COMPARATIVE ANATOMY OF HUMAN AND ANIMAL HEARTS: A STRUCTURAL, FUNCTIONAL, AND EVOLUTIONARY PERSPECTIVE - A COMPLETE REVIEW

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Abstract

The vertebrate heart is a critical organ with structural homologies and species-specific features for fulfilling an assortment of circulatory and metabolic demands. In the current review, the comparative anatomy of the human and animal heart, including ventricular trabeculation, valve structure, coronary circulation, and orientation of the heart, is reported. Combining existing literature, this article reveals how these differences affect cardiac physiology, susceptibility to disease, and their significance in medicine. In mammals, pigs and humans exhibit strong cardiac homologies in their powerful hearts, making pigs viable for xenotransplantation and cardiac research. Rodents, with high heart rates and heavy trabeculation, have been extensively employed in genetic and cardiac pharmacology studies. In birds, well adapted to flight, there are thin-walled but highly effective hearts to facilitate high metabolic levels. Evolutionary transition of the two-chambered fish heart to four-chambered mammalian and avian hearts is an instance of enhanced specialisation for oxygen efficacy and body circulation. Contrastive cardiac anatomy is of strong clinical relevance in the context of bioprosthetic valve substitution, ischemic cardiomyopathy research, and tissue engineering and regenerative medicine. Pig aortic valves have wide usage in cardiac surgery among humans, while zebrafish models serve to study the heart in terms of regeneration. Moreover, insights from reptilian hypoxia tolerance provide promise for stroke and myocardial infarction therapies. This review highlights cross-species cardiac comparisons as pivotal for the development of human cardiovascular medicine, enhancing surgical practices, drug development, and therapeutic research.

KEYWORDS: Comparative anatomy, ventricular trabeculation, coronary circulation, heart orientation, xenotransplantation, myocardial infarction.

INTRODUCTION

The heart is an essential organ in all vertebrates, with circulation, oxygenation, and metabolic homeostasis. Despite the evolutionarily conserved four-chambered avian and mammalian heart, there exist characteristic anatomical and functional divergences in place across species as a result of evolutionary stress, physiological requirement, and ecological requirement. Comparative cardiac anatomy avails scientists insight into divergences, and from it, researchers gain understanding regarding the dissimilarities and have implications to shed light on cardiovascular function in human beings, pathophysiology, and translational medical intervention.

While all vertebrate hearts are a pump, morphology varies to support species-specific metabolic demands. Man has a good cardiovascular system for longevity and long-term activity, but rodents, since they have a high metabolic demand, have small, very trabeculated hearts that beat very rapidly. Pigs, however, have a heart morphology almost as close to man as can be and are thus ideal models for xenotransplantation and surgical research. Birds have light but highly effective hearts, appropriate to the aerobic demand of flight, and reptiles and amphibians intermediate evolutionary solutions, with some having shunting mechanisms regulating oxygen supply.

Some of the significant anatomical differences among species are ventricular trabeculation, coronary perfusion, and valve anatomy. Trabeculae carneae or ventricular ridges of muscle are more intricate in rodents to support their elevated heart rates, whereas in humans and pigs, trabeculation is moderate in extent to ensure equilibrium contractility. Coronary circulation patterns also differ—humans and pigs rely on left coronary artery dominance, whereas rodents have bilateral inputs from both coronary arteries. Valves of the heart, being structurally conserved in mammals, are different in leaflet thickness, chordae tendineae strength, and papillary muscle development, and impact biomechanical properties and make pig heart valves optimal for bioprosthetic replacement in human patients. Apart from anatomical similarity, cardiac structural evolution is also of therapeutic and research significance.

Evolution from two-chambered fish hearts to four-chambered mammalian and avian hearts shows increasing requirements for oxygen efficiency and systemic circulation, and the development of separate pulmonary and systemic circuits. Studies of hypoxia-resistant reptiles and regenerating fish like zebrafish are relevant to cardiovascular resilience and possible therapies for ischemic heart disease. Pigs, rats, and canines are important models for surgical innovation, cardiology pharmacology, and models of disease as well.

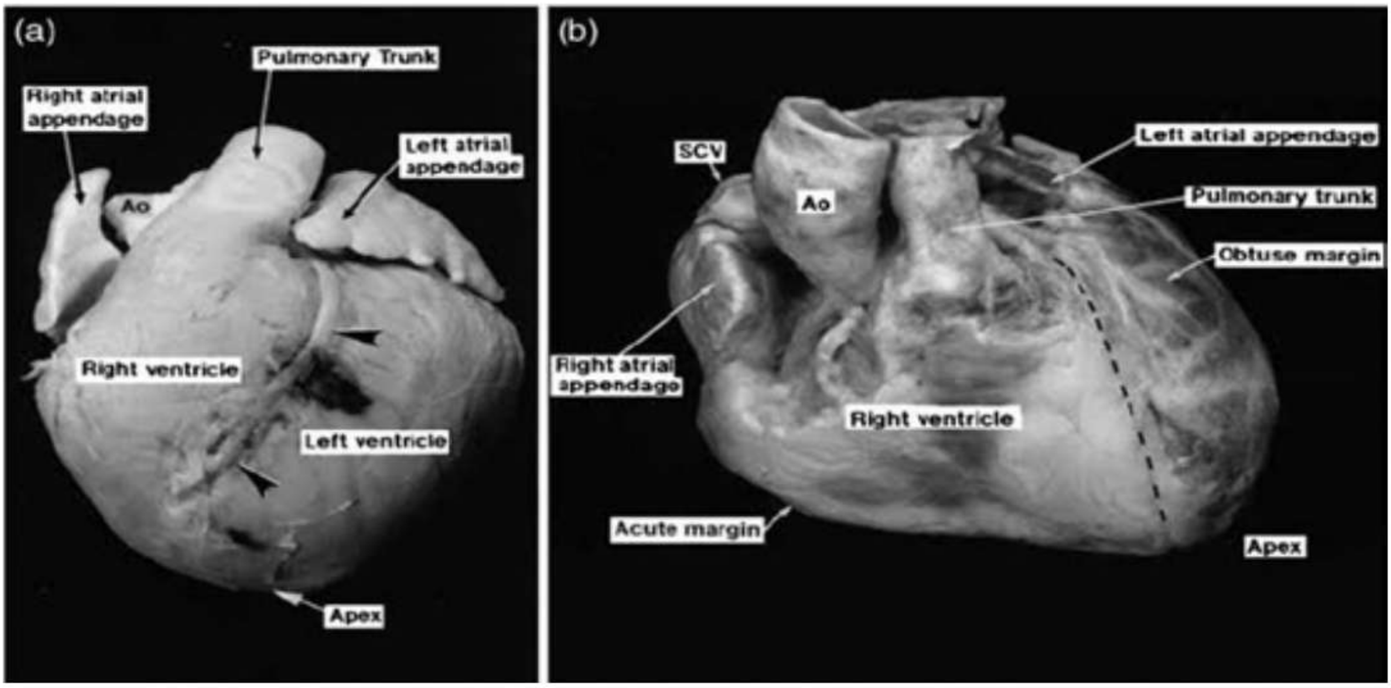

Fig No. 1: Human and pig heart morphology

GENERAL STRUCTURE OF THE HEART ACROSS SPECIES:

Human Heart Orientation

Position: Vertically aligned with the apex directed downward.

Thoracic Location: Positioned slightly to the left of the midline within the thoracic cavity.

Pig Heart Orientation

Position: Oriented more horizontally due to the quadrupedal stance.

Clinical Relevance: Closely resembles the human heart in size, structure, and function, making it an ideal model for xenotransplantation and cardiovascular research.

Rodent Heart Orientation

Position: Steeply vertical with the apex pointing downward.

Metabolic Adaptation: Due to high metabolic rates, rodents have a smaller heart-to-body ratio, requiring higher cardiac output to sustain rapid circulation.

Bird Heart Orientation

Position: Situated in the cranial part of the thoracoabdominal cavity, slightly right of the midline.

Structural Adaptation: More conical in shape compared to mammals.

Metabolic Demand: Birds have higher oxygen requirements, leading to relatively larger hearts than mammals to support sustained flight and high metabolic activity.

VALVE MORPHOLOGY ACROSS SPECIES

Heart valves prevent backflow and ensure unidirectional blood flow. While the four-valve system (tricuspid, mitral, aortic, pulmonary) is conserved, structural differences exist among species.

Feature	Humans	Pigs	Rodents
Atrioventricular valves	Tricuspid, mitral	Similar to humans	Thinner leaflets
Semilunar valves	Aortic, pulmonary	Similar but thicker	Well defined
Chordaetendinae	Strong, well developed	Similar	Less developed
Papillarymuscle's	Well defined	More prominent	Smaller, less developed

Medical Relevance

Pig heart valves are structurally closest to human valves, making them ideal for bioprosthetic valve replacements. Rodent valves are less developed and less commonly used in research for valve-related conditions.

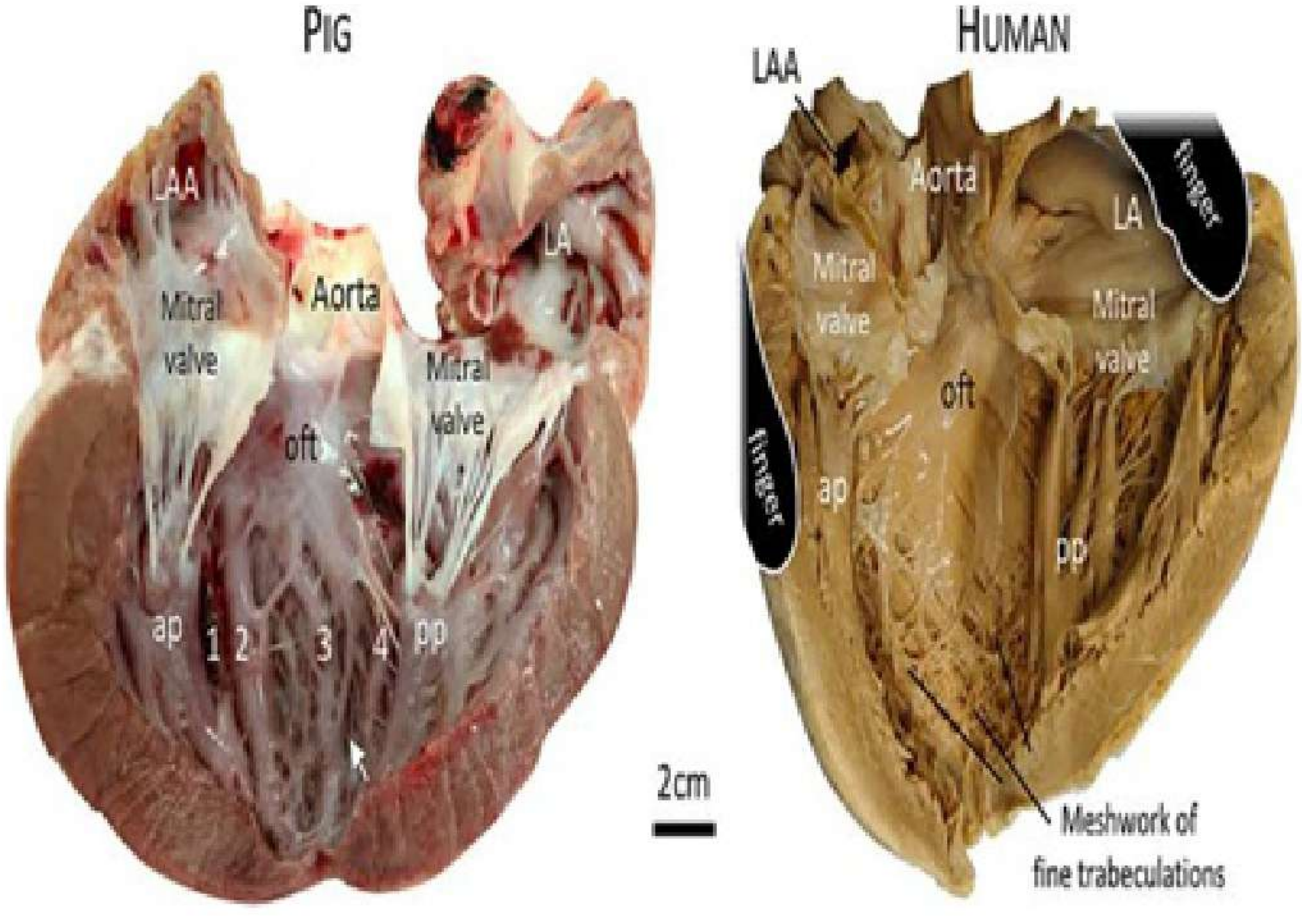

Fig No. 2: Left ventricle of pig and human

VENTRICULAR TRABECULATION AND MYOCARDIAL STRUCTURE

Trabeculae carneae are muscle ridges in the ventricles, essential for efficient contraction and conduction.

Feature	Humans	Pigs	Rodents
Trabeculae structure	Fine, well organized ridges	Coarser, more prominent trabeculae	Dense irregular network
Function	Assists in contractility and conduction	Similar function to humans but with thicker trabeculae	Supports high heart rates
Right ventricular trabeculae	Strong, well developed	Similar	Less developed
Papillarymuscle's	Moderatelydeveloped	Thick well developed	Highly trabeculated
Left ventricular trabeculae	Less trabeculated, smooth endocardial surface	More trabeculated than in humans	Very fine trabeculation
Clinical significance	Abnormal trabeculationlinked to conditions like left ventricular non compaction	Used in cardiac research due to similarities to humans	Helps study cardiac remodeling

Clinical significance:

Left Ventricular Noncompaction (LVNC): A human disorder where trabeculation remains excessive.

Rodents have extensive trabeculation due to their high heart rates and fast metabolism.

CORONARY CIRCULATION AND BLOOD SUPPLY

The coronary circulation varies significantly across species, affecting ischemia risk, cardiovascular research, and surgical approaches.

Comparative coronary circulation

Feature	Humans	Pigs	Rodents
Coronary dominance	Right coronary dominant in majority	Similar to human	Equal LCA RCA contribution
Capillary density	Moderate	Similar to human	High, supports high metabolism
Collateral circulation	Moderate, protective against ischemia	Minimal, higher risk of ischemia	Minimal, higher vulnerability to ischemia
Heart rate	60-100 bpm	70-90 bpm	300-600 bpm

Rodents have high capillary density but minimal collateral circulation, making them more vulnerable to ischemic injuries.

Pigs are ideal models for human cardiovascular research due to similar coronary dominance and circulation

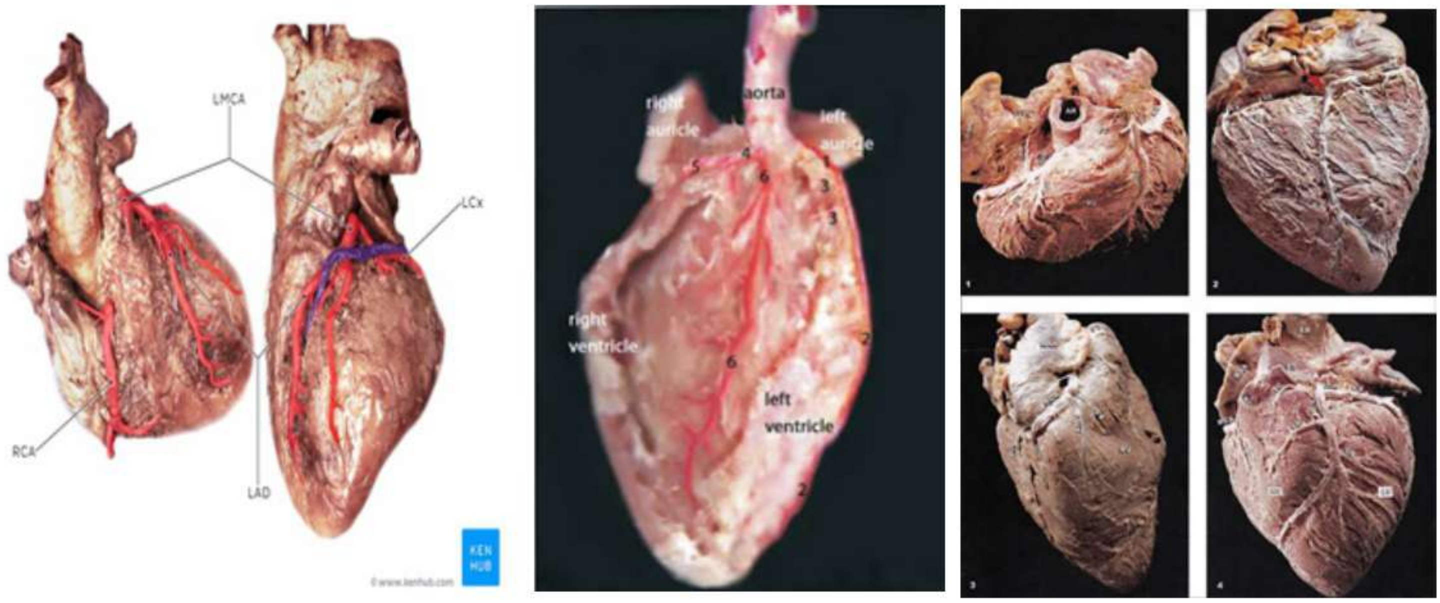

Fig No. 3: Coronary artery diagram of (i) human (ii) rodent (iii) pig

EVOLUTIONARY ADAPTATION AND FUNCTIONAL INSIGHTS

The heart has undergone significant evolutionary modifications across vertebrates to support diverse metabolic needs, environmental adaptations, and survival strategies. The transition from single-chambered hearts in fish to four-chambered hearts in birds and mammals reflects an increasing demand for efficient oxygen delivery and circulation.

Group	Heart chamber	Circulatory type	Key adaptation
Fish	2(1 atria and 1 ventricle)	Single circulation	Gills extract oxygen (less energy needed)
Amphibian	3 (2 atria and 1 ventricle)	Dual circulation (partial mixing)	Adapted to both water and land breathing
Reptile	3.5 (2 atria and partially divided ventricle)	Dual circulation with shunting ability	Can bypass lungs while diving (e.g. crocodile)
Bird and mammal	4 (2 atria 2 ventricle)	Dual circulation	High metabolic efficiency for warm blooded life

Adaptations in Different Animal Groups

Large Mammals (e.g., Whales, Horses, Elephants): Increased myocardial compliance to handle large stroke volumes. Lower heart rates (e.g., whales: ~10 BPM) to maintain energy efficiency.Strong coronary circulation to support extended oxygen supply.

Small Mammals (e.g., Rodents, Bats)Higher heart rates (300-600 BPM) due to high metabolism.Dense ventricular trabeculation to improve contractility.

Birds (e.g., Eagles, Hummingbirds): Largest heart-to-body ratio among vertebrates (supports flight metabolism).Thin-walled but highly elastic ventricles to maintain rapid blood circulation. Capillary-dense myocardium ensures maximum oxygen extraction.

Reptiles (e.g., Crocodiles, Snakes, Turtles). Ability to bypass lungs using the foramen of Panizza (in crocodiles).Lower metabolic demand, so a three-chambered heart suffices for survival.

Fish: Simple two-chambered heart adapted to low-energy aquatic life.Single circulation limits oxygen efficiency but is sufficient for cold-blooded metabolism.

MEDICAL APPLICATIONS OF COMPARATIVE CARDIAC ANATOMY Comparative cardiac anatomy provides critical insights into human cardiovascular physiology, disease mechanisms, and therapeutic innovations. Studying the structural and functional differences across species helps in medical research, drug development, and surgical advancements.

1.Insights from animal model for human cardiac disease

Animal model	**Relevance to human cardiology**
Rodents (mice, rats)	Used in research in hypertension, myocardial infarction and heart failure. Due to their rapid metabolism and genetics similarity to humans.
Pigs	Similar heart size, coronary anatomy, and electrophysiology make them ideal for heart transplantation research and stent testing.
Dogs	Used in studies of cardiac arrhythmias and pace maker technology due to similar conduction systems.
Zebra fish	Capable of heart regeneration, providing insights into cardiac repair and regenerative medicine.
Crocodiles and turtles	Study of hypoxia resistance can help develop treatment for stroke and heart attacks.

1. **Surgical and transplantation advantages**

- **Xenotransplantation:** Pig hearts are being genetically modified for potential use in human heart transplants.
- **Cardiac Valve Replacements:** Bioprosthetic valves from pigs and cows are commonly used in human heart surgeries.
- **Bypass Surgery Innovations:** Understanding coronary circulation in different species improves surgical techniques for arterial grafting.

2. **Drug Development and Pharmacology**

- Beta-blockers and anti-arrhythmic drugs are tested on dogs and pigs before human trials.
- Zebrafish models help study cardiotoxicity of new drugs, reducing the risk of adverse effects in humans.
- Rodent studies provide insights into heart failure treatment and genetic cardiomyopathies.

3. **Regenerative Medicine and Stem Cell Research**

- Zebrafish hearts can regenerate research in this area aims to develop treatments for post-heart attack recovery.

- Stem cell therapy studies in animals like rodents help in developing cardiac tissue regeneration techniques for human heart disease.

4. Hypoxia and Ischemic Heart Disease Research

- Crocodiles and turtles can survive low oxygen (hypoxia) due to their ability to shunt blood.
- Studying their adaptations may lead to treatments for stroke and myocardial infarction in humans.

CONCLUSION

The comparative study of human and animal heart anatomy provides valuable insights into cardiovascular evolution, function, and medical applications. Despite structural differences, the fundamental role of the heart in circulation remains conserved across species, with adaptations tailored to metabolic demands, body size, and environmental pressures.

This research highlights key differences in ventricular trabeculation, valve morphology, coronary circulation, and heart orientation, emphasizing their impact on cardiac physiology and clinical applications. Large mammals like pigs exhibit striking similarities to human cardiac structure, making them ideal models for xenotransplantation and cardiovascular research. Small mammals and birds, with their high metabolic rates and unique trabecular patterns, provide further insights into cardiac performance and disease susceptibility. Reptilian and fish hearts, though structurally distinct, offer models for hypoxia tolerance and evolutionary adaptations.

The medical applications of these findings extend to heart disease research, surgical innovations, drug testing, and regenerative therapies. Advancements in xenotransplantation, bioprosthetic valves, and ischemic heart disease treatments are directly influenced by comparative cardiac studies. Furthermore, exploring naturally regenerative species like zebrafish paves the way for novel cardiac repair strategies in humans.

In conclusion, understanding comparative heart anatomy bridges the gap between evolutionary biology and modern medicine, enabling improved diagnostics, treatments, and surgical approaches. As research progresses, integrating these insights will continue to shape the future of cardiovascular science and therapeutic advancements.

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