ocean is the deepest part, with its deepest point lying approximately 11,034 m below the ocean surface [2]. The Mariana Trench is home to some of the most enigmatic marine creatures, the existence of which is almost unimaginable. The extreme depth, darkness, and high-water pressure have made exploration of these areas challenging for humans, resulting in inhabitants of these regions remaining largely unknown to us. In this study, we will delve into the anatomical structure and lifestyle of one of the colossal organisms in the ocean depths, known as the giant squid, which inhabits these oceanic depths. One of the deepest trenches in the Pacific Ocean, the Mariana Trench, is depicted in this schematic. The habitat of the giant squid is highlighted at an approximate depth of 1,000 m. At this depth, there is extremely high pressure and challenging environmental conditions. Nevertheless, some giant squids have managed to adapt to these harsh conditions and thrive in these deep-sea regions [3].

Due to the limited number and remote habitat, biological knowledge regarding the anatomical structure and physiology of these marine giants is highly restricted. However, numerous fictional tales have been written about sea monsters, including giant squids, associating the sinking of sea vessels with the attacks of large-bodied creatures with multiple limbs. Renowned authors such as Jules Gabriel Verne, the French playwright, and Herman Melville, the American writer, known for their globally acclaimed maritime-themed works, have contributed to these narratives [4].

Giant squids belong to a group of mollusks known as cephalopods, and based on evidence, they have been living in oceans for approximately five hundred million years [5]. Giant squids exhibit a diverse range of species, varying from sizes smaller than a human finger to larger than a whale among them. Among the marine giants, approximately 21 species of giant squids have been identified so far [6]. Research indicates that giant squids are present in all the world's oceans [6], but their geographic distribution in tropical and polar regions is much less common. Giant squids are commonly found around the islands of New Zealand and the Pacific Ocean, and sightings have also been reported along the eastern and western coasts of the North and South Atlantic Ocean, extending along the shores of Africa. This geographical distribution suggests a preference for continental and island ranges for their habitat, likely driven by the availability of food resources[6].

Among the ocean giants, the blue whale is the largest animal in terms of weight and length known on Earth. Following the blue whale, giant squids, with a weight ranging from 400 to 700 kg, rank 10^{th} and 12^{th} in terms of weight. Interestingly, in terms of the largest body size, giant squids, such as the giant, with a length of 12 to 20 m, rank third after whales [5].

2. Body Structure and Lifestyle of Giant Squids

2.1. Growth and reproductive traits of giant squids

Giant squids exhibit rapid growth, reaching an approximate length of 18 m within one to two years. Therefore, they must inhabit oceanic regions with abundant food resources [7]. The diet of giant squids consists of a wide spectrum of fishes and other cephalopods.

Their life cycle, estimate based on growth rates and maturation times, is approximately 1 to 5 years [8]. There is a significant difference between the reproduction rate and lifespan of regular fishes and giant squids. Regular fishes have longer lifespans with lower reproductive rates, while giant squids have short life cycles, rapid growth, and high reproductive rates [5].

Figure 1: Appearance of a giant squid (*Sthenoteuthis oualaniensis*) [9].

2.2. Arms, tentacles, and efficient prey capture mechanisms

In terms of body structure, giant squids generally have long and soft bodies, large eyes, eight arms, and two long tentacles. In the case of the giant squid, its arms have a broad part measuring 50 cm in width and extending up to 3 m (Figure **1**). Each arm has protective membranes and two rows of sucker structures[10,11]. The tentacles of this giant squid are exceptionally long, enabling it to locate the prey within a 10-meter distance. It can then propel its two tentacles towards the prey, capturing it with a motion similar to a coiled spring. The tentacles also possess suckers, making prey capture more efficient. Around each funnel-shaped sucker, there are sharp, chitinous tooth-like structures that move upwards when capturing the prey, rotating and driving the prey into the body [12, 13].

2.3. Head of the giant squid

The cylindrical-shaped head of the giant squid, Architeuthis dux, measures approximately 1 m in length and is connected to the body by a neck with a locking cartilage [11]. At the anterior end of the head of giant squids, there are eight muscular arms and two extremely long tentacles that come together to form a crown. The mouth of giant squids is located at the center of this crown, which is circular and equipped with powerful muscular chitinous jaws capable of rotation and movement for capturing the prey. The muscular mouth of giant squids has upper and lower jaws composed of cartilaginous plates each exceeding 15 cm in length. The arrangement of these plates next to each other creates an appearance similar to a parrot's beak. These overlapping plates are movable, allowing them to open and close, capturing a large prey[10].

2.4. Giant squid's rachis and esophagus

The rachis, or tongue-like organ, in the mouth of the giant squid, Architeuthis dux, is positioned to cut the prey into pieces for swallowing [10, 14]. The rachis is composed of a long cuticular strip and rows of transverse chitinous teeth. Each row consists of a central tooth and three smaller teeth around it. This arrangement of teeth on the rachis ensures that the food is segmented. With twisting movements, the rachis moves towards the muscular esophagus. The muscular esophagus continues towards the stomach, propelling food with peristaltic movements. Digestive enzymes are secreted by large salivary glands, as well as the liver and pancreas. Waste material passes through the short intestine and is directed towards the rectum. The rectum serves as the main part of the body for cephalopods and is responsible for water pumping, expelling waste, egg deposition, respiration, and ink ejection. After water pumping, the rectum plays a crucial role in jet propulsion for cephalopods. Inside the rectum, there is a valve that prevents water from entering towards the front. To control the controlled expulsion of water, there are cartilaginous structures around the rectum, which enhance the speed and intensity of water expulsion [15, 16].

2.5. Giant squid's eyes

The eyes of the giant squid, Architeuthis dux, are approximately 30 cm in size, positioned laterally on both sides of the head, and are circular in shape. Each eye has an adjustable lens for both near and far vision, with a dark-colored iris (Figure **2**). Unlike other animals, the eyes do not have corneas but are covered by a transparent layer of skin [17, 18]. Interestingly, the giant squid possesses the largest eyes among all known animals. These unique eyes allow it to live in the very dark depths of the ocean, escape from predators, and also function as a formidable predator itself. The structure of the giant squid's eyes is similar to that of other fish. The lens, with two parts of different density, focuses light onto the retina to form a clear image. The retina consists of photoreceptor cells that transmit visual information to the central nervous system (CNS).

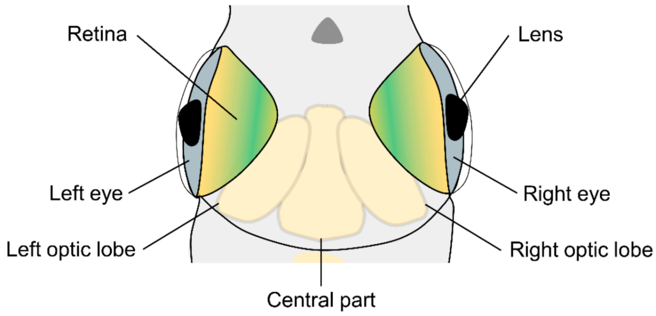

Figure 2: The dorsal perspective of the head of the oval squid, *Sepioteuthis lessoniana* [19].

2.6. Ink defense of squid

The possession of ink sacs is a characteristic feature of most cephalopods. Predators in the depths of the oceans exist that hunt cephalopods, considering them as their prey. The primary predators of giant squid, including the colossal squids, are sperm whales, which, due to their massive size of approximately 30 to 35 m, can confront and hunt giant squids. The forceful and widespread release of ink from the ink sacs of cephalopods leads to confusion and fear in the predators, providing a guarantee for the cephalopods' escape (Figure **3**). The ink sac is a slender and tall structure filled with the black pigment melanin, commonly referred to as black ink [20].

Figure 3: Inking humboldt squid, *Dosidicus gigas* [21].

2.7. The nervous system of the giant squid

The nervous system is considered to be one of the most important and fundamental systems in the body of any living organism. The rapid processing of environmental information in various conditions enhances the ability of organisms to cope and respond appropriately to environmental conditions. Due to the unique living conditions of the giant squid and its massive size, the brain and nervous system must evolve accordingly. The brain of the giant squid is similar to a donut, and interestingly, the digestive tract passes through its center [22]. Another noteworthy aspect of the nervous system of the giant squid is that, considering the total body weight, the brain's weight is not significantly more than 100 g [23]. The diameter of nerve cells in the giant squid is approximately 1 or 2 ml, enabling the transmission speed of nerve impulses to reach 10 m per second. Compared to the human nervous system, which consists of two main central parts, including the brain and spinal cord, and the peripheral nervous system (nerves branching from the spinal cord and extending to all parts of the body) [23], the nervous system of the giant squid is complex and includes the brain, sensory nerves, and motor nerves. As mentioned, the giant squid has long and axon-rich axons. Typically, messages are transmitted through three consecutive large nerve cells. The first and second nerve cells are sensory receptors, transmitting the received information to the central nervous system. The third group of nerve cells is motor, responsible for innervating the star-shaped nerves for innervating the circular muscle fibers in the specialized motor region responsible for jet propulsion [24].

2.8. Cardiovascular system of squid

The circulatory system in the giant squid is entirely unique. The giant squid has a closed circulatory system with three hearts. In the closed circulatory system of the giant squid, blood remains within the blood vessels (arteries, veins, and capillaries) and is not in direct contact with tissues [25]. Two smaller hearts are located near the gills (branchial hearts) and facilitate rapid exchange of respiratory gases with the environment. The third heart, larger than the other two, is more active and, through high mechanical activity and a high heart rate, pumps oxygenated blood throughout the large body of the giant squid (systemic heart). Another interesting point is that the blood of this aquatic creature is blue due to the presence of copper-based pigment in the blood, known as hemocyanin. Hemocyanin, similar to hemoglobin (iron-containing pigment), binds to oxygen and transports it to various parts of the body. Hemocyanin is blue in its oxygenated state and colorless in the deoxygenated form. Each hemocyanin molecule contains two copper atoms that bind to one molecule of oxygen [26].

2.9. Gills and respiratory system of squid

The respiratory system of the giant squid consists of two gills called ctenidia, allowing it to breathe underwater. The giant squid obtains the required oxygen from seawater. Seawater enters the main body of the giant squid through openings near the head called siphons and flows through the ctenidia. In this way, oxygen is extracted from the seawater, diffuses into the blood, and is transported through the circulatory system by the hearts located near the gills [26].

2.10. Reproductive system of squid

The giant squid, like other terrestrial beings, possesses a reproductive system adapted to its physiological conditions, comprising two genders, male and female. The male gender has sperm-producing glands, and the produced sperm is transferred to the arms of the giant squid, where it readies for release and fertilization [12]. The female gender has ovaries and oviducts. It releases eggs into the water, and the male, through its arms, releases sperm into the open water for fertilization to occur. An interesting point to note here is that the reproductive process typically occurs at great depths in the ocean, where water pressure is extremely high. To prevent damage to the laid eggs, the female secretes a gelatinous substance through its nidamental gland, enveloping all embryos. The embryos remain within this gelatinous space, which gradually enlarges with the gradual influx of water, supporting their growth [27]. A giant squid may deposit up to 200 eggs [28].

2.11. Squid's sclerite skin

Another intriguing feature of the giant squid is its specialized skin. The skin of the giant squid is tougher and more elastic than regular gelatinous skin, allowing it to thrive in the deep ocean. This unique skin is rich in specific amino acids, enabling the squid's rapid movement and resilience to high water pressure. In cephalopods, particularly in giant squids, visual processing and rapid skin color changes play a crucial role in adapting to the environment and escaping predators. The visual lobes in cephalopods, especially in giant squids, play a fundamental role in controlling the rapid skin color changes through the nervous system. Unlike the human nervous system, the visual lobes are not integrated with other parts of the brain but are rather large, located on both sides of the brain, connected to the donut-shaped brain through nerve axons [29]. The visual lobe in the giant squid is involved in detecting and interpreting information received from the eyes, such as images, movements, colors, etc. It also participates in processing information, allowing the giant squid to recognize and understand patterns, details, and various features. The visual lobe interacts with other lobes and neural systems in the giant squid to exhibit appropriate responses to environmental movements and ensure its visual functionality. As this creature lives in the dark depths of the sea, visual information processing is one of the most critical brain activities, accounting for over 80% of the giant squid's cerebral functions. In 2017, Taiwanese scientists conducted experiments to understand the connection between different parts of the visual lobes and other body parts, particularly pigmented skin cells. Their findings on 14 giant squids from the *Sepioteuthis lessoniana* species showed that the visual lobes mosaicly control other body organs. This mosaic-like pattern indicates a complex neural relationship between visual nerve cells and body parts, suggesting that the connection is not simple and one-to-one [5]. In the underlying skin cells of the giant squid, there are pigments with fluorescent properties that emit blue or red light in the dark depths of the ocean, illuminating a limited space around the squid. The stimulation mechanism for these cells and the fluorescent light-producing pigments raises questions for researchers in this field. However, it is generally agreed that when the giant squid comes closer to the water's surface to absorb more oxygen, sunlight is absorbed by the pigmented skin cells, and when it returns to the dark depths of the water, it uses this source to produce blue light [30, 31].

The skin of cephalopods, including giant squids, is multi-layered, highly elastic, and flexible, covering the entire body (Figure **4**). Usually, the head and arms tend to be dark reddish-purple, the back is brownish, and the ventral region is slightly lighter. The color intensity on the dorsal and ventral surfaces of the arms is less pronounced compared to the lateral surfaces[10]. The internal surface of the mantle and some of the intestines also contains pigments with a dark red hue, which is an unusual feature in giant squids [30, 31].

The skin consists of several layers, with one of these layers incorporating chromatophore organs responsible for red, yellow, or brown colors (Figure **5**). These organs have a central pigment cell surrounded by muscle cells. The mechanical action of muscle cells causes chromatophores to expand and contract between the layers, resulting in the reflection and transmission of specific wavelengths of visible light [33]. Each chromatophore has 10–30 radial muscle cells controlled by the central nervous system. Each fiber contains myofilaments that contract in a coordinated manner to expand the pigment-containing cell from a punctate and spherical state to a fully expanded,

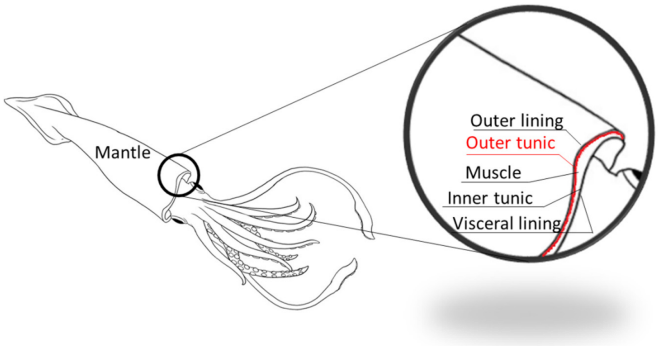

Figure 4: The mantle of *Dosidicus gigas* and its internal composition [32].

colored disc. Expansion occurs in less than 1 second and results in a 14-fold increase in the diameter of the pigment cell. Consequently, this highly evolved natural architecture blends the skin color with the surroundings, allowing the creature to easily camouflage [30].

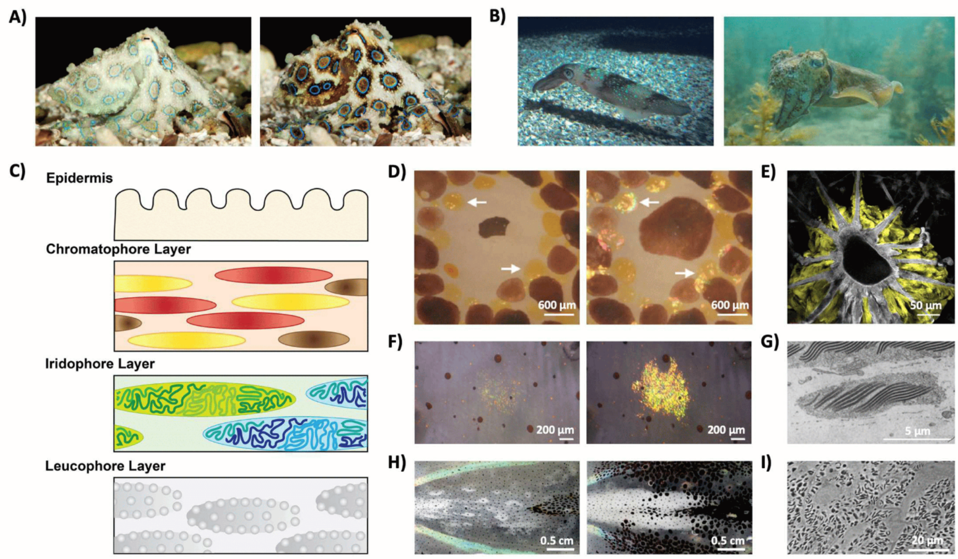

Figure 5: Illustrates the remarkable color-changing abilities of cephalopods and the intricate structures of their skin [34]. (A) Depicts images of a blue-ringed octopus (*Hapalochlaena lunulata*) undergoing coloration changes. (B) Displays images of a *Loligo pealeii* squid (left) and a *Sepia apama* cuttlefish (right). (C) Provides a schematic representation of squid skin, showcasing its complex architecture with an outer epidermis and layers consisting of chromatophore organs, iridophore cells, and leucophore cells. (D) Exhibits the contracted (left) and expanded (right) states of a chromatophore organ, with white arrows indicating the presence of iridophores. (E) Presents an electron microscopy image of a chromatophore organ, with yellow-highlighted portions denoting the positions of sheath cells. (F) Displays the non-iridescent (left) and iridescent (right) forms of an iridophore cell. (G) Features an electron microscopy image of an iridophore cell revealing intracellular lamellar structures (dark gray) responsible for the narrowband reflectance characteristic of the cell. (H) Depicts the transparent (left) and opaque (right) tissue in the mantle of a female *Doryteuthis opalescens* squid. (I) Shows an electron microscopy image of the layer of leucophores, indicating electron-dense proteinaceous particles called leucophores (dark gray) responsible for the dynamic opacity-changing capabilities of the squid. The images in part (A) are adapted from [35]. The images in part (B) are adapted from [36]. The images in parts (D, E) are adapted from [37]. The images in part (F) are adapted from [38]. The image in part (G) is adapted from [39]. The images in parts (H, I) are adapted from [40].

3. Conclusion

The giant squid is an extraordinary soft-bodied creature that has captured the attention of researchers and the public alike due to its colossal size. Its eyes, being the largest in the animal kingdom, have led scientists to conduct numerous studies on the giant squid's visual system. Additionally, its reproductive methods and camouflage techniques have piqued the interest of many. While this soft-bodied giant is not the only inspirational creature in nature, its unique features have made it a subject of interest in engineering and medical industries. Despite the conducted studies and research, the exploration of the giant squid's life and the investigation of its anatomical structure continue to provide a fertile ground for young and motivated researchers in the field of biomimicry.

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