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Research on the Physiological Mechanisms of Osmotic Pressure Regulation in Freshwater Fish

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Abstract: Freshwater environments possess an overall osmotic pressure that is considerably lower than the body fluids of fish, which leads to chronic osmotic stress in freshwater fish with passive water absorption and ion loss. In order to maintain the dynamic equilibrium of water and ions for stable cellular metabolism, neural transmission, and organ function, freshwater fish have developed a comprehensive physiological system for osmotic regulation. By means of the coordinated operations of multiple organs that involve enzymatic reactions and hormonal regulation, they accomplish water excretion and ion reabsorption, thereby stabilizing the osmotic pressure of body fluids. This article, in a systematic way, elucidates the osmotic environmental stresses that freshwater fish are faced with, and it analyzes the osmotic regulatory functions of those key organs, such as gills, kidneys, intestines, and skin. It also elucidates the regulatory mechanisms of those critical enzymes and endocrine hormones. It summarizes the energy metabolism patterns and environmental adaptation characteristics within the realm of osmotic regulation, and it provides a whole-scale overview of the entire physiological mechanism of osmotic regulation in freshwater species. The study aims to clarify the fundamental physiological principles that underlie the osmotic balance in freshwater fish, and it offers theoretical foundations for aquaculture water quality management, stress-resistant fish breeding, and aquatic organism physiological research.

Keywords: Freshwater fish; Osmotic pressure regulation; Physiological mechanism; Ion transport; Environmental adaptation

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1. Understanding the osmotic environmental stress faced by freshwater fish in survival

1.1. The freshwater environment possesses fundamental physicochemical characteristics of low permeability

Nature's freshwater bodies, such as rivers, lakes, and ponds, possess extremely low concentrations of inorganic salt ions, and the osmotic pressure is usually within the range of 5–10 mOsm/L. The majority of freshwater bony fish keep their body fluid osmotic pressure stable (250–300 mOsm/L), which is higher compared to the external environment, thus generating an internal osmotic gradient [1]. Through the process of osmosis, water molecules consistently enter the fish via the biofilm following the concentration gradient, whereas essential electrolytes (for example, sodium, chloride, calcium ions) disperse out because of the concentration differences. Lengthy and passive processes of water absorption as well as ion excretion continuously disrupt the balance of water-electrolytes in freshwater fish. In the absence of regulatory mechanisms, this situation causes the dilution of fluid, the depletion of electrolytes, the occurrence of cellular edema, and ultimately leads to metabolic disturbances or the event of mortality. The hypotonic environmental condition drives the process of evolution of specialized osmotic regulation within freshwater fish.

1.2. Water-salt imbalance can disrupt the normal physiological functions of fish

Water, as well as ions, are of fundamental nature for the metabolism of fish cells, the circulation of body fluid, and the transmission of neural signals, and stable osmotic pressure is of essential nature for the sustaining of life-related activities. When freshwater fish are not able to effectively counteract osmotic stress, an excessive amount of body water leads to the occurrence of tissue edema and an increase in blood volume, which worsens the burden of cardiac circulation [2]. Continuously, the phenomenon of electrolyte loss takes place, which brings about the situation where ion concentrations are not sufficient. This situation makes the cell membrane potential become unstable, and it inhibits the transmission of neural signals as well as muscle contraction. As a result, it leads to a state where swimming is sluggish, and the stress resistance is reduced. Additionally, the state of ion imbalance also causes the acid-base balance to be disrupted. It interferes with the function of metabolic enzymes, impairs the process of protein synthesis and the efficiency of energy utilization, suppresses the process of growth and development, and weakens the ability of disease resistance. Therefore, actively carrying out the regulation of osmotic pressure and maintaining the dynamic balance of water and electrolytes are crucial physiological capabilities that enable freshwater fish to adapt to their surrounding environment and ensure the processes of survival and reproduction.

2. Utilizing multi-organ collaboration to achieve osmotic homeostatic regulation

2.1. Glandular tissue dominates ion transport and exchange in fish

In fish living in freshwater, the gills are the most important peripheral organs that are used for the regulation of osmotic pressure. They play a variety of roles, which include the absorption of ions, the preservation of the water barrier, and the exchange of gases. So, they are a very important physiological structure for the adaptation to hypotonic environments [3]. The surface of the filaments of fish gills is densely covered with chloride cells that are differentiated and mature (also called ion cells). These cells have a large number of mitochondria, which provide the necessary energy for the active transport of ions. In hypotonic environments, chloride cells actively take in sodium and chloride ions from the water by using specific ion transporters. By doing this, they make up for the continuous loss of electrolytes from the body surface. The pathway that is fundamental for transport depends on the enzyme called sodium-potassium adenosine triphosphatase (which is Na^+/K^+-ATPase and is often abbreviated as NKA). It does the action of mediating the pumping outwards of the sodium ions that are inside the cells. By doing this, it creates a gradient of ion concentration that crosses the membrane. After that, this gradient makes it possible for the sodium ions to flow in reverse from the aqueous environment that surrounds the cells. At the same time, it works together with the transporters of chloride in order to help with the uptake of chloride ions. The spaces between cells that are packed densely within the epithelial cells of the gills effectively limit the infiltration of water passively and the rate of the flow out of ions. This allows for the retention of salt in an efficient way while reducing the losses due to osmosis and keeping a balance of water-electrolyte that is stable at the surface of the body.

2.2. The kidneys complete the excretion and purification of excess water

The kidneys serve as the principal organ that freshwater fish use to get rid of extra water, and they form a supplementary regulatory system together with gill tissues. The kidneys of freshwater fish are provided with a great number of glomerular structures. These structures offer a large area for filtration and have high efficiency in filtration [4]. This enables the quick removal of extra water from the bloodstream and the creation of large amounts of hypotonic and diluted urine. The glomeruli of fish are able to effectively filter free water out from the blood while keeping important solutes such as proteins and ions. In this way, they reduce the loss of electrolytes through urine. Within the locations of renal tubules as well as collecting ducts, the epithelial cells actively carry out the action of retrieving the ions that are essential, for example, sodium, chloride, and calcium. They do perform the action of pumping these electrolytes from the filtrate and then bringing them back into the bloodstream. At the same time, they only act by eliminating the water that is in excess and the trace metabolic by-products. By means of its operational framework, which has high-filtering and low-salt-discharge characteristics, the kidney efficiently carries out the action of resolving the central problem regarding the passive water absorption in freshwater fish. It works in a way that is in tandem with the salt-acquisition capability of the gills so as to construct a fundamental osmotic equilibrium system.

2.3. Intestinal assistance in completing ion replenishment regulation

The intestinal tract serves as an organ that provides supplementary function for osmoregulation in freshwater teleosts. It is mainly in a state of being in charge of the action of ion supplementation and the regulation of water by means of ingestion and the uptake of fluid[5]. The intake of the diet of freshwater fish contains a large amount of inorganic salt ions. This provides a source for intestinal epithelial cells so that they can actively carry out the absorption of electrolytes from both the food and the intestinal lumen. As a result, it can continuously carry out the restoration of ions that are lost through gill respiration and dermal diffusion in order to maintain ion homeostasis. In a situation that is in contrast to marine fish, which need to carry out significant uptake of water to counteract dehydration, freshwater fish have a very small amount of water consumption. This effectively reduces the continuous inflow of external water and lessens the load of renal excretion. Furthermore, the tract of the intestine does modulate the permeability of the mucosa so as to govern the rates of the absorption of ions and water, and thereby does precisely adjust the pressure of the osmosis in response to the variations in the levels of the ions and the quality of the external water. This does boost the ability of the fish to adapt to its environment and refines the system of regulatory coordination among the organs.

2.4. Ineffective barrier function of the superficial skin in preventing permeable substance exchange

The integument of the fish (skin as well as scales) has a function as the main physical safeguard against the disruption of osmosis. In the teleosts that live in freshwater, the layer of epidermal cells shows an arrangement that is dense and compact, and at the same time, the scales form a continuous and overlapping coverage across the surface of the body. This anatomical setup considerably lessens the permeability of the cell membranes, and by doing so, it minimizes the passive flow of external water in and suppresses the leakage of electrolytes out. By keeping up this surface barrier that is impermeable, the fish effectively eases the constant osmotic stress that is exerted by the hypotonic aquatic environments and eases the demands for physiological regulation that are placed on the respiratory organs (gills) and the renal systems. When scales are damaged or the skin is compromised, the barrier function is impaired, leading to a substantial increase in water infiltration and ion loss rates, which readily trigger issues such as water-electrolyte imbalance and stress-induced weakness. Thus, the physical surface barrier constitutes the fundamental safeguard for osmotic pressure regulation, providing a stable foundation for precise osmotic balance maintenance in internal organs.

3. Achieving precision penetration regulation through biomolecules

3.1. Key enzymes drive the ion active transport process

In the process of osmoregulation in freshwater, enzymes are the molecules that play a pivotal and functional role and that support the processes of active transport. The regulatory function of the enzyme called sodium-potassium adenosine triphosphatase (Na^+/K^+-ATPase) is especially essential. This enzyme is present in a widespread manner in chloride cells of the gill, epithelial cells of the renal tubule, and mucosal cells of the intestine. By causing the hydrolysis of adenosine triphosphate (ATP) to produce energy, it helps to make possible the counter-transport across the membrane of sodium and potassium ions. Eventually, it sets up and keeps up a stable gradient of ions across the membrane. This gradient of concentration, in turn, gently promotes the movement in a direction of a number of ions, including ions of chloride and ions of calcium, therefore directly determining the efficiency of the uptake of ions by fish and besides acting as enzymes that are core, carbonic anhydrase functions as a catalyst for the reaction in water between carbon dioxide and water, changing them into carbonic acid, which breaks apart to let out hydrogen ions and bicarbonate ions. This pathway of biochemistry makes it easier to exchange ions and helps to keep up the equilibrium of acid-base, indirectly stabilizing the conditions of osmosis within the organism. Through the activity with synergy of these enzymes that are functional, a system of ion transport that is continuous and efficient is kept, supporting the active regulation by the organism of levels of salt.

3.2. Endogenous hormones coordinate the overall osmotic regulation rhythm

The hormones that belong to the endocrine system play the role of signaling and regulatory molecules. They carry out the action of orchestrating the osmoregulatory rhythms across multiple organs so as to maintain the integrated systemic homeostasis [6]. Cortisol has the function of being the primary osmoregulatory hormone in freshwater fish. It stimulates the proliferation and differentiation of gill chloride cells. It boosts the activity of sodium-potassium adenosine triphosphatase (Na^+/K^+-ATPase, NKATPase). It enhances the ion uptake efficiency of gill tissues. And it optimizes the renal tubular reabsorption so as to minimize the electrolyte loss. Prolactin reduces the permeability of fish skin and gill epithelial layers [7]. It prevents the excessive water influx and the ion efflux. Thus, it stabilizes the baseline osmotic equilibrium. Both the hormone of growth and the factor of insulin-like growth jointly engage in the regulation of the expression of genes related to ion transport, which has the effect of enhancing the long-term adaptation of fish to the environment. These hormones act in a synergistic way while also balancing one another, and they dynamically make adjustments to the intensity of regulation in accordance with the changes in the external water so as to increase the precision and flexibility of osmoregulation. When fish are exposed to saline environments, the composition of endocrine regulatory hormones changes significantly. Growth hormone becomes the dominant regulatory factor, which can upregulate the expression of ion transporters in gill chloride cells, increase SPT activity, and promote the secretion of excess salt entering the body to maintain osmotic balance. Cortisol also plays a synergistic role in saltwater osmoregulation, supporting the transformation of chloride cell function to adapt to the demand of salt secretion. Prolactin's regulatory activity is relatively attenuated in high-salinity environments to avoid excessive inhibition of ion and water exchange that would disrupt osmotic balance. The dynamic transformation of this hormone regulation network is the key physiological basis for fish to adapt to different salinity environments, and it also provides an important theoretical reference for artificial breeding of migratory fish and improvement of aquaculture environment regulation strategies.

4. Balance energy consumption to adapt to environmental dynamic changes

4.1. Percolative regulation consumes the organism's metabolic energy throughout the entire process

Freshwater fish carry out the action of maintaining osmotic balance by means of an energetically active kind of physiological mechanism. This process depends on several energy-intensive sorts of functions. These functions are as follows: the action of actively pumping ions across cell membranes, the action of producing urine so as to adjust fluid volumes, the action of synthesizing regulatory hormones, and the action of maintaining optimal enzyme function. All of these functions demand a steady kind of supply of adenosine triphosphate (ATP). In order to keep up water and electrolyte equilibrium, these fish continuously make use of their respiratory and metabolic pathways to break down nutrients, and by doing so, they provide power for the complex regulatory processes. During periods when environmental conditions are stable, the process of osmotic regulation uses up a relatively constant amount of energy, and this amount typically makes up a minor fraction of their basal metabolic rate and does not interfere with growth and development. On the contrary, when environmental stability gets disrupted, for example, through significant fluctuations in water quality, imbalances in ion concentration, or the deterioration of aquatic conditions, fish have to strengthen their ion transport mechanisms and water excretion capabilities. As a result, there is a notable increase in enzyme activity and hormone secretion to restore balance [8]. This leads to a substantial rise in metabolic energy consumption, diverting energy resources required for growth, immunity, and reproduction, resulting in slowed growth and reduced stress resistance.

4.2. Fish can dynamically adapt to fluctuations in environmental osmotic pressure

In natural ecosystems of freshwater, the temperature, the concentration of ions, and the levels of pH experience fluctuations that are constant and are driven by shifts of seasonal nature and perturbations of an environmental kind. Freshwater fish do show flexibility of an extraordinary osmoregulatory nature, which allows them to adapt in a dynamic way to these variable external conditions. In environments with low ionic content, fish boost the efficiency of ion uptake by elevating the activity of enzymes for transport, augmenting the quantity of chloride cells in the gills, and enhancing the reabsorption of ions in the renal tubules, thereby offsetting the depletion of ions that is induced by gradients of osmotic pressure [9]. As the temperature of water ascends and the rates of metabolism increase, fish orchestrate the functions of organ systems via pathways of hormonal regulatory nature to optimize the distribution and utilization of energy and sustain the equilibrium of metabolism. Certain salt-tolerant freshwater species further rapidly adjust the permeability of their surface epithelium and ion transmembrane transport efficiency through gene expression regulation to respond to minor salinity fluctuations in the water. These comprehensive physiological and molecular adaptation mechanisms collectively demonstrate the exceptional environmental adaptability of freshwater fish in sustaining homeostasis within complex and dynamic aquatic ecosystems.

5. Conclusion

Freshwater fish have adjusted so as to prosper in hypo-osmotic aquatic environments, and they face difficulties like the influx of water passively and the depletion of electrolytes [10]. In order to keep up osmotic balance, they have brought about a complicated physiological network. Four main organs, that is, gills, kidneys, intestines, and skin, work together in order to form a double-defense system which combines physical barriers and physiological transport ways. Through actions that are synchronized (gills take in necessary salts, kidneys get rid of extra fluids, intestines provide metabolic energy, and skin acts as a semi-permeable barrier), these living things exactly control water-salt balance. Molecules such as Na^+/K^+-ATPase and carbonic anhydrase produce the needed transport energy, and hormonal signals, which are mediated by cortisol and prolactin, precisely adjust regulatory responses. By changing energy metabolism in a dynamic way, this combined system makes it possible for freshwater fish to get used to different aquatic conditions. The osmotic regulation mechanism is the result of long-term evolution, balancing water and ion concentrations, stabilizing cellular conditions, and ensuring normal metabolic, growth, and immune processes. Studying the osmotic regulation physiology in freshwater fish offers insights into their environmental adaptation, providing theoretical support for optimizing aquaculture water quality, developing stress-resistant fish strains, and conserving aquatic resources, thus promoting the scientific and high-quality development of freshwater aquaculture.

Disclosure statement

The authors declare no conflict of interest.

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