INTERNATIONAL JOURNAL OF CARDIOVASCULAR RESEARCH & INNOVATION
Jul-Sept 2024, VOL. 2, ISSUE 3, pp. 17-19
https://doi.org/10.61577/jcri.2024.1000016

RESEAPRO JOURNALS

MINI REVIEW

OPEN ACCESS

Comparative cardiovascular adaptations in aquatic vs. terrestrial vertebrates: Implications for human cardiovascular health

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ABSTRACT

Cardiovascular health is crucial in preventing heart disease, the leading cause of death worldwide. This article reviews the adaptations of cardiovascular systems in aquatic and terrestrial vertebrates, emphasizing their evolutionary significance and implications for human health. Aquatic vertebrates, such as fish, possess simpler cardiovascular structures, primarily a two-chambered heart, which effectively manages oxygen extraction in water. In contrast, terrestrial vertebrates, including amphibians, reptiles, birds, and mammals, have evolved more complex cardiovascular systems, with three or four-chambered hearts that support higher metabolic demands. Understanding these adaptations provides insights into potential therapeutic strategies for cardiovascular diseases in humans, particularly through comparative physiology and regenerative medicine.

KEYWORDS

Cardiovascular adaptations; Aquatic vertebrates; Terrestrial vertebrates; Evolutionary biology; Human health implications; Comparative physiology

ARTICLE HISTORY

Received 25 July 2024; Revised 22 August 2024; Accepted 29 August 2024

Introduction

Cardiovascular health is a crucial area of medical research, particularly as cardiovascular diseases (CVDs) remain the leading cause of mortality globally [1]. Understanding the evolutionary adaptations of cardiovascular systems in various vertebrate species can provide valuable insights for improving human health outcomes. The intricate designs of these systems have evolved in response to environmental demands, shaping how different organisms manage oxygen delivery and metabolic processes [2].

Aquatic vertebrates, such as fish, have developed highly efficient two-chambered hearts that optimize oxygen extraction from water, a medium where oxygen availability is often limited [3]. These adaptations allow for effective blood circulation while minimizing energy expenditure, enabling fish to thrive in diverse aquatic environments. Conversely, terrestrial vertebrates, including amphibians, reptiles, birds, and mammals, have evolved more complex three or four-chambered hearts that support higher metabolic rates essential for sustaining life on land [4]. This complexity enables the separation of oxygenated and deoxygenated blood, facilitating more efficient oxygen delivery to tissues during increased physical activity [5].

This article will explore the evolution of cardiovascular systems in both aquatic and terrestrial vertebrates, examining the structural and functional adaptations that have arisen in response to environmental challenges. It will further discuss the implications of these adaptations for human cardiovascular health, highlighting how insights gained from studying these diverse species can contribute to the development of innovative treatments and preventive strategies against heart diseases.

Evolution of Cardiovascular Systems

Aquatic vertebrates

Aquatic vertebrates, such as fish, have evolved a two-chambered heart consisting of one atrium and one ventricle [6]. This design is efficient for their environment, allowing for effective oxygenation of blood as it passes through gills. The blood is pumped from the heart to the gills, where it is oxygenated before being distributed to the rest of the body. This single-circuit system is suitable for aquatic living, where oxygen availability can vary, and allows fish to efficiently manage blood flow in response to their immediate environment [7].

Adaptations in fish hearts

Fish hearts are adapted to low oxygen levels, utilizing a high stroke volume and low heart rate to maximize oxygen extraction during gill respiration. Some species have developed structures like the spiral valve in the conus arteriosus, which helps maintain efficient blood flow and oxygen uptake. Additionally, certain teleosts exhibit the ability to adapt to varying oxygen levels through physiological changes, enhancing their cardiovascular performance [8].

Terrestrial vertebrates

In contrast, terrestrial vertebrates, including amphibians, reptiles, birds, and mammals, possess more complex three or four-chambered hearts that support a double-circuit system [6]. This adaptation is crucial for managing higher metabolic rates and the increased oxygen demands associated with life on land.

Evolution of the Heart Structure

Amphibians have a three-chambered heart (two atria and one ventricle), allowing for some separation of oxygenated and deoxygenated blood [6]. However, this system can lead to the mixing of blood, which is less efficient for oxygen delivery.

Reptiles also typically have three-chambered hearts, but some, like crocodiles, possess a four-chambered heart, effectively preventing the mixing of blood [3].

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Birds and mammals, both of which have evolved four-chambered hearts, exhibit complete separation of oxygenated and deoxygenated blood, supporting higher metabolic rates and endurance activities (Table 1). This structural evolution reflects their adaptation to diverse ecological niches and energetic lifestyles [9,10].

Table 1. Comparative Cardiovascular Features of Aquatic and Terrestrial Vertebrates.

Feature	Aquatic Vertebrates	Terrestrial Vertebrates
Heart Structure	Two-chambered heart	Three or four-chambered heart
Blood Flow Circuit	Single circuit (heart → gills → body)	Double circuit (heart → lungs → body)
Oxygen Extraction	High efficiency in gills	Efficient lung-based respiration
Response to Hypoxia	Reduced activity, altered flow	Increased heart rate, blood redistribution
Adaptation Mechanisms	Gill surface area adjustment	Enhanced chamber structure for increased output

Comparative Cardiovascular Function

Cardiac output and efficiency

Cardiac output, the volume of blood the heart pumps per minute, is a critical measure of cardiovascular efficiency [11]. In fish, lower heart rates and higher stroke volumes are observed, which are effective in their aquatic environments. In terrestrial vertebrates, especially mammals, the heart adapts to higher workloads with increased heart rates and specialized chambers that optimize oxygen delivery to tissues [10].

Oxygen utilization

Aquatic vertebrates have adaptations for efficient oxygen extraction in water, where oxygen levels are typically lower than in air [12]. For instance, many fish species can alter their gill surface area or blood flow to maximize oxygen uptake depending on environmental conditions. In contrast, terrestrial vertebrates utilize lungs for gas exchange, requiring a more robust and efficient heart to maintain the necessary oxygen levels for metabolic processes [13].

Response to environmental stressors

The cardiovascular systems of vertebrates also respond to environmental stressors differently. For example, during hypoxic conditions, fish may reduce their activity levels or alter their swimming patterns to conserve energy and maintain oxygen levels [14]. Terrestrial vertebrates, however, have developed more complex regulatory mechanisms, including the ability to increase heart rate and redistribute blood flow to vital organs during stress, ensuring that oxygen delivery remains optimal [15].

Cardiovascular Pathologies and Implications for Human Health

Understanding the cardiovascular adaptations of different vertebrates offers insights into potential treatments for human heart diseases [16]. Research into the cardiovascular systems of these animals may uncover novel therapeutic strategies and preventive measures against conditions like ischemic heart disease (IHD) and heart failure [17].

Cardiovascular diseases in humans

Cardiovascular diseases (CVDs) are characterized by disorders of the heart and blood vessels, including conditions such as coronary artery disease, hypertension, and heart failure [18]. These diseases often result from a combination of genetic, environmental, and lifestyle factors. Studying adaptations in other vertebrates can provide clues about potential protective mechanisms against these diseases.

Insights from aquatic adaptations

The heart's efficiency in fish, particularly in oxygen extraction and metabolic regulation, could inspire new approaches to enhancing heart function in humans. For instance, understanding how certain fish manage blood flow under hypoxic conditions may lead to new treatments for heart conditions characterized by reduced blood flow [19]. Additionally, research into the regenerative capabilities of some fish species, such as zebrafish, which can regenerate heart tissue after injury, may inform regenerative medicine approaches for treating damaged human hearts.

Learning from terrestrial adaptations

Mammals and birds exhibit cardiovascular features that enable them to sustain high levels of physical activity and endurance. Insights into how these species regulate heart rate and blood pressure during exercise could lead to better management strategies for human cardiovascular health, particularly in populations at risk for heart disease [20]. Furthermore, understanding the mechanisms underlying the complete separation of blood flow in four-chambered hearts may highlight targets for therapeutic interventions in patients with congenital heart defects [21].

Future Directions in Research

Cross-species comparative studies

Future research should focus on cross-species studies that explore the physiological differences and similarities in cardiovascular function across vertebrates [22]. Such studies could reveal novel mechanisms that underlie cardiovascular adaptations and may contribute to developing innovative therapeutic strategies for heart diseases.

Genetic and molecular studies

Investigating the genetic and molecular bases of cardiovascular adaptations in different vertebrates will be crucial. Identifying genes and signaling pathways involved in heart development, function, and response to stressors could offer potential targets for drug development and regenerative therapies [23].

Clinical applications of comparative physiology

Integrating findings from comparative physiology into clinical practice could lead to more effective prevention and treatment strategies for cardiovascular diseases [24]. For example, therapies that mimic the protective effects observed in fish during hypoxia or harnessing the regenerative capabilities of certain species may provide new avenues for heart disease management.

https://doi.org/10.61577/jcri.2024.1000016

Conclusions

The study of cardiovascular adaptations in aquatic and terrestrial vertebrates provides valuable insights into the evolution of heart function and its implications for human health. By understanding how these adaptations have allowed different species to thrive in diverse environments, we can develop novel strategies for preventing and treating cardiovascular diseases. As research in this area continues to evolve, the potential for cross-disciplinary applications in medicine and biology will only grow, paving the way for enhanced cardiovascular health in humans.

Disclosure Statement

The authors declare that there are no conflicts of interest that could affect the results or conclusions of this study.

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