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COMPARATIVE MORPHOLOGY AND STRUCTURAL-FUNCTIONAL FEATURES OF THE MAMMALIAN HEART

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This monograph summarises the results of comprehensive studies (anatomical, histological, morphometric and statistical) devoted to the morphology of the heart and the development of comparative morphology at the species level, at both the macroscopic and microscopic levels, in clinically healthy domestic animals of the class Mammalia: Oryctolagus cuniculus L., 1758 – European rabbit; Canis familiaris L., 1759 – domestic dog; Sus scrofa forma domestica L., 1758 – domestic pig; Ovis aries L., 1758 – domestic sheep; Bos taurus L., 1758 – domestic cattle; Equus ferus caballus L., 1758 – domestic horse.

The patterns of macro- and micromorphology formation in the heart are described, and morphometric markers of diagnostic and practical significance are identified. The results obtained can be used to develop preventive and therapeutic measures for pathologies of the cardiovascular system, as well as to identify morphofunctional changes under the influence of various environmental factors. The materials in this monograph are also of practical significance in forensic veterinary medicine, particularly for interpreting changes in cardiac tissue during expert assessment of the causes of animal death, establishing the mechanisms of pathological processes, and determining normative morphometric indicators in forensic morphological practice.

The monograph is intended for students, postgraduate students and morphologists in the fields of biology, veterinary science and medicine.

ISBN 978-973-147-625-4

CONTENTS

LIST OF ABBREVIATIONS

AM – absolute mass
AMS – absolute heart mass
RM – relative mass
RHM – relative heart mass
CH – cardiac height
CW – cardiac width
CC – cardiac circumference
NHM – net heart mass
Cattle – cattle (Bos taurus)
BM – body mass
LV – left ventricle
RV – right ventricle
LA – left atrium
RA – right atrium
AMLV – absolute mass of the left ventricle
AMRV – absolute mass of the right ventricle
AMLA – absolute mass of the left atrium
AMRA – absolute mass of the right atrium
RMLV – relative mass of the left ventricle
RMRV – relative mass of the right ventricle
RMLA – relative mass of the left atrium
RMRA – relative mass of the right atrium
HDI – heart development index
AVI – atrioventricular index
VHI – ventricular–heart index
AHI – atrial–heart index
LVT – thickness of the left ventricular wall
RVT – thickness of the right ventricular wall
LAT – thickness of the left atrial wall
RAT – thickness of the right atrial wall

NCR – nuclear–cytoplasmic ratio
M – arithmetic mean
m – standard error of the mean
n – number of experimental animals
p – level of statistical significance

INTRODUCTION

The human and animal organism is a complex, dynamically organized biological system that functions at several levels of structural and functional organization – from molecular and cellular to tissue, organ, and systemic [113, 345, 238]. All these levels are closely interrelated functionally, ensuring the integrity, stability, and adaptability of a living organism in conditions of constant interaction with the environment [112, 22, 197, 734, 218, 130, 700, 215, 350, 749].

As an open biological system, the body constantly exchanges substances, energy, and information with the environment, responding to physical, chemical, and biological factors in the environment [13, 745, 600, 301, 190, 322, 750]. This ensures homeostasis, self-regulation, and the ability to adapt to changes in the external and internal environment.

Understanding the systemic organization of the body is key to modern morphology and veterinary medicine, as it allows the integration of anatomical, physiological, biochemical, and clinical knowledge into a single holistic view of the organism as a complex adaptive unit [557, 117, 39]. This approach is particularly relevant in light of the development of interdisciplinary research, practical medicine, and a personalized approach to animals in veterinary practice [515, 183, 289].

The biological organization of the human and animal body is the result of a complex and multi-level evolutionary process spanning long periods of historical development of living systems. Over millions of years, there has been a gradual improvement in morphofunctional characteristics that have ensured the adaptation of organisms to their living conditions [706, 205, 330]. This process, known as phylogenesis [545, 348], is the foundation for the formation of modern biodiversity and explains the structural

and functional complexity of organisms [287, 361, 400, 3, 68, 71, 693].

The evolutionary history of living beings shows that phylogenetic changes were caused by a combination of factors such as hereditary variability, natural selection, mutation processes, and recombination, which contributed to the emergence of new phenotypic traits and adaptive properties [534, 101, 110, 368, 686]. It is these mechanisms that determine both the structural uniqueness of individual species and the presence of common morphological features that can be traced between different taxonomic groups [38, 49, 63, 448, 480].

Humans and animals, as biological beings, are an integral part of living nature and the result of a long evolutionary development, during which organisms gradually adapted to environmental conditions. This process was accompanied by the formation of complex morphofunctional systems and regulatory mechanisms that ensure the stability of the internal environment – homeostasis – despite external changes [355, 344, 555, 492, 493].

One of the most important characteristics of living beings is their ability to interact dynamically with the environment [132, 500]. From primitive life forms such as prokaryotes to highly organized mammals, organisms have developed a wide range of adaptive responses, including behavioral reactions, neuroendocrine and metabolic regulations, the development of immune responses, and the improvement of sensory functions [28, 143, 310, 536, 588, 651].

The functioning of the body is ensured by a complex hierarchy of physiological systems: nervous, cardiovascular, respiratory, digestive, endocrine, musculoskeletal, urinary, reproductive, etc. Their coordination is carried out at the level of integration of cells, tissues, and organs, which ensures a

coordinated response to stimuli and the effective functioning of the body as a whole [307, 540, 446, 572].

In addition, an important aspect of the functional interaction of organs and systems is their ability to adapt to various physiological conditions – growth, development, physical exertion, disease, or changes in the environment. Understanding these mechanisms is key to modern medicine and veterinary medicine, particularly in the context of disease prevention and treatment.

Phylogenetic changes also contributed to the emergence of unique features of the human organism, such as bipedalism, a developed cerebral cortex, language, and social behavior [537, 657, 743]. In animals, these adaptations take various forms, ranging from the development of specialized sensory organs to complex social structures in certain species [518, 636]. Possessing sophisticated mechanisms of self-regulation and control of biological processes, the functional systems of mammals (nervous, cardiovascular, immune, respiratory, digestive, excretory, endocrine, sensory, sensory organs, reproductive) are closely interconnected with each other and the environment, ensuring the coordinated functioning of biological systems characteristic of the organism's vital activity [25, 13, 467, 189, 263, 407, 707].

Thanks to the interaction of organs and systems, the mammalian body functions as a single living biological system with different levels of organization, characterized by the basic properties of its existence – metabolism, growth, development, reproduction, heredity, etc. [316, 466, 286]. Thanks to the effective interaction of nervous and hormonal self-regulation in mammals, the constancy of the internal environment and physiological activity of the body – temperature, blood pressure, etc. – is maintained at a certain level [640, 468, 517].

The body's response to changes in the external environment or internal state, uniting all organs and systems into a single whole, occurs only with the normal functional coordination of all its systems, including the cardiovascular system, which is one of the integrating systems of living organisms, comprising the heart and blood and lymphatic vessels, which are systematically interconnected [159, 548, 447].

The cardiovascular system in humans and animals performs extremely vital functions: it regulates blood supply to organs, blood pressure, ensures lymph drainage from organs and its transport to veins, plays an important role in maintaining homeostasis, and contributes to the functioning of the nervous and endocrine systems and immune organs [751, 465, 687, 253].

The organs of the cardiovascular system ensure metabolism, are important in regulating the functions of all organs and systems of the body, participate in ensuring respiratory, trophic, and excretory functions, and, together with the nervous system, connect all organs and systems of the body into a single whole [107, 150, 53]. The constant movement of blood through a closed system of vessels ensures the basic functions of the circulatory system: the transport of substances to and from cells. Thanks to the cardiovascular system, oxygen, nutrients, and biologically active substances – hormones, vitamins, and minerals—are delivered to the tissues of the organs with the blood, and carbon dioxide and metabolic waste products are removed from them [420, 505, 738].

The central organ of the cardiovascular system is the heart, which, thanks to the constant contraction of myocardial cardiomyocytes, carries blood through a closed system of blood vessels [715].

The morphoarchitecture and functional state of the organs of the cardiovascular system are of great importance and have a

significant impact on the vital activity of all the most important systems of the human and animal body in normal conditions and in pathologies associated with the organs of the cardiovascular system [683, 104, 288].

Currently, various diseases of the cardiovascular system are widespread and tend to increase, which is an important medical and social problem in human and veterinary medicine [15, 55, 158, 162, 549, 615, 176, 182]. Recently, there has been an increase in the number of diseases of various origins associated with the organs of the cardiovascular system [356, 347, 608, 613, 336, 105]. Therefore, there is no doubt that effective treatment and prevention of these pathologies in veterinary medicine is impossible without knowledge of the species-specific features of the morphological structure of the cardiovascular system, which must be taken into account both when conducting diagnostic and preventive measures to prevent animal diseases and when providing them with medical care, etc.

Therefore, it is important to study the morphofunctional characteristics of the cardiovascular system [264, 270, 606, 643, 285, 495, 652], which performs vital functions in the body of animals and is of cognitive importance, allowing for improved diagnosis, prevention, and treatment of cardiovascular diseases in animals, which is the basis for clinical veterinary medicine.

The current priority for timely and reliable diagnosis of diseases is morphometric studies of organs and systems in clinically healthy animals, which are diagnostic criteria as indicators of the norm for the diagnosis of infectious and non-infectious pathologies [268, 266, 269, 273, 274, 557, 619, 624, 622, 625, 627-629, 666, 667, 682]. Mathematical analysis of morphological structures has gained recognition as a modern method distinguished by its objectivity and reliability, which allows for a deeper understanding of the development of

pathological processes and logical interpretation of scientific research results [62, 723, 208, 662, 643, 595, 597] . This approach is widely used in modern cardiology, providing objective information about the course of various physiological and pathological processes that occur in the organs and systems of the body when the cardiovascular system is affected [429, 524, 621]

Based on the set goals and objectives, we studied the macro- and microscopic structures of the heart and conducted a macro-, histo-, and cytomorphometric assessment of the morphological structures of the heart in domestic animals of the Mammalia class in a comparative species aspect, whose indicators are morphological criteria for physiological and pathological changes in the cardiovascular system and can be used in the diagnosis of diseases of various origins [620, 618, 89, 223, 224, 306, 321].

CHAPTER I

LITERATURE REVIEW

1.1. Structure, functions, and role of the cardiovascular system in the body's vital functions

The study of the structure of organs at the tissue and cellular levels, as well as the patterns of changes in their morphoarchitecture under the influence of various endogenous and exogenous factors on the body, is a pressing issue in modern morphology [209, 227, 246, 411, 546, 564, 142, 605, 607, 31, 402]. This allows not only a deeper understanding of the mechanisms of structural and functional organization of organs in normal conditions, but also the identification of early morphological markers of pathological processes. This fully applies to the cardiovascular system, especially the heart as the central organ of blood circulation, as one of the first to respond to the influences of the external and internal environments [20, 235, 241, 160, 161, 748, 749, 402, 377, 729]. In addition, the study of the morphology of the human and animal heart is of great importance in modern biology, medicine, and veterinary medicine. This is due to the widespread prevalence of cardiovascular diseases, which are the leading cause of death worldwide. One of the most serious consequences of such diseases is heart failure, a condition characterized by a decrease in the heart's ability to pump the blood necessary to meet the body's metabolic needs [352, 353, 345, 456, 95, 99, 332, 81, 614, 732].

Domestic animals have a closed cardiovascular system (Fig. 1.1). It consists of the heart, aorta, arteries, microcirculatory vessels, including capillaries and veins. It is divided into the circulatory and lymphatic systems, which are genetically

interconnected – they develop from the same source (embryonic connective tissue, or mesenchyme), morphologically (the largest collecting lymphatic vessels flow into the cranial vena cava) and functionally (they perform common functions in the body). In addition, the cardiovascular system in mammals is closely related to the organs of hematopoiesis and immune defense.

The cardiovascular system in humans and animals ensures metabolism, regulates blood pressure and blood supply, and plays an extremely important role in maintaining homeostasis, etc. [654, 739, 164]. Thanks to the unique morphological structure of the cardiovascular system, nutrients and oxygen are delivered to the tissues of the body's organs, and metabolic waste products are removed from the body [375, 554, 672, 295].

The organs of the cardiovascular system are important in regulating the functions of all organs and systems of the body: they participate in ensuring respiratory, trophic, and excretory functions [25, 750, 467, 203, 519]; together with the nervous system, they connect all organs and systems of the body into a single whole, ensuring harmonious interaction and synchronization of physiological processes [35, 531, 331, 699]. They also play a key role in maintaining homeostasis by regulating blood circulation, transporting oxygen and nutrients, and removing metabolic waste [18, 404].

Blood circulation is one of the most important systems in the body, ensuring the integration of physiological functions and maintaining its ability to adapt to changes in the external environment. This system is the basis for the exchange between individual organs and systems, ensuring the efficient delivery of nutrients, oxygen, hormones, and the removal of metabolic waste products. Blood circulation provides constant support for vital functions and regulates body temperature and immune processes, keeping the body in a state of equilibrium.

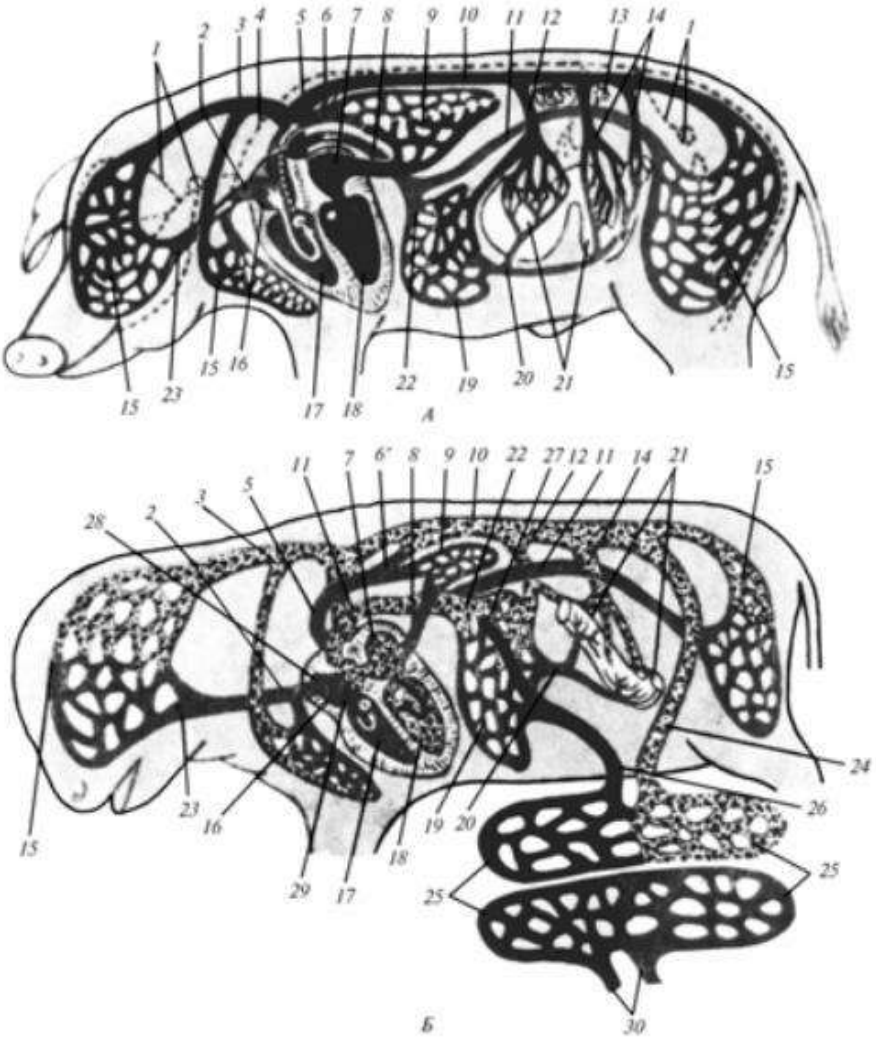

Fig. 1.1. General diagram of the structure of the cardiovascular system and blood circulation in an adult animal (A) and a fetus (B): 1 – lymphatic vessel; 2 – cranial vena cava; 3 – brachiocephalic trunk; 4 – thoracic duct; 5 – pulmonary artery; 6 – arterial ligament; 6′ – arterial duct; 7 – left atrium; 8 – pulmonary vein; 9 – pulmonary capillaries; 10 – aorta; 11 – caudal vena cava; 12 – abdominal artery; 13 – lymph node;

14 – mesenteric arteries; 15 – body capillaries; 16 – right atrium; 17 – right ventricle, 18 – left ventricle; 19 – liver capillaries; 20 – portal vein; 21 – stomach and intestines; 22 – hepatic vein; 23 – jugular vein; 24 – umbilical artery; 25 – capillaries of the placenta and uterus; 26 – umbilical vein; 27 – venous duct; 28 – intervenous tubercle; 29 – oval foramen; 30 – arteries and veins of the uterus [345].

It is thanks to the stable transport of biologically important substances that blood ensures the exchange between different systems and organs, supporting their integrated and coordinated work. This process not only contributes to the stability of individual organs, but also ensures the optimal functioning of the entire body as a whole. Blood circulation is the basis for maintaining homeostasis in the body, as it allows the level of oxygen and nutrients necessary for cellular functioning to be maintained and ensures the removal of metabolic waste, preventing the accumulation of toxins in the body. Thus, blood circulation plays a crucial role in maintaining the health of the body and its ability to adapt to changes in the external environment [591, 231, 565, 121, 256].

The circulatory system consists of the heart and a closed network of blood vessels (Fig. 1.1), which form the complex architecture of the organism. The central organ of this system is the heart, composed of myocardium, which includes contractile cardiomyocytes, connective tissue, blood vessels, and nerve elements, providing a high degree of structural organization and enabling the coordinated function of the different heart chambers [127, 440, 679]. The blood vessels form a branched network of arteries, veins, and capillaries, the density and thickness of which vary according to the functional demands of the organs and the type of tissue [25, 24, 262, 246, 467, 337, 32, 391, 685, 715].

Morphological features of the cardiovascular system, such as vessel wall thickness, endothelial structure, the development of

myocardial muscular and connective tissue components, as well as the proportional relationships of the heart chambers, determine the organism's ability to adapt to physiological loads and maintain stable blood circulation. These characteristics are important subjects of morphological studies, as they allow for the assessment of species-specific features of the heart and vessels, the spatial organization of the vascular network, and the patterns of development and growth of the cardiovascular system during ontogenesis.

To ensure continuous and effective blood flow in the body, several mandatory conditions must be met.

First of all, an important condition is the volume of circulating blood, which must correspond to the total capacity of the heart chambers and vascular bed. This is necessary so that blood can circulate freely, providing every organ and tissue with the necessary nutrients and oxygen [418, 584, 710]. The volume of blood in the body is not constant and varies depending on the physiological state of the body, such as physical activity or diseases that can affect circulation. Disruption of this balance can lead to various pathological conditions, such as hypovolemia or hypertension, which disrupt the normal function of the cardiovascular system.

In addition, it is important that both ventricles of the heart work synchronously, pushing the same amount of blood into the small and large circles of blood circulation during each systole. The systolic function of the heart depends on the coordination of its parts, which allows it to create optimal pressure for blood flow through the vessels. Disruption of this synchrony, for example, in cardiac arrhythmias or heart failure, can lead to one part of the heart working too hard and the other not functioning properly. This balance ensures a constant minute blood volume and maintains optimal pressure in the vascular system, which is

critical for the normal functioning of the body, in particular for the transport of oxygen and nutrients to cells [677, 716, 141, 257]. This ensures the effective functioning of organs and tissues, supporting their ability to self-repair and adapt.

Under normal conditions, the blood supply to each organ corresponds to its metabolic needs, in particular, the need for oxygen saturation, delivery of nutrients, and removal of waste products. This is regulated by a complex system of vascular and nervous mechanisms that allow blood flow to be adjusted depending on the physiological state of the body and the needs of the organs [114, 193, 284]. For example, during physical activity, blood flow to the muscles increases to provide them with oxygen and energy, while blood supply to organs that do not require such active support (e.g., the stomach) decreases. This allows the body to use available resources as efficiently as possible.

The main source of energy needed to keep blood flowing through the vessels is the mechanical work of the heart, which acts as a biological pump that constantly pumps blood through a closed system of vessels. The work of the heart also contributes to the creation of so-called arterial pressure, which is necessary to maintain blood flow even at great distances from the heart, for example, to the extremities or organs located at the periphery. However, the heart is not the only factor that maintains blood circulation. Other mechanisms, such as skeletal muscle contraction, vascular elasticity, and venous return mechanisms, also contribute to normal blood circulation. The properties of the blood itself are also important: its viscosity, ability to clot, and regulation of its volume by the kidneys and other organs, which allows for stable pressure and effective blood circulation [650].

Thus, blood circulation acts as a fundamental system of the body, providing communication between all organs and tissues. This system not only supports the vital functions of organs, but

also allows the body to adapt to various physiological and external changes. Blood circulation regulation is the result of complex interactions between the heart, blood vessels, nervous and endocrine systems, which ensure the adaptation of blood flow to specific conditions.

The importance of the circulatory system in maintaining homeostasis in the body cannot be overestimated, as it has a direct impact on the body's ability to self-repair, maintain normal body temperature, and metabolic processes. Blood circulation not only ensures physiological stability, but is also an important factor in the development and treatment of many diseases, as disturbances in it can lead to serious pathological conditions.

Thus, blood circulation is a dynamic process that is constantly adjusted according to the needs of the body, which emphasizes its critical role in ensuring the health and optimal functioning of all systems.

1.2. Phylogenetic patterns in the structure of the cardiovascular system in vertebrates

Evolutionary processes cover a wide range of natural phenomena and patterns that cause gradual changes in the structure, functions, and biological properties of living organisms [650, 544, 584]. Biological evolution is an irreversible process of historical development of life on Earth, accompanied by changes in the genetic structure of populations, the emergence of adaptive traits, diversification of forms, and the extinction of individual species [102, 120]. At the macro level, it includes transformations of biocenoses, ecosystems, and even the biosphere as a whole [747, 214].

Phylogeny (from the Greek phylon, meaning “family” or “tribe,” and genesis, meaning “origin”) is a branch of evolution that considers the historical development of certain groups of

organisms or species [451, 378, 388, 452]. This concept was introduced into scientific terminology by the German evolutionary biologist Ernst Haeckel in 1866 [386, 678]. The study of phylogenetic transformations belongs to the field of phylogenetics, whose main task is to reconstruct the evolutionary history of species, identify their family relationships, and establish the directions of morphological changes that occurred during evolution [365, 342, 177].

The phylogenetic approach allows us to trace how complex morphofunctional systems, in particular the cardiovascular system, evolved from simple tubular structures in invertebrates to the four-chambered heart in mammals and birds [341, 727]. The example of vertebrates shows a clear sequence of complications in the structure of the circulatory system, accompanied by a transition to more sophisticated mechanisms of oxygen transport, blood pressure maintenance, metabolism regulation, and thermoregulation [357, 408].

The level of research into the phylogeny of different groups of animals varies significantly. The most complete information has been gathered on vertebrates and higher plants, thanks to numerous paleontological finds and embryological data [567, 576]. In particular, the phylogenetic relationships between representatives of such groups as hominids, proboscids, rodents, and other orders of mammals have been reconstructed in detail to the level of genera and even species [746, 366, 232]. At the same time, the origin and relationships between individual types of invertebrates or less studied orders of vertebrates remain a subject of debate [633, 646, 194].

Phylogenetic studies are based not only on the analysis of fossil remains, but also on comparisons of the morphology of modern species [43, 737, 719]. The study of the structures of the cardiovascular system in representatives of different taxonomic

groups allows us to identify both evolutionarily stable features (for example, the presence of a closed vascular system in all vertebrates) and variable adaptations related to the type of respiration, habitat, or metabolic needs [367, 744, 258].

In this context, comparative anatomy of the heart and blood vessels is of particular importance, serving not only as a tool for studying phylogeny, but also as a practical basis for clinical anatomy, physiology, pathomorphology, and veterinary medicine in general.

In higher vertebrates, the cardiovascular system is closed. In lower vertebrates and invertebrates, the cardiovascular system is open. It is usually hemolymphatic, as it performs the function of the circulatory and lymphatic systems, ensuring the transport of nutrients, gases, and metabolic waste [750, 433, 575, 64, 180, 185, 410, 444, 577]. In such animals, the hemolymph circulating in the vessels is not clearly divided into blood and lymph, but is a single medium for metabolism and ensuring the vital functions of cells. This organization of the cardiovascular system reflects adaptation to the characteristics of the metabolism and structure of the organism.

In the process of phylogenetic development of vertebrates in accordance with their functional needs, progressive changes in the formation of the cardiovascular system as a whole and the heart in particular occur throughout phylogenesis (Fig. 1.2).

In the circulatory system of vertebrates, the main evolutionary changes in the structure of the cardiovascular system are associated with the conditions of the animals' environment, with the transition of animals (fish) from gill-type respiration to pulmonary respiration (birds, mammals) (Fig. 1.3). [750, 349, 433, 575, 351].

In arthropods, particularly crustaceans, the circulatory system is open [426, 219]. This means that hemolymph circulates

partly through vessels and partly in open spaces of the body called sinuses. This type of blood circulation allows transport functions to be combined with adaptation to different types of motor activity and environmental conditions [109].

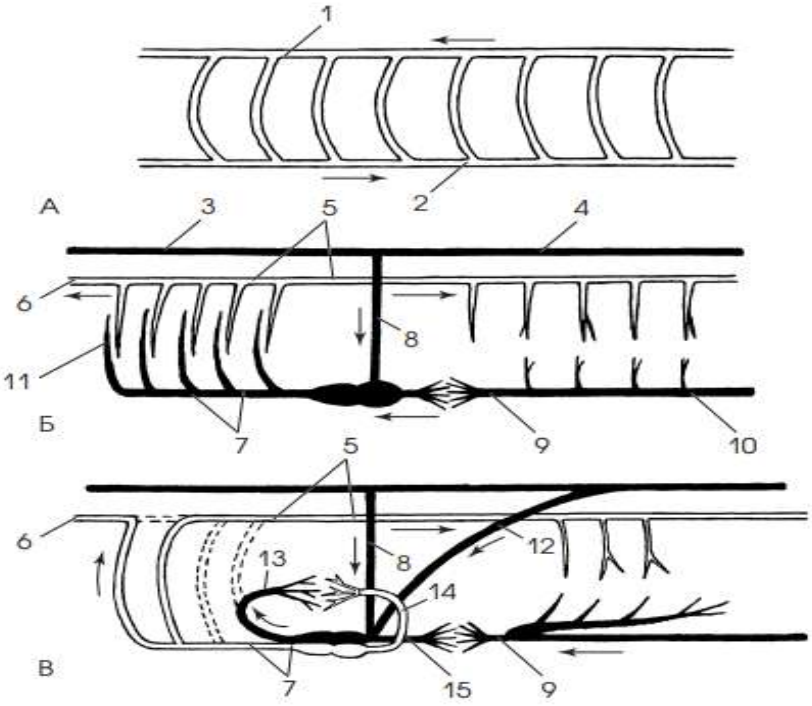

Fig. 1.2. Blood circulation diagram. A – annelid worm; B – lancelet or lower fish; C – terrestrial vertebrate. 1 – dorsal vessel; 2 – ventral vessel; 3 – anterior cardiac vein; 4 – posterior cardiac vein; 5 – dorsal aorta; 6 – carotid artery; 7 – abdominal aorta; 8 – Cuvier's canal; 9 – portal vein; 10 – subintestinal vein; 11 – gill arteries; 12 – posterior vena cava; 13 – pulmonary artery; 14 – pulmonary vein; 15 – hepatic vein [349].

In more primitive representatives, such as some branchiopods, the heart has a metameric organization and looks like an elongated tubular structure located on the dorsal side of the

body. This tube may contain ostia (special openings) in each segment, allowing blood to flow back into the heart after passing through the body [423, 424, 445].

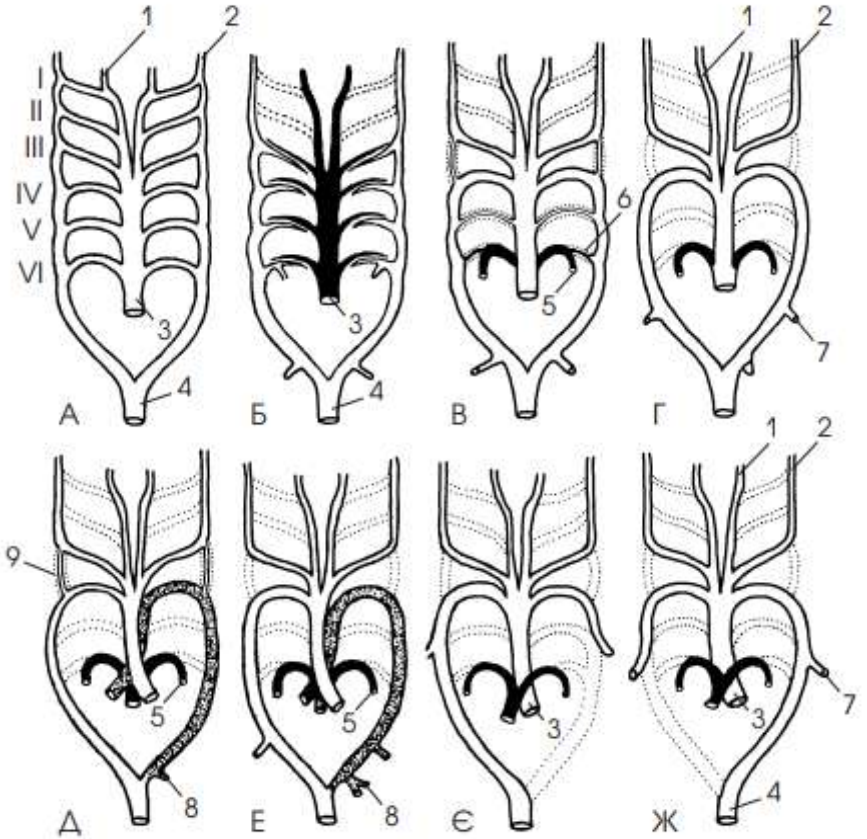

Fig. 1.3. Transformation of aortic arches in different vertebrates (view from the abdominal surface). A – initial location in the embryo; B – fish (diphyllobranch); C – tailed amphibian; D – frog; E – snake; F – lizard; G – bird; G – mammals; I-V – arterial arches. 1 – internal carotid artery; 2 – xternal carotid artery; 3 – abdominal aorta; 4 – dorsal aorta; 5 – pulmonary artery; 6 – arterial (Botal) duct; 7 – subclavian artery; 8 – gastrointestinal artery; 9 – carotid duct [349].

Among the higher forms of crustaceans, there are species with an elongated tubular heart and species with a more compact, shortened organ. A striking example of a well-differentiated circulatory system is the crayfish. Its heart is located dorsally and has the shape of a sac, from which large arterial vessels branch off: the anterior aorta, antennal (antenna) arteries, superior abdominal artery, descending artery, and others [425, 416, 36, 219].

After leaving the heart, the arteries branch out, but their distal sections are not connected to veins: the vessels open into interorgan spaces – lacunae, where hemolymph washes over the internal organs, supplying them with oxygen and nutrients. From there, it collects in the venous sinuses and flows to the gills, where gas exchange takes place.

After being enriched with oxygen in the gills, the hemolymph enters the pericardial cavity through special gill-heart channels. In crayfish, the pericardium is an anatomically closed chamber that surrounds the heart and is separated from the main body cavity. Through the ostia-valve openings in the heart wall-the hemolymph returns to its cavity. In some other crustacean species, the pericardium is less clearly defined and may be part of the general body cavity. [133, 247, 539].

Thus, although the blood circulation in crustaceans does not have a closed cycle, it provides a sufficient level of transport of oxygen, metabolic substances, and immune components, which allows the organism to function effectively even in a changing environment.

Thus, in the process of phylogenetic development, starting with aquatic vertebrates, represented by fish, the lymphatic system separated from the circulatory system into an independent system (Fig. 1.4).

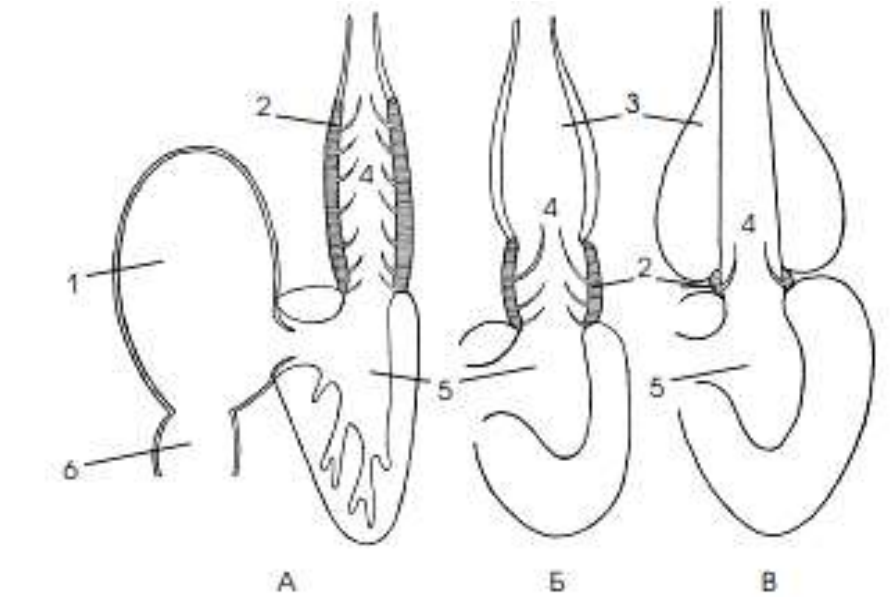

Fig. 1.4. Schematic longitudinal section through the heart of different fish. A – selachii; B – ganoid; C – bony fish; A, B, and C atria are not shown. 1 – atrium; 2 – arterial cone; 3 – arterial bulb; 4 – valves; 5 – ventricle; 6 – venous sinus [349].

In the circulatory system of fish, these changes are aimed at ensuring intensive metabolism, due to their active lifestyle in aquatic environments. Fish have a heart that ensures high blood flow through the vessels. It consists of two chambers: the atrium and the ventricle. However, the heart of fish is not divided into separate chambers by partitions, as in mammals, and therefore only venous blood enters the heart and is pushed into the gill arteries. Fish have only one atrium, which connects to the venous sinus, and one ventricle, which transitions into the ventral aorta. The aorta carries venous blood through paired afferent gill arteries (III, IV, V, VI pairs) to the gills, where it is enriched with oxygen (the I and II pairs of afferent gill arteries are reduced during the

embryonic period). Arterial blood from the gills enters the unpaired dorsal artery through the efferent gill arteries, and from there to the organs [242, 46, 325, 328, 434, 523, 702].

In amphibians, as they adapt to life on land, gill breathing disappears and pulmonary circulation appears, and changes occur in the structure of the heart and blood vessels. The heart of amphibians already has three chambers in its structure: two atria and a ventricle. Both atria open into the ventricle through a common opening. In amphibians, a longitudinal septum appears in the atrium, dividing it into the right and left atria. Venous blood from the veins of the body enters the venous sinus, then the right atrium, and then the right side of the common ventricle, where partial mixing of arterial and venous blood occurs.

In adult amphibians, the gills are atrophied, as the lungs are already functioning [750, 553, 571]. As in fish, the first and second pairs of gill arteries in amphibians are reduced during the embryonic period of their development. The third pair of gill arteries develops into the carotid arteries, the fourth pair into the right and left aortic arches, and the fifth pair in tailed amphibians forms the second pair of aortic arches (in tailless amphibians, they are reduced). The sixth pair of gill arteries transforms into pulmonary arteries. In tailed amphibians, these arteries connect to the previous arch via the arterial duct.

Venous blood flows from the right ventricle of the heart into the arterial cone, then through the pulmonary arteries into the lungs. Enriched with oxygen through the pulmonary veins, arterial blood enters the left atrium, then from there into the left part of the common ventricle, and then through the carotid arteries and dorsal aortas to the organs.

In reptiles (reptiles), further changes occur in both the structure of the heart and the differentiation of blood vessels: the reptile's heart is three-chambered, with two atria and one ventricle

[275, 72, 111, 324, 514, 731]. The reptilian heart differs from the amphibian heart in that each atrium opens into the ventricle through its own opening, and an incomplete septum is formed in the ventricle. In the process of evolutionary development, two more septa appear in the heart of reptiles: the interventricular septum, which does not completely separate the common ventricle, and the aortopulmonary septum, which divides the arterial cone into the aorta and pulmonary trunk. In all reptiles, the interventricular septum is incomplete, so the mixing of arterial and venous blood occurs to a lesser extent than in amphibians. In the process of phylogenetic development, the first and second pairs of gill arteries in reptiles are reduced, and the third pair develops into the carotid arteries, the fourth pair develops into the two roots of the aorta, and the sixth pair develops into the pulmonary arteries.

In the process of phylogenetic development in birds, compared to fish, amphibians, and reptiles, the cardiovascular system is improved. The circulatory system of birds is already formed by a 4-chambered heart (similar to mammals), arteries, and veins, which perform vital functions: they carry nutrients, oxygen, carbon dioxide, metabolic waste, hormones, etc. This unique structure of the circulatory system of birds is quite effective, as it allows them to meet their metabolic needs, thus enabling birds to move (run), fly, dive, or swim intensively. The morphological and architectural features of this cardiovascular system in birds contribute not only to the distribution of oxygen contained in the blood that flows to the body's cells, but also to the removal of metabolic waste products from the body and the maintenance of the birds' body temperature [26, 25, 750, 73, 84, 101, 372, 589].

In mammals, as in birds, the heart has four chambers: two (right and left) atria and two (right and left) ventricles, where the

process of separating oxygenated blood from oxygen-depleted blood takes place. The right ventricle pumps blood to the lungs, while the left ventricle generates blood pressure to pump it throughout the animal's body [467, 575, 324, 430, 431].

Such progressive changes in the circulatory system in mammals consist in the formation of a complete septum in the ventricle, which is why the heart becomes four-chambered [750, 467, 575, 41, 308]. The atria and ventricles of the heart in mammals are completely separated from each other. Therefore, arterial blood from the lungs enters the left atrium through the pulmonary veins and from there into the left ventricle of the heart without mixing with venous blood, which moves through the hollow veins into the right atrium and right ventricle of the four-chambered heart [144, 617].

Thus, in the process of evolutionary development of the circulatory system in a number of classes of vertebrate animals at different stages of their formation (fish – amphibians – reptiles – birds – mammals), progressive adaptive changes occur in the structure of the cardiovascular system as a whole, and especially in the heart, manifested by an increase in the number of its chambers, from two to four, which is due to the adaptation of animals to a more intense lifestyle.

1.3. Comparative analysis of heart formation in the phylogenesis and ontogenesis of vertebrate animals

The formation of the cardiovascular system, in particular the heart, is a key stage in both the individual (ontogenetic) and historical (phylogenetic) development of vertebrates [496, 149, 689, 671]. The evolutionary complexity of the heart structure directly correlates with the level of metabolic activity of organisms, type of respiration, and lifestyle [393, 290, 551, 171,

97]. During phylogenesis, the morphology of the heart gradually became more complex, from the most primitive contractile structures in lower chordates to a four-chambered organ in higher vertebrates [419, 96, 291, 203, 106]. At the same time, the embryonic development of the heart in modern vertebrate species reflects the general patterns of the historical evolution of this organ, which gives reason to consider ontogenesis as a condensed repetition of phylogenesis [52, 508, 708, 90].

The heart is the central and vital organ of the cardiovascular system of all chordates. Its main function is to ensure blood circulation, which transports oxygen, nutrients, hormones, and other biologically active compounds to tissues and organs [735, 74, 92, 144, 717].

In vertebrates, the heart is one of the first organs to form during embryogenesis, and even in the early stages of development, it performs the critically important function of ensuring exchange between the embryo and the environment through the circulatory system [449, 252, 254]. Initially, the heart looks like a simple cardiac tube formed from myogenic cells capable of contraction. This tubular structure functions as a primitive pump, supporting the basic circulatory needs of the body.

Subsequently, sequential morphological regionalization of the heart occurs, which includes the separation of the atria and ventricles, the formation of valve structures, and, in birds and mammals, the development of a fully-fledged four-chambered heart. This type of structure provides two separate blood circulation circuits: pulmonary (small circle) and systemic (large circle), which significantly increases the efficiency of oxygen transport to tissues, especially in conditions of high metabolism [448, 450, 733].

This evolutionary restructuring of the heart was an important step towards increasing the viability and functional autonomy of the organism. The presence of a clear separation of blood flows creates favorable conditions for ensuring stable gas exchange and adaptation to different environments. In addition, during embryonic development, the heart indirectly influences the formation of other organs and systems by regulating their trophism, oxygenation, and growth [489, 78, 85, 199, 248].

From a phylogenetic perspective, the heart as an element of the cardiovascular system evolved from the anterior part of the venous sinus located in the ventral aorta. Its gradual complexity in different groups of vertebrates reflects the patterns of adaptation of the circulatory system to the growing functional needs of the body.

Recent studies have suggested that cardiogenesis occurs from a single source of myocardial progenitor cells. However, current understanding of cardiogenesis has identified two independent sources of these cells. Studies on chicken and mouse embryos show [415, 724] that removal of the cardiac crescent does not completely eliminate the formation of the cardiac tube, as there is a second source of myocardial cells located in the pharyngeal mesoderm. Such studies have also shown that the early cardiac tube in mouse embryos has significant qualitative features of the left ventricle: the heart changes its shape as a result of loop formation and myocardial expansion, which contributes to the formation of cardiac chambers [626, 76, 65, 115, 169, 186, 202, 725]. In most vertebrates, the cellular precursors of the heart are located next to the precursors of the head cells. In frogs and mammals, the tissue layers responsible for the induction of the heart and head are typologically different but most likely functionally similar [438, 482, 568].

In ontogenetic terms, the heart of a fish develops rapidly in the early stages of embryonic development, and its growth and development do not stop in the postnatal period of ontogenesis: the most characteristic manifestation of this development is a threefold increase in the mass of the heart ventricle in adult fish (a relatively large ventricle mass in fish is necessary for the development of high blood pressure and active metabolism [739, 93, 196, 498, 653].

According to Kozlov V. O. et al. (2004), the shape of the heart of a fish embryo and a mature individual corresponds to the stage of the tubular heart of a human embryo, which indicates the reproduction of the stages of ontogenetic development during the phylogenesis of this organ [454].

The heart of fish has a mixed type of ventricle, which consists of an outer compact layer and an inner spongy layer [420, 505].

During heart development, the thickness of the compact layer increases. In the spongy layer, the diameter of the trabeculae and the diameter of the vessels supplying blood to the myocardium increase [362, 93, 461, 463]. The trabecular apparatus in the ventricle of fish develops on the fifth day after fertilization.

The development of the compact layer of the myocardium is associated with the size of the fish's body and metabolic activity, while the development of the trabecular layer depends entirely on nutrition and oxygen saturation. The trabecular apparatus in the ventricle of sexually mature fish becomes significantly thicker compared to that in earlier stages of development. Depending on the thickness of the compact layer of the myocardial wall, the length of the trabeculae, the size and number of intertrabecular cells change [239, 653]. Trabeculae make up a significant part of

the ventricular mass and support the heart during systole and diastole [202, 498].

When studying the embryonic development of the heart in frogs in the early stages, the heart tube appears first: the atrioventricular cushion forms in the inner heart tube and the cardiac notch appears, and the heart tube takes on an S-shape. Then the trabecular apparatus of the myocardium develops, the atrioventricular valve forms, and the formation of the septum in the atrium begins. At this stage of embryonic development, a difference between the thicker ventricle and the thinner atrium becomes apparent. The next stage is the final formation of the atria, the formation of cardiac endothelial cells, and the formation of the valves and partitions of the heart. In the final stage of embryonic development of the amphibian heart, a large number of heart structures characteristic of sexually mature animals are formed: the ventricle is formed, and a spiral valve is formed in the arterial trunk. Then, three chambers are differentiated in the formed heart: a single ventricle and two atria [697, 201, 338, 343, 443, 487, 494].

The heart of a lizard, turtle, and snake consists of two atria separated by a complete septum and a single common ventricle. At the same time, a comparative analysis of the structure of the hearts of lizards, turtles, snakes, and crocodiles shows that the heart of the latter differs from other reptiles in the formation of a complete septum, which divides the heart into four chambers [51, 56, 233, 320].

In frogs, turtles, and snakes, the LV has a spongy structure. To separate the somatic and pulmonary circulation in frogs, the spongy myocardium of the heart is adapted to generate high systolic pressure in the ventricular-atrial direction, and the bulbous spiral valve prevents reverse blood flow [184, 720].

In birds, trabeculae and septa form in the apical region during early embryonic development. Marked cells migrate upward and to the right, forming the myocardium. Research results indicate heterogeneity in the inner surface of the compact and trabecular layers. This transmural heterogeneity is partly responsible for the formation of the trabecular recess in later stages, which is formed next to the compact layer [172, 304, 413, 453, 485, 656, 696, 707, 718].

In birds, blood enriched with oxygen and nutrients flows from the left ventricle of the heart through the aorta and numerous arteries to all parts of the body and its organs. Oxygen and nutrients from the blood diffuse through the capillary walls into the surrounding tissues, and metabolic products and carbon dioxide from them return to the heart, directly into the right atrium through the veins. From the right atrium, oxygen-depleted blood is pumped into the right ventricle, which pumps blood directly into the lungs to saturate it with oxygen. In the lungs, the blood is re-saturated with oxygen and enters the left atrium, from where it is pumped into the left ventricle [26].

In terms of morphological structure, the cavity of the left ventricle of the heart, through which blood flows, is the strongest, as its wall is formed by more developed muscle (myocardium) tissue than that of the right ventricle and the right and left pericardium. This is because blood from the left ventricle of the heart is pumped through the arteries to the entire body. Therefore, the wall of the left ventricle is the thickest, due to the muscular membrane.

In birds, the heart is proportionally larger than in mammals. The relatively large mass of the heart is due to the high metabolic rate and significant energy expenditure associated with active movement, primarily flight. The heart of birds is characterized by high functional power, which ensures intense blood circulation

and rapid delivery of oxygen and nutrients to tissues. This feature of the cardiovascular system is an important adaptation that allows birds to maintain a high level of metabolic activity and effectively perform prolonged physical exertion.

The heart is one of the first organs to form during embryogenesis, as it provides the early blood circulation necessary for the growth and differentiation of embryonic tissues. The development of the cardiovascular system is characterized by a high level of structural and functional complexity, which determines the sequence and interdependence of morphogenetic processes. The formation of the heart is closely linked to the development of embryonic layers, the formation of axial structures, and the differentiation of the mesoderm, which determines the further organization of the organ and its adaptation to the needs of the body.

The heart is formed during the second or third week of embryonic development in mammals. Organ formation begins in the early stages, when the embryo has the appearance of a three-layered embryonic plate (Fig. 1.5).

During this period, the heart is formed in the visceral mesoderm of the anterior part of the body, where the so-called heart field arises. Initially, the heart appears as two endocardial tubes, which later merge into a single primary heart tube. At the beginning of development, the wall of the organ consists of two main layers – the endocardium and the epicardium. In the process of further differentiation, the epicardium is stratified into the myocardium and the epicardium, as a result of which the wall of the heart acquires a definitive three-layer structure characteristic of a mature organ. Simultaneously, the heart chambers, the beginnings of the septum, and the valve apparatus are formed, ensuring the further transition from a simple tubular to a four-chambered mammalian heart [25, 467, 575].

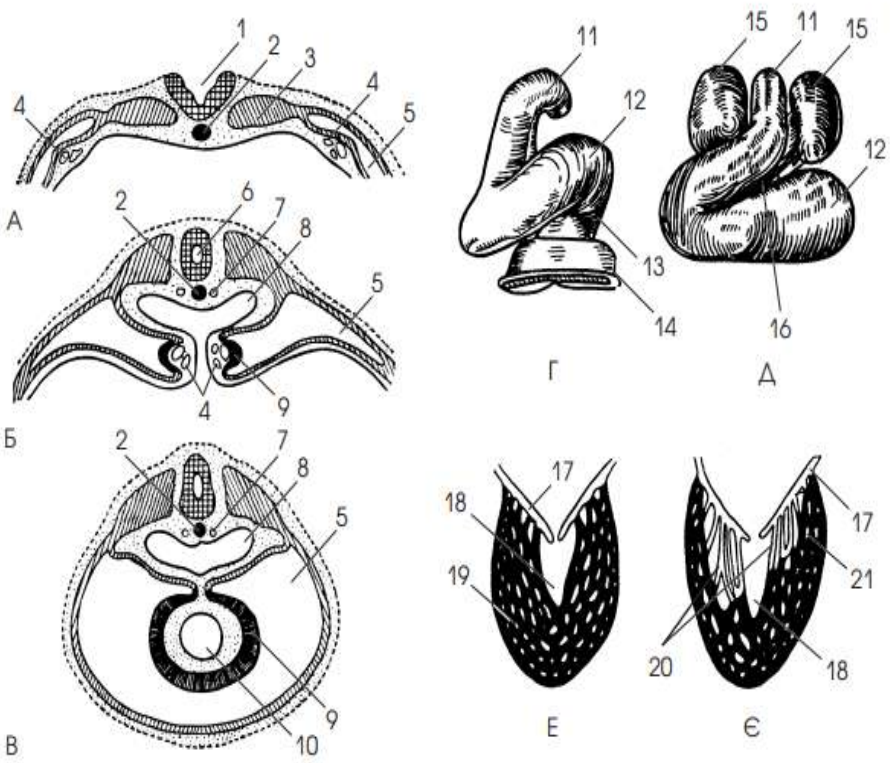

Fig. 1.5. Ontogenesis of the heart. A, B, C – gradual stages of development of the paired heart primordium; D, E – subsequent stages of heart development; F, G – stages of heart valve formation. 1 – neural groove; 2 – chord; 3 – primary segment; 4 – heart primordium; 5 – body cavity; 6 – neural tube; 7 – dorsal aorta (paired); 8 – main intestine; 9 – myocardium and epicardium; 10 – cavity of the cardiac tube; 11 – arterial trunk; 12 – ventricle; 13 – atrium; 14 – venous sinus; 15 – atrial appendages; 16 – coronary sulcus; 17 – mitral valve; 18 – ventricular cavity; 19 – muscular septa; 20 – tendinous cords; 21 – myocardium [349].

The ventricles of the mammalian heart, during the prenatal period of ontogenesis, are formed from the ventricular loop.

Initially, the ventricular parts of the primary tube are formed from the stem of the cardiac tube, formed from the primary cardiac crescent, and the distal part, formed from the second cardiac region [510, 77, 103, 118, 146–148, 198, 249, 469, 513, 616].

After careful study of the process of division of the heart into chambers, scientists put forward the hypothesis that the septa are nothing more than folds of extracardiac adipose tissue included between the folded layers of the myocardium [147, 679, 428]. According to their data, the normal geometric shape of the left ventricle of a four-chamber heart is that of an elongated ellipse.

The heart cavity is heterogeneous due to the presence of the papillary-trabecular apparatus. There are also significant heterogeneities in the walls of the LV in terms of their thickness. The caudal lateral wall of the LV is significantly thicker than the septum. A gradual thinning of the LV wall is observed in the direction of the apex [323, 339, 382, 438].

According to recent studies, heart development in human ontogenesis is a complex, multi-stage process that occurs in close connection with the overall development of the body and its functional needs. Morphogenesis and functional maturation of the heart are characterized by gradual structural changes that reflect the adaptation of the organ to increasing metabolic and hemodynamic loads. In the scientific literature, most authors distinguish three main periods in the development of the heart: differentiation, stabilization, and involution [190, 112, 507, 533, 365, 593, 163, 711, 742, 685].

The first period (differentiation) begins in the embryonic period and lasts until about 20 years of age. During this period, cardiac cardiomyocytes are enriched with sarcoplasm and various ultrastructures, myofibrils grow, reticular fibers decrease, and are replaced by collagen fibers. During the differentiation period, the

nuclear-cytoplasmic ratio decreases in cardiomyocytes [123, 157, 340, 363, 392].

The second period (stabilization) lasts from 20 to 30 years. During this period, the formation of heart valves, blood vessels, and other structures is completed.

The third period (involution) is characterized by certain changes in the structure and functions of the heart, particularly during periods of aging and decreased functional activity. This may include a decrease in the heart's ability to adapt to changes in physiological conditions. According to the majority of researchers, this period occurs after the age of 40. In the third period, the amount of connective tissue in the myocardium increases, the walls of the blood vessels thicken, their lumen narrows, and adipocytes appear in the epicardium.

1.4. Morphological features of the heart of vertebrate animals

The heart of vertebrates is a key element of the cardiovascular system, ensuring blood circulation and the transport of oxygen, nutrients, and other vital components to all organs and tissues [699, 204].

The cardiovascular system is one of the basic functional systems of vertebrate animals, ensuring the integration of metabolic processes, maintaining homeostasis, and adapting to living conditions. Its formation and complexity occurred during the course of evolution in parallel with changes in lifestyle, metabolic rate, and the morphofunctional organization of the organism. The heart occupies a special place in this system as the central organ of blood circulation, whose structure and functions reflect the general patterns of evolutionary development of vertebrates.

The heart of vertebrates is a key element of the cardiovascular system, ensuring continuous blood circulation, transport of oxygen, nutrients, hormones, and other vital components to all organs and tissues, as well as the removal of metabolic waste products [699, 204]. Its morphological organization is determined not only by species characteristics, but also by the functional needs of the organism, the level of metabolic activity, and the nature of motor activity.

The morphology of the heart in different groups of vertebrates varies significantly depending on the level of organization, type of metabolism, environmental conditions, and evolutionary development [635, 691]. From the simplest forms, represented by the two-chambered heart of fish, to the complex four-chambered structures of birds and mammals, there is a clear trend towards a more complex heart structure, increased efficiency, and autonomy of the circulatory system [373, 659].

Unlike plants, animals are capable of exhibiting a wide range of physiological, morphological, and behavioral adaptations aimed at regulating body temperature [486, 98, 170]. Depending on the level of organization and evolutionary position, thermoregulation in animals can be permanent or temporary, active or passive. The main directions of temperature adaptation are:

Chemical (metabolic) thermoregulation is an active increase in heat production due to the intensification of metabolic processes. It is especially characteristic of warm-blooded (homeothermic) animals, which are able to maintain a stable body temperature regardless of environmental conditions due to complex neuroendocrine mechanisms of metabolism regulation.

Physical thermoregulation involves changing the body's heat transfer rate. It is achieved through morphophysiological features of the body: the density of wool or feathers, skin structure,

capillary network distribution, subcutaneous fat, and evaporative cooling mechanisms (sweating, panting). For example, some species have the ability to vasodilate or vasoconstrict, which allows them to control heat loss.

Behavioral responses are an important component of the thermoregulatory apparatus. Through spatial activity (moving into the shade, into a burrow, into water, or, conversely, into an open area), changing posture, grouping, or isolation, animals effectively avoid extreme temperatures. In many poikilothermic species, behavioral mechanisms of thermoregulation are almost the only means of maintaining viability in unfavorable conditions.

Poikilothermic (ectothermic) animals, unlike homeothermic animals, are characterized by a low basal metabolic rate even at the same body temperature. Due to their limited ability to produce heat, these animals have almost no chemical thermoregulation, and their body temperature largely depends on the temperature of the environment. A decrease in ambient temperature causes a slowdown in all physiological processes, including metabolism, cardiac activity, and nervous regulation, which can lead to a state of torpor or suspended animation. This state is accompanied by the ability to tolerate low temperatures, caused by the activation of specific biochemical mechanisms, including the accumulation of cryoprotectants, changes in the composition of cell membranes, and the restructuring of enzyme systems. Thanks to these adaptations, poikilothermic animals are able to survive in conditions of significant temperature fluctuations and prolonged exposure to low temperatures.

In order to return to active functioning, poikilothermic animals need to obtain a certain amount of external heat, which will allow metabolic processes to start. Thus, the vital activity of cold-blooded creatures is closely linked to fluctuations in the

ambient temperature, which determines the seasonality of their behavior, reproductive cycles, and physiological states [369, 698].

This section will examine the anatomical and morphological features of the heart in the main classes of vertebrates, divided into two functionally important groups: poikilothermic (cold-blooded) and homeothermic (warm-blooded) animals. This classification allows for a more precise analysis of the evolutionary adaptations of the cardiovascular system to the specifics of thermoregulation, metabolic rate, and physiological needs of the organism.

1.4.1. Morphological features of the heart in poikilothermic (cold-blooded) animals

During the course of evolutionary development, living organisms have developed a range of adaptive mechanisms that allow them to efficiently regulate metabolism under conditions of fluctuating environmental temperatures [225, 6, 630]. The main pathways of this adaptation are: 1) biochemical restructuring of metabolic processes; and 2) the ability to maintain body temperature at a level higher or more stable than that of the surrounding environment [401, 54].

One of the key factors in thermoregulation is the intensity of endogenous heat production [33–35]. However, a significant portion of organisms lack both a high metabolic rate and morphophysiological mechanisms for heat conservation, such as insulating layers or specialized vascular structures. In these organisms, body temperature fluctuates with ambient temperature, and thermoregulation is primarily achieved through behavioral or external factors [665, 383, 499]. Such organisms are classified as poikilothermic (or ectothermic). Poikilothermy is characteristic of

most invertebrates, amphibians, reptiles, fish, as well as all plants and microorganisms [300, 175, 370, 181].

In poikilothermic species, the mixing of arterial and venous blood, due to incomplete septation of the heart, limits the efficiency of oxygen transport and reduces heat dissipation [211, 178, 44]. This, in turn, affects metabolism, which in these animals is 20–30 times slower than in homeothermic (warm-blooded) species.

The body temperature of poikilotherms typically does not exceed ambient temperature by more than 1–2 °C. Their physiological activity largely depends on environmental conditions [476, 296, 61]. At low temperatures, these animals become sluggish, and further cooling can lead to anabiosis—a temporary suppression of vital functions. The cyclic nature of activity in cold-blooded animals determines the seasonal pattern of their life processes, which directly affects the structure, function, and metabolic demands of the cardiovascular system.

From a functional and spatial perspective, the heart serves as the principal organ of the circulatory system, ensuring the movement of blood through the vessels via rhythmic contractions [25, 722, 279, 166, 357, 467, 465, 639].

The cardiovascular system of fish consists of the following components: the circulatory system, the lymphatic system, and hematopoietic organs. The circulatory system of fish differs from that of other vertebrates by having a single circulatory loop and a two-chambered heart filled with venous blood [582, 156, 217].

In fish, the heart is located ventrally – anterior to the pectoral fins and the coelomic cavity, usually posterior to the branchial (gill) structures (Fig. 1.6). In the literature, the terms “branchial heart” and “systemic heart” are used because the heart first pumps blood to the gills, from where it proceeds to the systemic circulation [680]. Thus, both the branchial and systemic

circulations are arranged sequentially along the course of blood flow from the heart.

During the course of vertebrate phylogenetic development, significant changes occurred in the structure of the heart's accessory components, particularly the venous sinus and arterial cone [302, 303, 680, 237]. At early stages of evolution, in primitive fish such as hagfish and lampreys, the venous sinus is represented by a simple chamber that functions as a reservoir for venous blood before it enters the atrium [91, 9]. In more evolutionarily advanced species, including cartilaginous fish (sharks), ganoid fishes, and lungfishes, the venous sinus is well-structured and highly developed, ensuring stable blood flow and reducing hydrodynamic fluctuations prior to blood entry into the heart [406, 671].

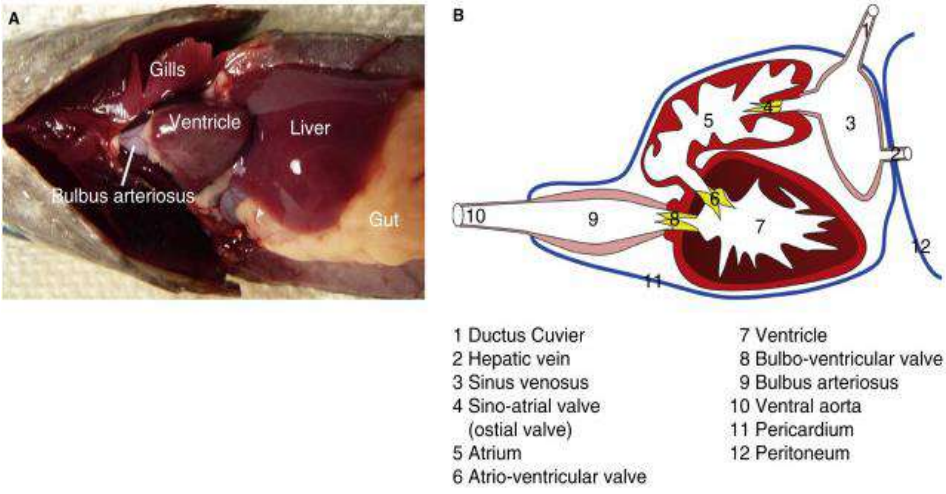

Fig. 1.6. (A) A ventral view of a rainbow trout with a mid-line incision to reveal the anatomical organization and shape of the cardiac chambers. The pericardial cavity was opened for this view. Note the coronary artery visible on the white surface of the bulbus arteriosus. (B) A schematic diagram of the cardiac chambers as seen from a lateral view [67].

In the subsequent evolutionary process, particularly in bony fish, the arterial cone undergoes reduction, losing its muscular component and valvular apparatus. It is replaced by the arterial bulb (bulbus arteriosus), an elastic structure that primarily performs a passive function of dampening the pressure generated by ventricular contraction [250, 309].

This transformation reflects a transition to a more energy-efficient type of circulation, corresponding to a reduced need for active regulation of blood pressure in these species.

According to studies by M. C. Cerra et al. (2004), M. H. Braun et al. (2003), H. U. Norman et al. (2001), and N. Hu et al. (2000), the heart of fish has a pyramidal shape, and its mass as well as the linear dimensions of the whole heart and its individual sections increase proportionally to the body mass of the animals [593, 93, 196, 653].

According to studies by C. A. Simões et al. (2002), Eija Aho and Matti Vornane (1999), J. R. Bailey and R. William (1990), D. Sánchez-Quintana et al. (1995), and P. Harrison et al. (1991), the ventricles of fish hearts exhibit various shapes—tubular, sac-like, or pyramidal – depending on the activity level of their lifestyle. In more active fish species, the ventricles are pyramidal, whereas in less active species, they are sac-like [86, 42, 239, 458, 461, 463].

The heart in fish is two-chambered, consisting of an atrium and a ventricle. The venous sinus is adjacent to the atrium, while the arterial cone is located at the distal end of the ventricle [653]. The relative heart mass of fish is considerably lower (ranging from 0.33% to 2.5%) than in terrestrial vertebrates [362].

The heart of fish possesses a mixed-type ventricle, consisting of an outer compact layer and an inner spongy layer. The compact layer is composed of an outer longitudinal layer and an inner circular layer, the thickness of which is variable. The muscle fibers in the compact layer are arranged chaotically: some

are longitudinally oriented, while others are positioned transversely or at an angle. Coronary arteries are well identifiable in the compact layer and are more prominent on the dorsal surface of the ventricle than on the ventral surface [8, 292, 461, 721].

In fish, the ventricle exhibits external symmetry, but its cavity is asymmetrically constructed. The ventricular wall thickness is uneven: the left wall is thickened, and the atrioventricular orifice is relatively small.

Amphibians (Amphibia) are a class of ectothermic tetrapod vertebrates that play an important role in the transition from an aquatic to a terrestrial lifestyle [173]. They represent one of the oldest groups of tetrapods and, from an evolutionary perspective, are a transitional form between fish and amniotes (mammals, birds, and reptiles). In a systematic context, modern amphibians belong to the subclass Lissamphibia, which includes three main orders: Anura (frogs and toads), Urodela (salamanders), and Gymnophiona (caecilians) [140, 87].

In Ukraine, 20 amphibian species are found, inhabiting a variety of ecosystems-from wetlands to forest and steppe landscapes [556, 79, 137]. The life cycle of most amphibians is characterized by metamorphosis, a complex transformation from a larval (aquatic) form to an adult (predominantly terrestrial) form, accompanied by the restructuring of respiratory organs, sensory organs, limbs, and other systems.

A physiological characteristic of amphibians is their inability to maintain a constant body temperature, which defines their poikilothermic type of organization. Consequently, ambient temperature directly influences the rate of metabolic processes, locomotor activity, digestion, and other vital functions. Due to this temperature dependence, amphibians exhibit peak activity primarily during the warm season, whereas in colder periods their mobility and metabolic rate decrease significantly. Similar to fish,

amphibians retain the capacity for growth throughout their lifetime, which ensures prolonged adaptation to changing environmental conditions and provides opportunities for studying regeneration processes, metamorphosis, and age-related morphofunctional changes [385, 134].

The circulatory system of amphibians already exhibits a double-circuit structure, representing an important evolutionary step toward a more efficient blood circulation. The emergence of pulmonary respiration led to the formation of a pulmonary (small) circulation, which functions in parallel with the systemic (large) circulation [12, 550, 131].

The small circulation begins with the pulmocutaneous arteries, which transport venous blood to the lungs and skin. After gas exchange, oxygenated blood returns via the pulmonary veins to the left atrium.

The systemic circulation originates from the aortic arches and carotid arteries, which branch throughout the body tissues. Venous blood from the organs returns via the anterior (paired) and posterior (unpaired) venae cavae to the right atrium. Since part of the oxygenated blood from the skin enters the anterior venae cavae, the right atrium contains mixed blood [587].

This organization of the cardiovascular system allows amphibians to maintain an adequate level of tissue oxygenation despite the partial separation of arterial and venous blood flow. This feature is characteristic of animals with a semi-aquatic lifestyle and the capacity for cutaneous respiration, which serves a compensatory function alongside pulmonary respiration.

The hearts of amphibians and reptiles are morphologically complex, reflecting transitional forms between the primitive heart structure of fish and the more advanced structures found in birds and mammals [405, 312, 741].

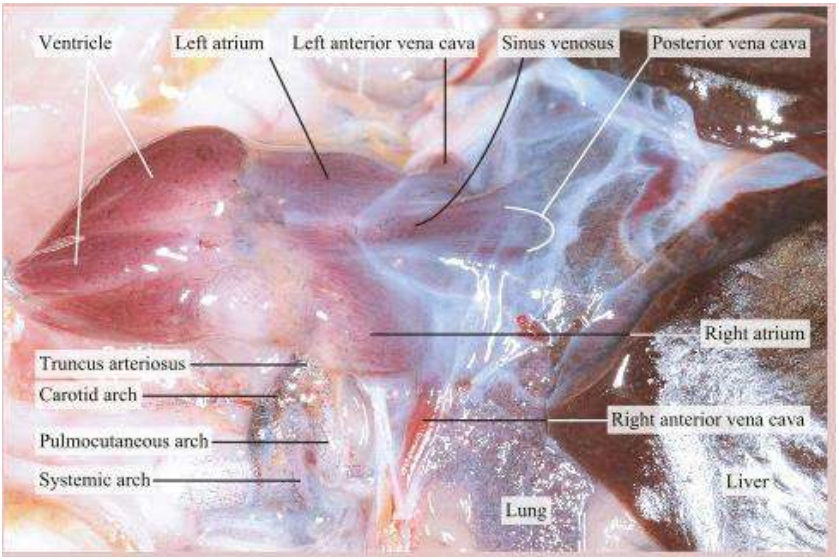

Fig. 1.7. Dorsal side of the heart frog [39].

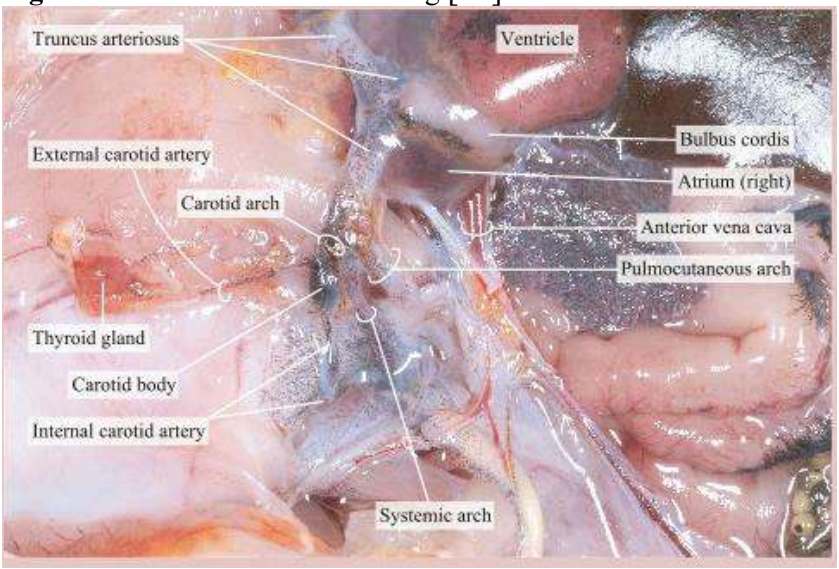

Fig. 1.8. The heart frog, the right truncus arteriosus and the aortic arches. (Anterior end is to the left) [39].

In the frog, as a typical representative of amphibians, the heart is located in the thoracoabdominal cavity directly beneath the sternum. It has a three-chambered structure, consisting of two atria (right and left) and a single ventricle (Fig. 1.7, 1.8).

The interatrial septum completely separates the chambers; however, both atria communicate with the ventricle through a single atrioventricular orifice, which contains valve leaflets that regulate the direction of blood flow (Fig. 1.9) [750, 362, 433].

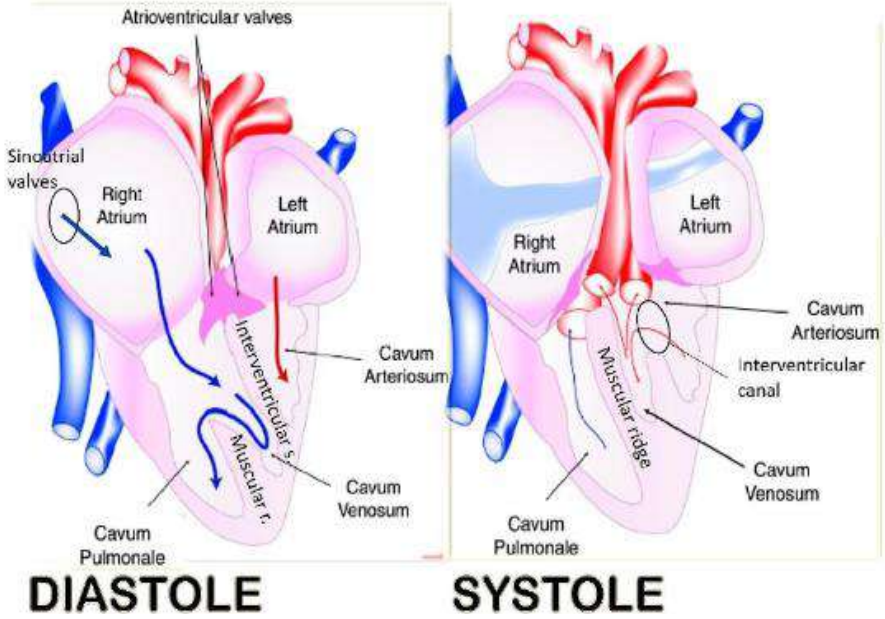

Fig. 1.9. Normal blood flows in the reptilian heart [541].

In addition to the main chambers, the structure of the frog heart includes the sinus venosus, which opens into the right atrium, and the conus arteriosus, which represents a continuation of the ventricle and plays an important role in the separation of blood flow during the cardiac cycle.

The muscular wall of the heart (myocardium) in anuran amphibians, particularly in the common toad (Bufo bufo), has a spongy, or trabecular, structure, which facilitates the mixing of blood within the ventricle; however, partial separation is achieved due to functional trabeculae [362, 612].

In reptiles, as the next stage of evolutionary complexity, the heart generally remains three-chambered; however, its structure already exhibits an incomplete interventricular septum, which partially separates blood flow. The interatrial septum, as in amphibians, is complete. In the sand lizard (Lacerta agilis), for example, a vertical septum is present that temporarily divides the ventricle into left and right parts during systole, allowing partial direction of oxygenated and deoxygenated blood into different circulatory circuits [362, 83].

Such an anatomical and functional improvement of the heart provides more efficient blood supply to organs under terrestrial conditions, reducing the degree of blood mixing and increasing the level of metabolic activity.

According to the results of several studies, the morphology of the heart in representatives of the order of lizards exhibits a number of specific features [740, 82]. In particular, the heart shape in some species is described as oval and somewhat elongated, with predominant development of the dorsal part (Fig. 1.10).

In these reptiles, the interventricular septum is oriented horizontally and partially divides the ventricle into dorsal and ventral chambers. Anatomical observations indicate that the dorsal chamber has a larger volume than the ventral one. In the region of the cardiac apex, this septum is continuous, whereas near the base of the ventricle it assumes an oblique orientation, which likely influences hemodynamics [81, 327].

Comparative anatomical analysis of the cardiac morphoarchitectonics in representatives of different reptilian groups (lizards, turtles, snakes, and crocodilians) revealed significant differences in the degree of morphological organization. In crocodilians, unlike other reptiles, the heart possesses a complete interventricular septum that anatomically and functionally divides the organ into four chambers, similar to the hearts of birds and mammals. This represents a unique adaptation among reptiles and indicates a high level of evolutionary development of the cardiovascular system [51].

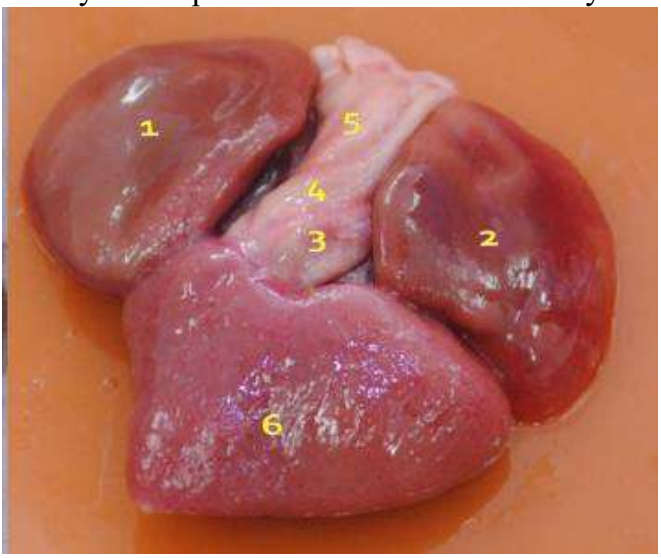

Fig. 1.10. Anatomy of the lizard heart (Pogona vitticeps on the left, Iguana iguana on the right):1 – right atrium; 2 – left atrium; 3 – pulmonary artery; 4 – left aortic arch; 5 – right aortic arch; 6 – ventricle [541].

In most reptiles, an intermediate type of cardiac organization is observed, combining features of both lower and more highly organized vertebrates, whereas in crocodilians these processes reach the highest degree of morphological completeness. Such differentiation indicates a close relationship between the structural

organization of the heart and ecological conditions of existence, including environmental factors, activity level, and type of respiration, which shape specific adaptive strategies of the cardiovascular system in different groups of reptiles.

In contrast, the hearts of lizards, turtles, and snakes exhibit the typical three-chambered structure characteristic of most reptiles-two atria separated by a complete interatrial septum and a single common ventricle. At the same time, the internal structure of the ventricle has its own specific features. In particular, a muscular ridge (trabecula septomarginalis) is present within its cavity, originating from the ventral wall of the ventricle and the apex, and partially dividing the ventricle into two functional chambers. Researchers distinguish a smaller ventrolateral and a larger dorsolateral cavity, which differ in volume and functional load [233, 320].

This type of internal ventricular organization may facilitate partial direction of blood flow within a single ventricle, which, despite the absence of a complete septum, allows for functionally separated circulation, albeit with a certain degree of blood mixing that is characteristic of most reptiles.

The ventricular myocardium of reptiles consists of an outer compact layer and an inner spongy layer [362].

Histological studies indicate that in the hearts of fish, the number of cardiomyocytes in the compact layer decreases, while it contains a greater number of myofibrils compared to the spongy layer; at the same time, intercellular spaces are significantly reduced with growth, being replaced by muscle fibers. The main components of the ventricular wall are myocytes–elongated cells with large nuclei [93, 239, 479].

In the compact myocardium of fish hearts, the fibers in the ventricular walls are densely arranged, while connective tissue provides structural support for muscle fibers, blood vessels, and

myocytes. Regardless of the type and shape of the ventricles, the trabecular myocardium is consistently characterized by a chaotic arrangement, except in areas near the ventricular orifices, where it performs a valve-like function [480].

After hatching, active processes of myofibrillogenesis are observed in the cardiomyocytes of frogs: myofibrils consisting of 5–6 sarcomeres appear. Cardiomyocytes within the trabeculae of the myocardium exhibit heterogeneous tinctorial properties, which become evident after the completion of metamorphosis. The trabeculae of the mature myocardium show specific features in terms of size and arrangement depending on their localization within the heart: the apical myocardium contains longer and thinner trabeculae than the central part of the ventricle. The greatest trabecular length is characteristic of the atrial myocardium [611, 610].

Ventricular myocytes in turtles are spindle-shaped, with a length of approximately 190 nm and a width of 5–7 nm [477, 695].

Thus, the morphological features of the hearts of poikilothermic animals reflect adaptive strategies to specific environmental conditions, levels of physiological activity, and lifestyle. Observed variations in chamber structure, myocardial wall thickness, and the degree of vascular network branching indicate a close relationship between heart structure and its functional load. Despite the absence of constant thermoregulation, the heart of cold-blooded animals provides efficient circulation within the available temperature range, which is crucial for maintaining vital functions, growth, and overall adaptation. Therefore, the study of heart morphology in poikilothermic animals provides a solid foundation for the comparative anatomy of the cardiovascular system and for understanding the evolutionary patterns underlying its development in vertebrates.

1.4.2. Morphological features of the heart of homeothermic (warm-blooded) animals

The morphology of the heart of homeothermic animals is an important subject of study in modern morphology, physiology, and veterinary medicine, since it is the cardiovascular system that maintains homeostasis, adapts the body to changes in environmental conditions, and enables high-level metabolic processes. The study of the structural and functional features of the heart of warm-blooded animals allows for a deeper understanding of the patterns of evolutionary development, mechanisms of adaptation, and species-specific features of the structure of this organ.

Mammals are the highest level of evolutionary development among terrestrial vertebrates [322, 100]. Representatives of this class are characterized by a high level of organization, complex behavior, and well-developed neurohumoral regulation of vital processes [50, 190, 13]. One of the key features of mammals is their ability to maintain a constant body temperature despite fluctuations in the ambient temperature. The formation of homoeothermy led to significant morphofunctional changes in the organization of the cardiovascular system, in particular, the complication of the heart structure, the differentiation of its chambers, the development of the valve apparatus, and the specialization of the conduction system.

This phenomenon is known as homeothermy or endothermy (warm-bloodedness) and is considered one of the most significant adaptations in the animal world [215, 700, 350]. Thermal homeostasis is achieved through internal thermoregulatory mechanisms, which include chemical (metabolic) and physical thermoregulation. In mammals, heat production is closely related to the intensity of metabolism, which allows them to effectively

store or dissipate heat depending on environmental conditions [69, 600, 301].

Maintaining a stable body temperature creates optimal conditions for enzymatic activity, high metabolic rate, and functional stability of internal organs, which is especially important for organisms with an active lifestyle [117, 119]. In addition, thermal stability allows mammals to colonize a wide range of habitats, from the Arctic tundra to arid deserts. These physiological features are also related to the morphofunctional structure of the heart and circulatory system, which in mammals have the most complex organization among vertebrates. A completely divided four-chambered heart and a dual-circuit circulatory system ensure effective tissue oxygenation, maintenance of high blood pressure, and intensive gas exchange, which are important conditions for high thermoregulatory capacity.

One of the important morphometric indicators of the heart is its absolute and relative mass, which directly depends on age, sex, breed, species of animals, etc. In pigs, these indicators are 307.2–334.3 g and 0.28–0.3%, respectively; in horses, 2150–4300 g and 0.58–0.60%; in cattle – 1300–2400 g and 0.35–0.4%, in dogs – 72.4–154.0 g and 0.66–2.0% [136]. According to S.V. Guralskaya (2006), the absolute weight of the heart in pigs with a live weight of up to 120 kg is 434 g, while the relative weight of the organ is 0.37% [297].

Birds have a four-chambered heart [26]. According to Kulchitsky K. I. (1985), birds more often have a conical heart shape, and only in some species is it strongly elongated (Fig. 1.11, 1.12). According to his data, the heart mass in small birds is relatively larger than in larger birds, which is associated with a more intense metabolism [362]. There is also a certain correlation between the relative heart mass and the energy of movements.

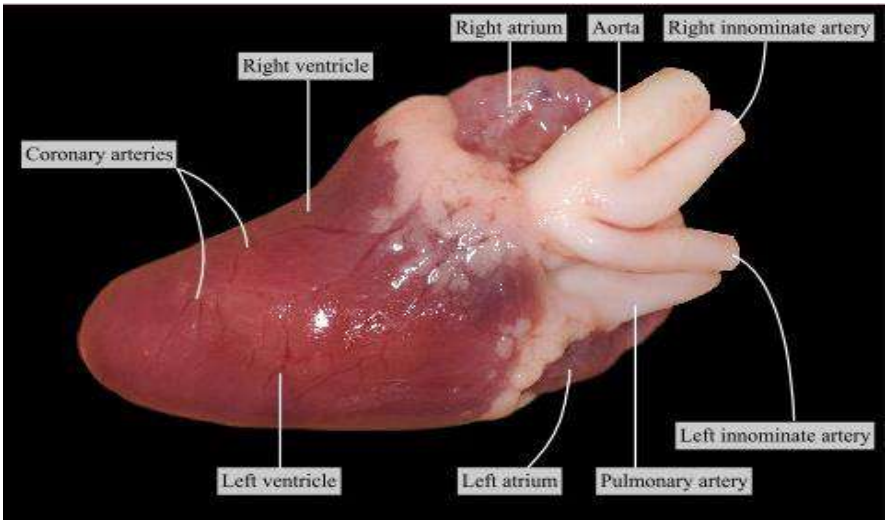

Fig. 1.11. The isolated chicken's heart with the large arteries [39].

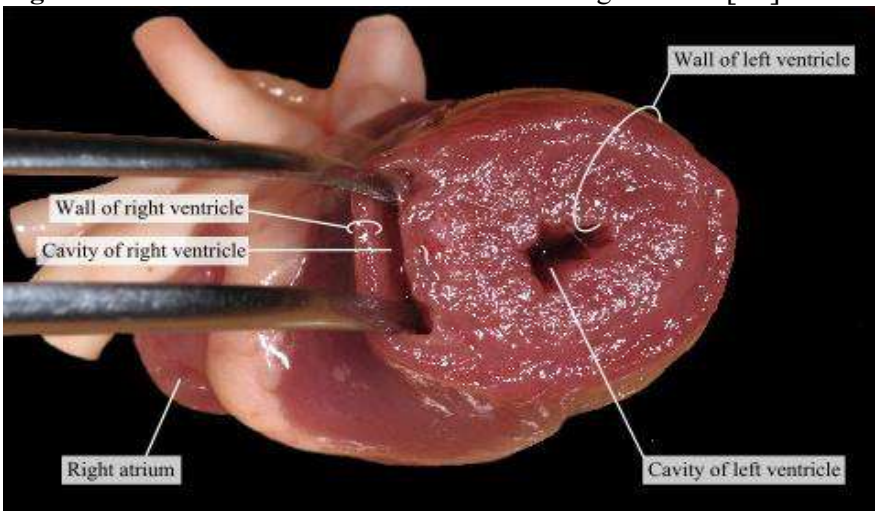

Fig. 1.12. The walls of the two ventricles of the chicken's heart are highly asymmetric [39].

Birds, as representatives of the class Aves, occupy a special place among homeothermic vertebrates, since their evolutionary

development was accompanied by the formation of unique morphofunctional adaptations associated with the ability to fly, high motor activity, and intense metabolic processes. Birds are characterized by high metabolic rates, an efficient respiratory system with air sacs, and perfect blood circulation regulation, which ensures stable body temperature and adaptation to various ecological conditions.

In terms of morphological structure, the heart of birds is similar to that of mammals, but its morphoarchitecture is slightly different due to the lifestyle and adaptation of birds to environmental conditions. For example, birds have proportionally larger hearts than mammals [26, 57, 168, 632].

The heart of mammals has four chambers and consists of two atria and two ventricles [25, 567, 575]. Since the relative sizes of the heart vary among species with different lifestyles and different metabolic rates, their cardiac index averages 1.7. In addition, the relationship between the body size of animals and the size of the heart correlates with the cardiac index of ecologically similar species: in the large ground squirrel, this index is 0.61, in the small ground squirrel, 0.82, and in the rabbit, 0.2. This indicates that the cardiac index depends on the motor activity of animals. Therefore, the relative size of a rabbit's heart is three times smaller than that of a hare [750].

In 80% of rats, the heart is cone-shaped, and in 20%, it is ellipsoidal [345].

The weight of an animal's heart depends on its breed, sex, and lifestyle. The absolute weight of the heart increases significantly with an increase in the animal's body weight. In small animals, the relative weight of the heart is higher than in large animals, which is associated with metabolic stress, oxygen demand, and heart rate.

The smaller size and weight of the heart and its components is explained by the lower mobility and, accordingly, lower metabolic rate in sedentary animals compared to animals that lead a more active lifestyle. This is because more active animals, which are significantly more resilient, require intensive nutrition and respiration to sustain their vital functions.

The myocardium of the mammalian heart is characterized by heterogeneity, in particular, the architectonics of the working myocardium and the conduction system are distinguished [129, 14, 47, 414, 497, 512, 725].

Correlation analysis with functional indicators of the left ventricle of the heart shows that a significant increase in the volume of the left ventricle of pigs, compared to the right, is determined to a greater extent by blood filling rather than contraction [380, 566, 664].

Superficial and deep layers are found in both ventricles, while the middle layer is found only in the LV. The greatest changes are characteristic of the superficial fibers of the muscle layer: in the LV, the subepicardial fibers are longitudinal, while in the RV they are transverse to the longitudinal axis of the heart. Most of the myocardial mass in the LV, with the exception of the apex, is represented by the middle layer of circular fibers. In the deep layer, the fibers are oriented lengthwise, forming trabecular and papillary muscles [313,438, 641, 688].

In the ventricles of the bull's heart, muscle fibers form three layers of ventricular myocardium, which are completely identical in structure to the myocardium of rats [638].

The myocardium of the right and left ventricles of the pig's heart has a three-layer structure: superficial, middle, and deep layers of myocardial fibers. The fibers of the superficial layer have a spiral direction. The middle layer in the ventricles of the heart is represented by circular fibers, which are absent at their

apices. The fibers of the deep layer in the right ventricle are located obliquely on the free wall, while in the interventricular septum they are directed toward the apical-basal cardiac axis. In the left ventricle, the fibers of the deep layer are arranged in a spiral, from the apex to the base of the heart.

Thus, when comparing the hearts of animals from different ecological groups, a dependence of the size and shape of the heart on physical exertion, metabolic intensity, etc. can be traced.

Depending on the species, breed, and age of animals, seven heart shapes can be distinguished in mammals: narrowed-elongated (cattle), narrowed-shortened (rabbit), widened-shortened (horse), round-oval (dog), slanted-oval (badger), flattened-oval (human), and bifurcated (dugong). In dogs, it can be ellipsoidal (43%), conical-ellipsoidal (24%), ellipsoidal-spherical (26%), and spherical (7%); in cattle, it can be elongated-narrowed, conical, and enlarged-shortened. Pigs have three main types of heart: elongated-narrowed, cone-shaped; shortened, relatively narrowed; widened-shortened, triangular [136, 575, 464].

In the postnatal period of ontogenesis, the shape of the heart in animals undergoes significant changes. Thus, after the birth of calves, the heart has a highly developed right ventricle for ten days. The walls of the right and left ventricles are of equal thickness. The heart in calves of this age is wide and acquires an oval or even rounded shape. The left interventricular groove shifts to the middle of the left surface of the heart. The right groove runs along the right surface of the heart close to the caudal edge. In calves aged 6–9 months, the heart becomes elongated and narrowed, but by the age of 12–15 months, the organ becomes wider and relatively short [241].

The wall of the heart is formed by three layers: the inner layer (endocardium), the middle layer (myocardium), and the outer layer (epicardium) (Fig. 1.13).

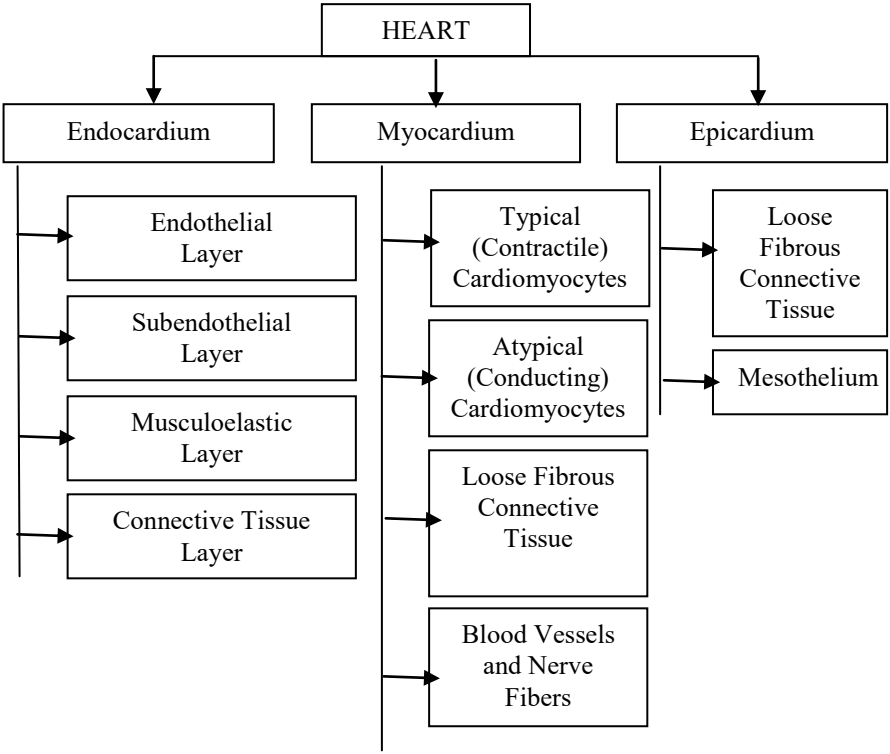

Fig. 1.13. Schematic diagram of the heart [293].

The inner lining covers the inside of the heart chambers, covering the fleshy septa, papillary muscles, tendinous cords, and valves. The main mass of the heart chambers is made up of the myocardium. It is formed by cardiac muscle cells – cardiomyocytes, which are connected by intercalated discs (Fig. 1.14, 1.15). The epicardium covers the muscular membrane (myocardium) externally and is the visceral layer of the serous

pericardium. In terms of structure, the outer membrane of the heart (epicardium) is similar to serous membranes, the surface of which is covered with mesothelium, and the subserous layer is tightly fused with the myocardium [167, 348, 609, 593].

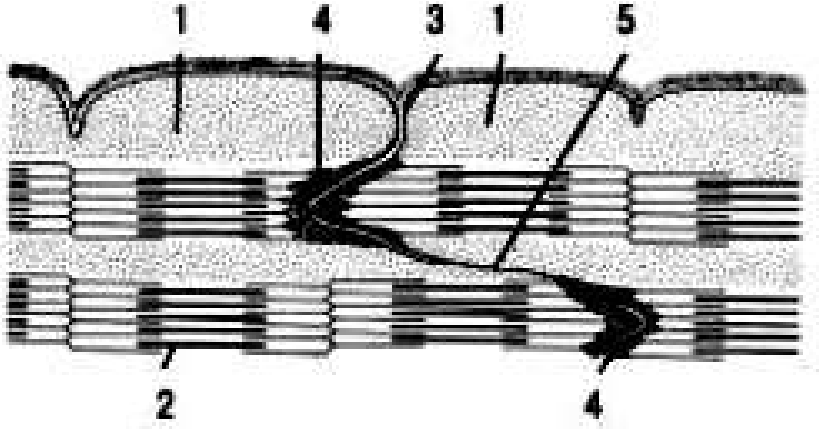

Fig. 1.14. Diagram of the structure of the intercalated disc. 1 – cardiac myocytes; 2 – myofibrils; 3 – intercalated disc; 4 – section of intercalated disc with desmosome-like contacts; 5 – section of intercalated disc with gap contacts [125].

The thickness of the atrial wall is significantly less than that of the ventricular wall. Among the membranes of the mammalian heart wall, the myocardium is the most developed, especially in the left ventricle, where it is almost three times thicker than in the right. The myocardium consists of a single array of muscle fibers oriented in three directions: subepicardial fibers are longitudinal, middle fibers are circular, and subendocardial fibers are also longitudinal. Muscle fibers consist of cells – cardiac myocytes (cardiomyocytes) (Fig. 1.16), which have a rectangular shape in longitudinal section. Between the muscle fibers are layers of

connective tissue. It contains a large number of blood and lymphatic vessels [25, 294, 262, 504].

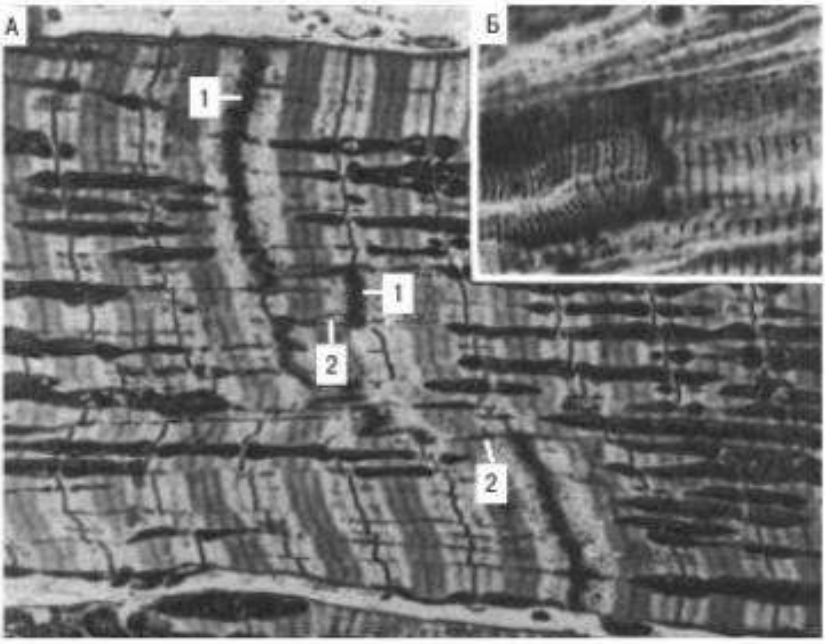

Fig. 1.15. Ultrastructure of the intercalated disc (TEM). 1 – areas of the intercalated disc located across the axis of myocytes; 2 – areas of the intercalated disc located along the axis of myocytes [125].

Each biological species, including humans, is characterized by a certain number of heart muscle fibers–ardiomyocytes–hich is determined by the evolutionary, physiological, and morphometric characteristics of the organism. Thus, the number of cardiomyocytes in the human heart is 1,000 times greater than in the heart of a rat, 100 times greater than in a rabbit, and 10 times greater than in a dog. On the one hand, a larger number of muscle cells provides a higher pumping capacity of the heart, which is necessary to maintain blood circulation in organisms with a large

body mass. On the other hand, an increase in the mass and number of cardiomyocytes reduces the structural strength of the heart wall, which in turn increases the risk of mechanical damage or rupture, especially in conditions of pathological overload or ischemia.

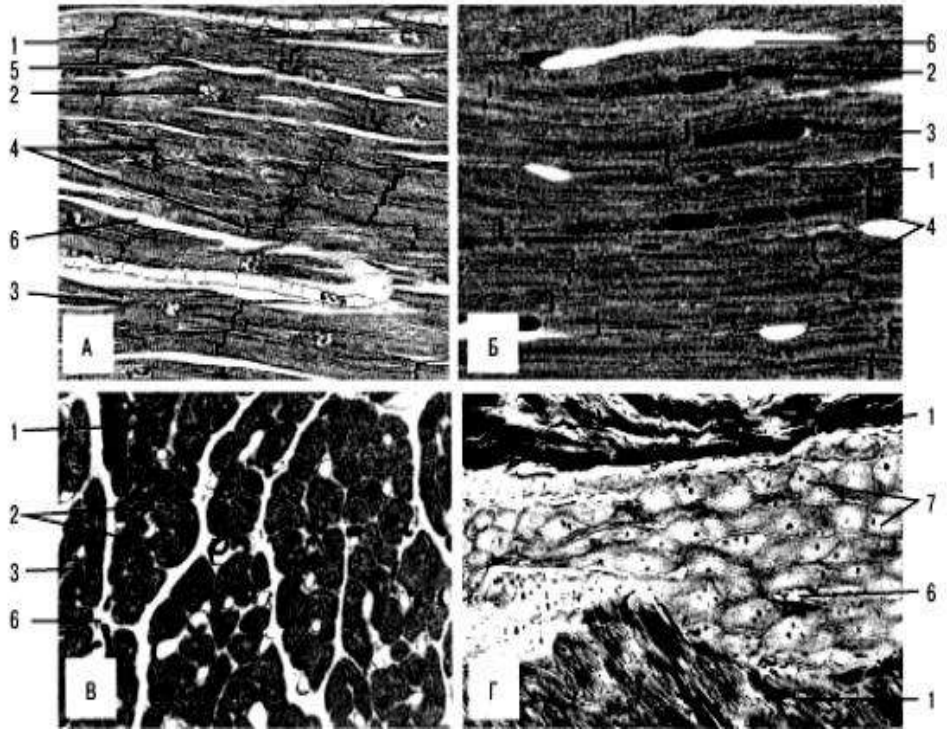

Fig. 1.16. Myocytes of cardiac muscle tissue. Contractile: A – diagram; B – longitudinal section (CM); C – transverse section (CM); D – conductive (CM). 1 – contractile cardiac myocytes; 2 – nucleus; 3 – sarcoplasm; 4 – intercalated discs; 5 – anastomoses; 6 – endomysium; 7 – conductive cardiac myocytes [125].

Recent studies have significantly expanded our understanding of the microstructure and functional properties of cardiomyocytes [272, 271, 136, 619, 625, 152, 195]. It has been

established that these cells are not only responsible for generating contractions, but also participate in complex signaling cascades that coordinate the activity of the heart as a single functional organ. However, a number of important questions remain open, in particular: how exactly is the activity of individual cardiomyocytes coordinated within the whole organ; how does this coordination change under conditions of physiological regulation, physical exertion, or aging; and how it is disrupted by pathological factors such as ischemia, hypoxia, intoxication, autoimmune processes, etc. [412, 666, 667, 728].

According to most modern researchers, the heart muscle of mammals is formed by cardiac myocytes (cardiomyocytes): contractile (typical), conductive (atypical), and secretory cardiomyocytes. The latter are found mainly in the atria and are also called myoendocrine cells or myoendocrinocytes [5, 603, 670].

The main part of the myocardium is formed by contractile cardiomyocytes, which provide the working effect (increase pressure in the heart cavity and move blood). In the ventricles of the heart, they are predominantly cylindrical in shape. Such cells contain 1–2 nuclei, which are located in the central part of the sarcoplasm and on its periphery – myofibrils [398, 399].

The nuclei of cardiomyocytes are elongated or oval in shape. The average volume of nuclei in farm animals varies. The highest value is found in cattle (126.85 ± 8.58 μm^3), followed by horses (105.75 ± 8.4 μm^3) and the smallest in pigs (62.98 ± 1.25 μm^3) and sheep (59.35 ± 4.76 μm^3) [228].

In the myocardium of the atria, the shape of contractile cardiomyocytes is elongated. Contractile cardiomyocytes contact each other via intercalated discs [354, 358, 491, 502, 503, 525, 570, 661, 124, 520].

Contractile cardiomyocytes have pronounced longitudinal (due to the presence of myofibrils) and transverse (due to the presence of actin and myosin proteins) striations. Concentrated bundles of myofibrils, which are tightly adjacent to each other, are located closer to the periphery. They pass from one fiber to another through anastomoses. With a relatively small number of myofibrils, the longitudinal striations of muscle tissue are quite pronounced, while the transverse striations are relatively weak. When staining the myocardium with hematoxylin and eosin, large-diameter muscle fibers in transverse and longitudinal sections do not take up the stain well, transverse striation in them is indistinct, and myofibrils become refined. Small-diameter muscle fibers on the transverse section are oval in shape. Myofibrils in them are densely located [228].

The diameter of cardiomyocytes in different layers of the heart muscle ranges from 15 to 20 μm. They vary in length and thickness. The thickness of myocardial muscle fibers in sheep and horses is 9.19±0.71 μm and 9.87±1.1 μm, respectively, while in cattle (13.2±0.36 μm) and pigs (12.23±0.12 μm) this indicator increases [228].

According to M.S. Gnatyuk (1915–1917), the diameters of atrial cardiomyocytes are smaller than those of ventricular cardiomyocytes: in the left and right atria – 5–30 μm (modal class – 15 μm), in the left and right ventricles – 10–45 μm (modal class – 25 μm). The length of cardiac myocytes ranges from 50 to 120 μm: in the left and right ventricles – 60–120 μm (modal class 90 μm), in the right and left atria – 70–90 μm (modal class – 100 μm) [274, 272, 271, 278].

The activity of pacemaker (atypical) cardiomyocytes is associated with excitation in the heart and its conduction through the tissue. Their structure is similar to that of contractile cardiomyocytes, but they are larger in size, contain eccentrically

located nuclei, and have few myofibrils that do not have a specific orientation. Therefore, the striation of conducting cardiomyocytes is poorly reflected or completely absent. Conducting cardiomyocytes form the conduction system of the heart [25, 277, 276, 467].

Conducting cardiomyocytes are divided into three types: P-cells, transitional cells, and Purkinje cells.

P-cells are filamentous structures with large nuclei. Such cells are located mainly in the sinoatrial node of the cardiac conduction system and in the interatrial conduction pathways. P cells are usually the main source of impulses that ensure rhythmic heart contraction.

Transitional cells are structures that occupy an intermediate position between P cells and contractile cardiomyocytes. Such cells are located mainly in the sinoatrial and atrioventricular nodes, and they are also found in the areas of the atria adjacent to these nodes [1, 221, 530, 604].

Purkinje cells are mainly located in the atrioventricular bundle (His bundle). It should be noted that these cells are numerically dominant in the His bundle and its left and right legs. Purkinje cells are also found at the periphery of the sinoatrial and atrioventricular nodes [66, 116, 169, 319, 432, 532, 730].

Secretory cardiomyocytes, which are located mainly in the atria, especially in their auricles, have a developed synthetic apparatus [590, 220, 390, 438, 578, 637, 703]. The cytoplasm of myoendocrine cells contains dense granules that contain a hormone. The latter is called atrial natriuretic factor or natriuretic hormone [40, 154, 192]. The natriuretic hormone is a peptide that, when released into the blood, travels to the kidneys, adrenal glands, and brain. This hormone increases diuresis, especially natriuresis, and relaxation of arterial vessels [70, 305]. As a result of the expansion of the arterial vessels, blood pressure decreases.

1.5. Conclusion from the literature review

Analysis of scientific sources shows that the formation of the morphological structure of the heart in vertebrates has a clearly evolutionary character and reflects the gradual complication of its structure in accordance with the growth of the level of organization of the organism and functional needs. Changes in the ratio of myocardial layers, features of the development of the valve apparatus and the cardiac conduction system are the result of adaptation to different types of blood circulation, levels of motor activity, and metabolic processes. At the same time, a number of aspects of heart morphogenesis, in particular, the species-specific features of its structural organization and their connection with functional parameters, remain insufficiently studied, which determines the relevance of further morphological research.

During embryogenesis in representatives of different classes of vertebrates, the heart in the early stages of embryonic development in representatives of different classes of vertebrates has the appearance of a simple cardiac tube, in which the atrial and ventricular sections are not yet differentiated. During cardiogenesis, there is a gradual flattening of the endothelial cells, as well as active growth of the connective tissue elements of the subendothelial layer of the endocardium, particularly in areas where the heart valves are formed.

As it develops, the heart wall becomes thicker due to the proliferation of myocytes. Trabecularization processes begin in the myocardium – the formation of muscle strands separated by cavities. This leads to the formation of two layers: the outer (subepicardial) layer, which is formed by densely packed cardiomyocytes, and the inner (trabecular) layer, which has a

spongy structure. The process of trabecularization occurs primarily in the ventricles and later in the atria.

In fish and reptiles, the development of the trabecular layer of the myocardium prevails, which ensures effective hemodynamics while maintaining a simple heart structure. In mammals, on the contrary, there is an increased growth of the compact layer, into which blood vessels grow in later stages of ontogenesis, improving the vascularization of the heart muscle and the functional capacity of the heart under conditions of high metabolic activity [334, 417, 569].

CHAPTER II

SELECTION OF RESEARCH DIRECTIONS, MATERIALS, AND METHODS OF THE STUDY

2.1. Selection of Research Directions

The organism of mammals is a highly organized, complex biological system that has developed over a long period of phylogenetic development in close interaction with environmental factors and under the influence of natural selection [287, 400, 58, 68, 403, 435, 704]. Evolutionary adaptation to different living conditions has contributed to the improvement of the morphofunctional organization of all organs and systems [48, 736, 59, 34, 151].

The functional systems of mammals – nervous, cardiovascular, immune, respiratory, digestive, excretory, endocrine, sensory (sense organs), reproductive – are interconnected, forming a single integrated system of vital activity of the organism. Their coordination ensures the maintenance of homeostasis, adaptive responses to external stimuli, as well as physiological processes of growth, development, and reproduction [267, 7, 690].

The complexity of the morphological organization of the mammalian organism was accompanied by the formation of a multilevel system of regulation of vital processes, combining morphological, physiological, and biochemical mechanisms. Such integration of structural and functional components ensures the coordination of organs and systems, maintenance of homeostasis, and implementation of adaptive responses of the organism in response to external and internal environmental factors.

The functional reliability of the mammalian organism is based on the complex interaction of regulatory systems, among which the nervous, endocrine, and immune systems play a leading role in the fine coordination of physiological processes. In the course of evolution, such coordination has contributed to the formation of highly specialized morphological structures and regulatory mechanisms that ensure the effective functioning of the organism in various environmental conditions.

Therefore, the study of individual organs and systems requires their consideration not only as autonomous structures, but also as interconnected elements of a holistic biological organism, the functioning of which is determined by a complex set of structural and functional relationships. This approach allows for a deeper understanding of the patterns of morphogenesis, functional specialization, and adaptive capabilities of organs and systems, which is important for substantiating the directions of modern morphological and physiological research.

In view of this, the choice of areas of scientific research in the anatomical and physiological aspect should be based on an understanding of the systemic organization of the animal organism, the morphological prerequisites for the functioning of organs and systems, as well as the role of external and internal factors in regulating their activity. This approach involves a comprehensive analysis of the relationship between structure and function, which allows for an objective assessment of the patterns of development and adaptation of the organism.

An important place among the vital regulatory mechanisms is occupied by blood circulation, which ensures the transport of oxygen, nutrients and biologically active substances, hormones, and metabolic products. The functioning of the heart and blood vessels determines the efficiency of metabolic processes, the maintenance of homeostasis, the implementation of adaptive

responses, and participation in thermoregulatory mechanisms. The morphological features of these structures reflect the level of organization of the organism, the intensity of physiological loads, and the specifics of living conditions, which determines their special scientific significance in modern morphological studies.

In this context, it is important to conduct a comprehensive morphological study of the heart and blood vessels at different stages of ontogenesis, compare the structural features of representatives of different systematic groups of mammals, and study phylogenetic changes in the structure of the cardiovascular system caused by the specifics of the environment and physiological stress.

An important area of human and veterinary medicine is the prevention, diagnosis, and treatment of infectious and non-infectious diseases, which cannot be carried out without in-depth study of the human and animal body at the macro- and microscopic levels, in particular the organs of the cardiovascular system [552, 153]. Macroscopic examination of anatomical structures allows the detection of external pathological changes, such as: hypertrophy or atrophy of organs; developmental abnormalities or traumatic injuries; the presence of neoplasms or necrotic processes [207, 521, 547, 88, 243, 658, 80, 333, 631, 490, 644]. Microscopic examination of tissues and cells allows the diagnosis of inflammatory processes, such as myocarditis or vasculitis; degenerative changes, including fibrosis and fatty degeneration; infectious lesions caused by bacteria, viruses, or parasites [596, 174, 684, 713, 712, 191, 94, 312, 17, 374]. These studies provide a comprehensive approach to the analysis of structural changes underlying pathological processes.

Therefore, the study of the macro- and microscopic structure of organs and systems of the body, including the cardiovascular system, which ensures all vital functions of the body in normal

conditions, is particularly relevant. Morphological indicators often serve as criteria for the early detection of pathological changes, allowing for the timely application of appropriate therapeutic or preventive measures [97, 138, 240, 281]. This is no coincidence, because in the context of modern lifestyles, cardiovascular diseases have become epidemic, ranking among the leading causes of mortality in both humans and domestic and productive animals [15, 158, 162].

In addition, the results of morphological studies can be used to improve clinical diagnosis, substantiate the pathogenetic mechanisms of disease development, and develop effective treatment methods. Of particular importance are comparative morphological studies of the heart and blood vessels of different animal species, which allow us to identify species-specific features of structure, adaptive mechanisms, and patterns of pathological processes. Such knowledge is necessary for the professional competence of veterinarians and biomedical specialists, as well as for ensuring an effective animal and human health care system.

2.2. Materials and methods used in the work

The work is part of the complex topics of the research project “Development, morphology, and histochemistry of animal organs in normal and pathological conditions,” state registration No. 0120U100796, and “Features of the morphology of the heart of domestic mammals,” state registration No. 0121U108884.

Animals for the study were selected according to the principle of analogues, taking into account breed and age characteristics: a total of 30 animals of six species belonging to the class Mammalia were used: Orictolagus cunicalus L., 1758 – European rabbit; Canis familiaris L., 1759 – domestic dog; Sus

scrofa, forma domestica L., 1758 – domestic pig; Ovis aries L., 1758 – domestic sheep; Bos Taurus L., 1758 – domestic cattle; Equus ferus Caballus L., 1758 – domestic horse.

Anatomical, histological, morphometric, and statistical methods were used to conduct the study.

Fresh hearts were subjected to anatomical dissection, selected from clinically healthy, sexually mature animals (rabbits, pigs, sheep, cattle, horses) that had just been slaughtered at a meat processing plant (n = 5 in each group), as well as from dogs that died as a result of life-threatening injuries and had no pathological changes in the cardiovascular system according to the results of pathomorphological examination.

Immediately after removal, the heart samples were washed with saline and fixed in 10% neutral formalin for further histological processing. Morphometric measurements were performed using an electronic caliper and digital microscopy, which allowed us to establish quantitative indicators of the structural features of the heart.

All procedures complied with bioethics standards and were approved by the local ethics committee of the institution where the study was conducted.

During the research, the general rules of good laboratory practice (GLP) (1981) and the provisions of the "General Ethical Principles of Animal Experiments" adopted by the First National Congress on Bioethics (Kyiv, 2001) were followed. The entire experimental part of the study was conducted in accordance with the requirements of the international principles of the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (Strasbourg, 1986) and the Rules for Conducting Work with Experimental Animals, approved by Order of the Ministry of Health No. 281 of November 1, 2000, "On measures to further improve the

organizational forms of work with experimental animals" and the relevant Law of Ukraine "On the protection of animals from cruel treatment" (No. 3447-IV of February 21, 2006, Kyiv) [137, 212, 376, 439, 506, 509].

The study has been preliminarily agreed upon and approved by the relevant bioethical review committee of the higher education institution that trains specialists in the field of veterinary medicine. The protocol of experimental studies complies with the regulatory and legal requirements for the protection of animals, their conditions of keeping, and ethical treatment for scientific purposes.

For macroscopic studies and organometric analysis, the heart was dissected from the chest cavity of animals together with the pericardium. During organometric examination, linear parameters and absolute and relative mass of the heart and its macrostructures were determined [605, 666, 667]. At the same time, the following morphometric indicators were taken into account in the quantitative macroscopic examination of the heart: heart height (HH); heart width (HW), heart circumference (HC); net heart mass (NHM) – heart mass without epicardial fat; absolute heart mass (AHM); relative heart mass (RHM); absolute mass of the left ventricle (AMLV); absolute mass of the right ventricle (AMRV) – the mass of the ventricle proportional to the mass of the interventricular septum; absolute mass of the left atrium (AMLA); absolute mass of the right atrium (AMA), relative mass of the left ventricle (RLMV); relative mass of the right ventricle (RRMV); relative mass of the left atrium (RLMA); relative mass of the right atrium (RRMA); atrial-ventricular index (AVI) – the ratio of the absolute mass of the atria to the absolute mass of the ventricles; ventricular-cardiac index (VCI) – the ratio of the mass of the ventricles to the net mass of the heart; atrial-cardiac index (ACI) – the ratio of the mass of the atria to the net

mass of the heart; right ventricular wall thickness (RVWT); left ventricular wall thickness (LVWT); left atrial wall thickness (LAWT); right atrial wall thickness (RAWT).

The absolute mass of the heart, its ventricles, and atria was determined by weighing. The relative mass of the heart (RM) was calculated using the formula:

$$RM = \frac{AM}{BM} * 100\%,$$

where: AM – is the absolute mass (AM) of the heart;

BM – is the body mass of the animal.

The linear parameters of the organ (length, width, and thickness) were determined by direct measurement.

The heart development index (HDI) was calculated as the ratio of its total length to its width using the following formula:

$$HDI = \frac{LS}{WS} * 100,$$

where: LS – length of the heart;

WS – width of the heart.

For microscopic studies, standard methods of fixation and preparation of histological sections were used [226].

To do this, pieces of material 0.2–0.3 cm thick were cut from the side walls of the left and right atria, left and right ventricles, and interventricular septum, which were fixed in a cooled 10–12% aqueous solution of neutral formalin (for staining with hematoxylin and eosin and using the Van Gieson method) for 24 hours or more, and in a Zanker-formol fixative (for staining using the Haigh method) for 8 to 24 hours (at room temperature or for 4–6 hours (in a thermostat at $+37^0$C).

After fixation and washing of the corresponding pieces of material, they were passed through alcohols of increasing strength (40º, 60º, 70º, 80º, 96º, and 100º) and xylene and poured into paraffin blocks according to the schemes proposed in the manual by L. P. Goralsky, V. T. Khomych, and O. I. Kononsky [226]. Histological sections 6–8 μm thick were made from the paraffin blocks using an MS-2 microtome [226].

To study the morphology of heart cells and tissues and conduct morphometric studies, histological sections, after deparaffinization, were stained with hematoxylin (Diapath, Italy, 2020) and eosin (LeicaGeosystems, Germany, 2020), using the Van -Gison method and the Heidenhain method, which is specific for staining transversely striated muscle tissue and allows the detection of contact sites (insertion discs) between cardiomyocytes, enabling clear differentiation of cardiomyocytes in the structure of muscle fibers [226].

Stained histological sections were used to obtain overview preparations and conduct histometric studies. The qualitative characteristics of tissue components at the microscopic level and histometric studies of structural elements of the myocardium (measurements of the length and width of cardiomyocytes, the volume of their nuclei) were performed under light microscopy using Micros and MBS-10 light microscopes with a fixed tube length, at low and high magnification, in accordance with the recommendations set out in the manual by Goralsky, V. T. Khomych, O. I. Kononsky [226].

The volume of cardiomyocytes was determined using the formula: $V = \pi \times A \times (B/2)^2$,

where: V is the volume of the cardiomyocyte;

π is 3.14;

A is the length of the cardiomyocyte;

B is the width of the cardiomyocyte.

The volume of cardiomyocyte nuclei was determined using the formula:

$$V = \frac{\pi}{6} * A * B^2$$

where: V is the volume of the nucleus;
π is 3.14;
A is the length of the nucleus;
B is the width of the nucleus.

The nuclear-cytoplasmic ratio was determined using the following formula:

$$NCR = \frac{\text{core volume}}{\text{core volume} - \text{cell volume}}$$

Photography of histological preparations was performed using a CAM V–200 video camera (InterMed, PRC, 2017) mounted in the tube of a Micros MC-50 microscope.

Morphological terms for structural parts of the heart are given in accordance with the International Veterinary Histological Nomenclature (Terminology Dictionary) [318] and the International Veterinary Anatomical Nomenclature [317].

The digital material was processed using variational-statistical methods on a personal computer using the licensed program Statystica 6.0 for Windows XP. The arithmetic mean (M), statistical error of the arithmetic mean (m), standard deviation (s), indicator of significant difference between the arithmetic means of two variation series according to the

reliability criterion (td), and Student's tables were determined. The difference between two values was considered significant at $p \leq 0.05$; 0.01; 0.001 [226].

CHAPTER III

RESULTS OF ORIGINAL RESEARCH

3.1. Morphology of the Heart in Domestic Mammals

3.1.1. Morphology of the Rabbit Heart (*Oryctolagus cuniculus L.,* 1758)

The rabbit (Oryctolagus cuniculus L., 1758) is a common laboratory animal widely used in biomedical, toxicological, physiological, and morphological studies. Due to its anatomical and physiological characteristics, it serves as a convenient model for studying the cardiovascular system. Knowledge of the detailed morphology of the rabbit heart is important not only for fundamental science but also for veterinary medicine, particularly in the diagnosis and treatment of cardiovascular diseases in both pet and farmed rabbits.

Knowledge of the detailed morphology of the rabbit heart is of great importance not only for fundamental science but also for veterinary medicine, particularly in the diagnosis and treatment of cardiovascular disorders in pet and farm rabbits. At the same time, morphological studies of the heart of this species allow us to deepen our understanding of the general patterns of myocardial structural organisation, inter-chamber relationships and morphofunctional adaptations in mammals. This makes the rabbit a valuable biological model for comparative anatomical studies and the extrapolation of the results obtained to other animal species.

Thus, the rabbit is not only a convenient experimental model, but also an important subject for in-depth study of the morphofunctional patterns of cardiac organisation in mammals.

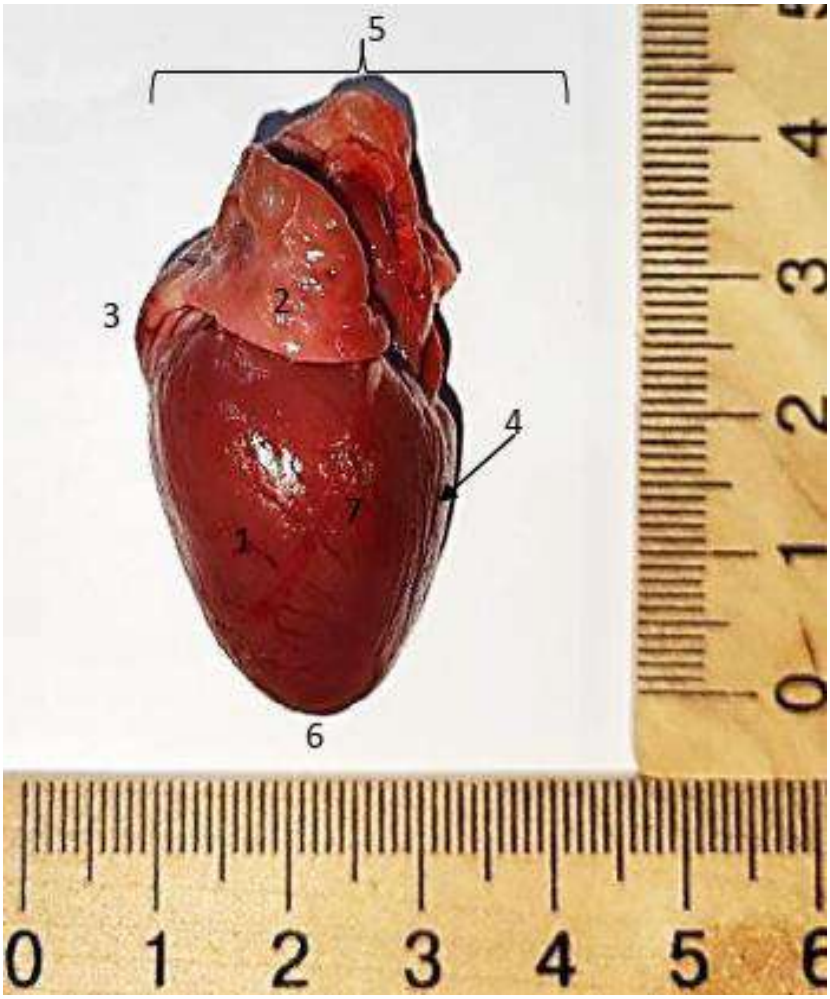

Fig. 3.17. Macroscopic structure of the heart of a sexually mature rabbit: 1 – left ventricle; 2 – left auricle; 3 – left atrium; 4 – paraconal interventricular groove; 5 – base of the heart; 6 – apex of the heart; 7 – left coronary artery. Macroscopic specimen.

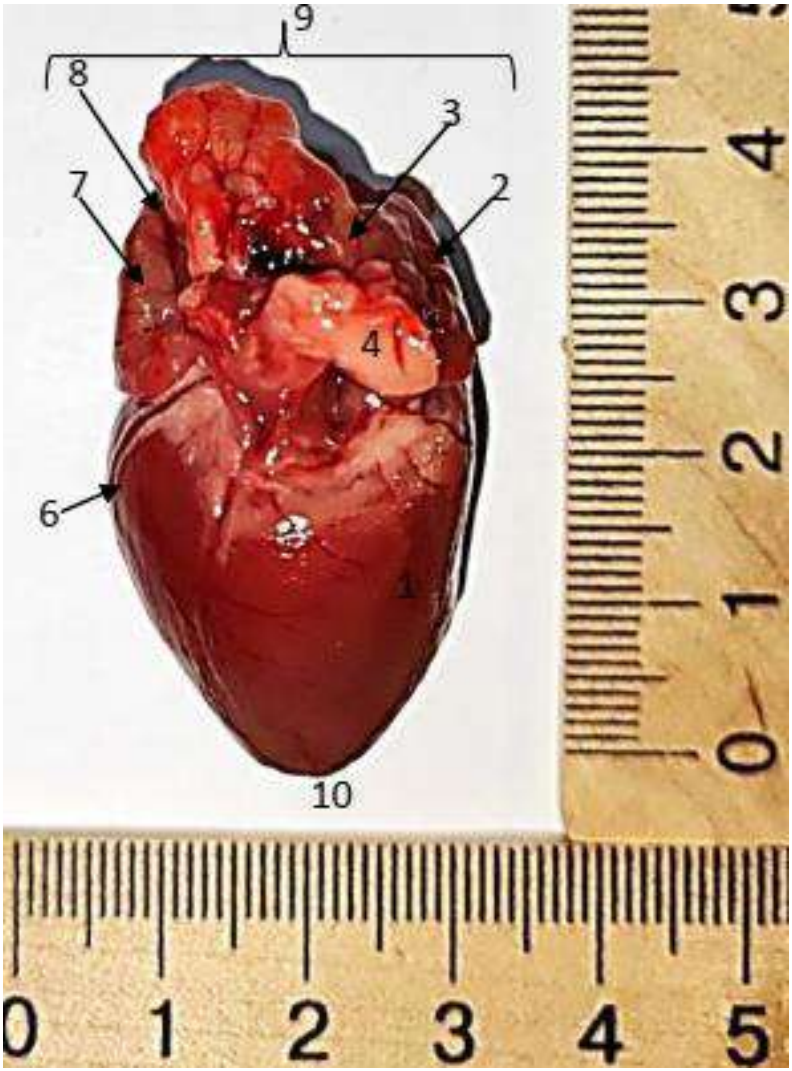

Fig. 3.18. Macroscopic structure of the heart of a sexually mature rabbit: 1 – right ventricle; 2 – right auricle; 3 – right atrium; 4 – aorta; 5 – subsinuosal interventricular groove; 6 – left ventricle; 7 – left auricle; 8 – left atrium; 9 – base of the heart; 10 – apex of the heart. Macroscopic specimen.

The rabbit heart (Figs. 3.17; 3.18) is located in the thoracic cavity within the mediastinum (the space bounded by the pleural layers of the central mediastinum) and is slightly shifted to the left side. Compared to other domestic mammalian species, the rabbit heart is relatively underdeveloped; it has a more oval, elongated-constricted shape, is somewhat flattened, and features a blunt apex. The groove separating the atria from the ventricles is poorly expressed (Figs. 3.17; 3.18).

The rabbit heart, as in all domestic mammals, consists of four chambers – two atria and two ventricles. Its cranial and caudal surfaces are continuous, with a faintly expressed groove on their surface separating the atria from the ventricles.

The right wall of the rabbit heart on the cranial surface is thin and flattened, whereas the left wall is thicker and more rounded. The apex of the heart is smoothly rounded. The auricles are well defined but relatively small in size.

Table 3.1

Linear parameters of the heart of a sexually mature rabbit (Oryctolagus cuniculus L., 1758), M ± m, n = 5

Parameter	Values
1. Heart height (cm)	3,5±0,04
2. Heart width (cm)	2,4±0,03
3. Heart thickness (cm)	1,6±0,02
4. Heart circumference (cm)	6,6±0,06
5. Heart development (shape) index (%)	145,8±4,16
6. Mean ventricular wall thickness (mm)	4,51±0,08
7. Left ventricular wall thickness (mm)	5,91±0,11
8. Right ventricular wall thickness (mm)	3,12±0,09
9. Mean atrial wall thickness (mm)	3,21±0,08
10. Left atrial wall thickness (mm)	3,82±0,04
11. Right atrial wall thickness (mm)	2,61±0,02

The absolute weight of the heart of a sexually mature rabbit, according to our research, is 10.3 ± 0.86 g, the net weight (without epicardial fat) is 9.7 ± 0.82 g, and the relative weight is $0.31 \pm 0.008\%$. Linear measurements of the heart revealed a height of 3.5 ± 0.04 cm, width of 2.4 ± 0.03 cm, thickness of 1.6 ± 0.02 cm, and a circumference of 6.6 ± 0.06 cm (Tables 3.1, 3.2).

The heart development index of the California breed rabbit is $145.8 \pm 4.16\%$, classifying the heart as a broad-shortened type (Figs. 3.17; 3.18; Table 3.1).

The most developed morphological structures of the heart are the left and right ventricles, followed by the left and right atria, which directly correlate with their linear characteristics – wall thickness, absolute and relative mass, relative to the net heart weight (Tables 3.1; 3.2). The left ventricular wall thickness (5.91 ± 0.11 mm) is 1.9 times greater than that of the right ventricle (3.12 ± 0.09 mm; $p \leq 0.01$). The mean thickness of both ventricular walls is 4.51 ± 0.08 mm. The left atrial wall thickness is 3.82 ± 0.04 mm, while the right atrial wall thickness is 2.61 ± 0.02 mm. The mean thickness of both atrial walls is 3.21 ± 0.08 mm (Table 3.1).

According to these linear parameters and morphological components of the heart, the mean mass of the left atrium is 1.5 ± 0.14 g ($15.46 \pm 0.08\%$). The mean mass of the right atrium is 1.1 ± 0.11 g ($11.34 \pm 0.62\%$), which is significantly smaller ($p < 0.01$) by 1.36 times compared to the left atrium. Accordingly, the mean mass of both atria of the rabbit heart is 2.6 ± 0.33 g, representing $26.8 \pm 1.42\%$ of the mean heart mass without epicardial fat (Table 3.2).

The mass of the left ventricle of the rabbit heart is the largest, amounting to 4.6 ± 0.37 g ($47.42 \pm 2.76\%$). The mean mass of the right ventricle is intermediate relative to the left

ventricle and both atria, and is 2.5 ± 0.19 g ($25.77 \pm 1.28\%$). Accordingly, the mass of the right ventricle is significantly smaller ($p < 0.01$) by 1.84 times compared to the left ventricle. The mean mass of both ventricles is 7.1 ± 0.52 g, representing $73.19 \pm 3.92\%$ of the net heart weight (9.7 ± 0.82 g) (Table 3.2).

Based on these morphometric parameters, the combined mass of both ventricles of the rabbit heart is significantly greater ($p < 0.001$) by 2.7 times compared to the mean mass of both atria.

Table 3.2

Morphometry of the heart, ventricles, and atria of a sexually mature rabbit (Oryctolagus cuniculus L., 1758), M ± m, n = 5

Parameter	Absolute Mass (g)	Relative Mass (%)
1. Left atrium	1,5±0,14	15,46±0,88
2. Right atrium	1,1 ±0,11	11,34±0,62
3. Right and left atria (together)	2,6±0,33	26,8±1,42
4. Left ventricle	4,6±0,37	47,42±2,76
5. Right ventricle	2,5±0,19	25,77±1,28
6. Left and right ventricles (together)	7,1±0,52	73,19±3,92
7. Heart mass (without epicardial fat)	9,7±0,82	100
8. Ratio of ventricular mass to net heart mass	1:0,73	
9. Ratio of atrial mass to net heart mass	1:0,27	
10. Ratio of atrial mass to ventricular mass	1:0,37	

According to these parameters, the ratio of the mass of the ventricles of the hearts of sexually mature rabbits to the net heart mass is 1 : 0.73, the ratio of the mass of the atria to the net heart mass is 1 : 0.27, and the ratio of atrial mass to ventricular mass is 1 : 0.37 (Table 3.2).

The heart wall is composed of three layers: the inner layer – endocardium, the middle layer – myocardium, and the outer layer – epicardium. Each layer performs specific functions and possesses distinct morphological features, ensuring the structural integrity and functional activity of the heart as a single organ.

The endocardium, the innermost layer of the heart, is a thin connective tissue structure that lines the interior of the heart chambers, chordae tendineae, papillary muscles, and heart valves. Four layers can be distinguished within the endocardium: the endothelium (lining the endocardial surface), subendothelial layer, muscle-elastic layer, and outer connective tissue layer. It should be noted that the thickness and structure of the endocardium may vary slightly among the different heart chambers.

The outer layer of the heart (visceral layer of the pericardium – serous membrane) covers the myocardium externally. It is composed of fibrous connective tissue containing numerous collagen and elastic fibers, is covered by mesothelium, and contains blood vessels and nerves. In the outer layer, particularly near blood vessels, adipose cells are often present, forming fat tissue.

The myocardium, the middle layer of the heart, is the most developed layer, particularly in the left ventricle, where it is more than twice as thick as in the right ventricle (Table 3.1).

According to histological studies, the myocardium is composed of muscle cells – cardiomyocytes, which form a continuous mass of muscle fibers (Figs. 3.19; 3.20). When stained using Heidenhain's method, cardiomyocytes in longitudinal sections exhibit a rectangular shape, are clearly delineated by the sarcolemma, and contain sarcoplasm and nuclei. The sarcoplasm displays both transverse and longitudinal striations (Fig. 3.21). Layers of loose connective tissue are present between cardiomyocytes, containing blood vessels and nerves (Fig. 3.22).

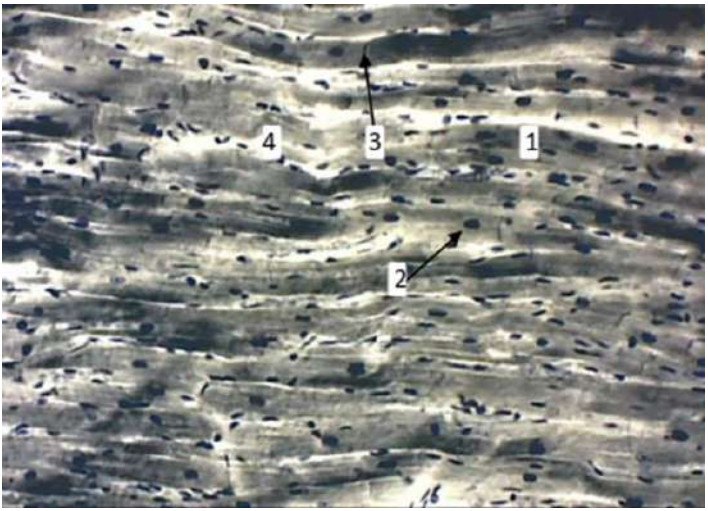

Fig. 3.19. Microscopic structure of the myocardium of the left ventricle of a sexually mature rabbit: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – intermuscular connective tissue. Heidenhain staining. ×120.

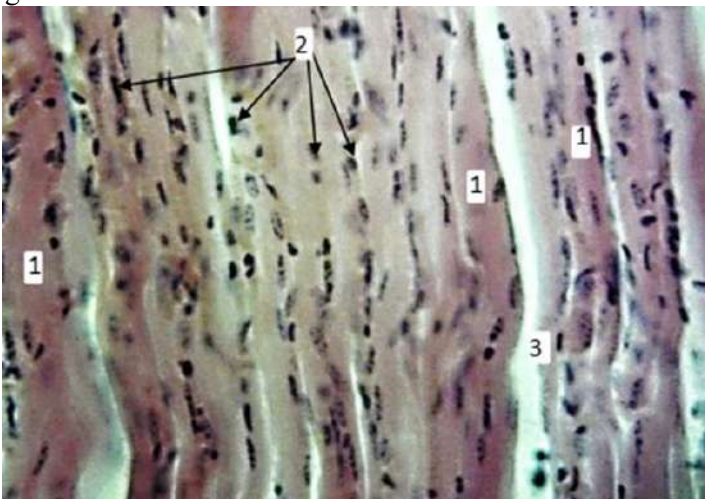

Fig. 3.20. Microscopic structure of the myocardium of the left ventricle of a sexually mature rabbit: 1 – muscle fibers; 2 – cardiomyocyte nuclei; 3 – intermuscular connective tissue. Hematoxylin and eosin staining. ×280.

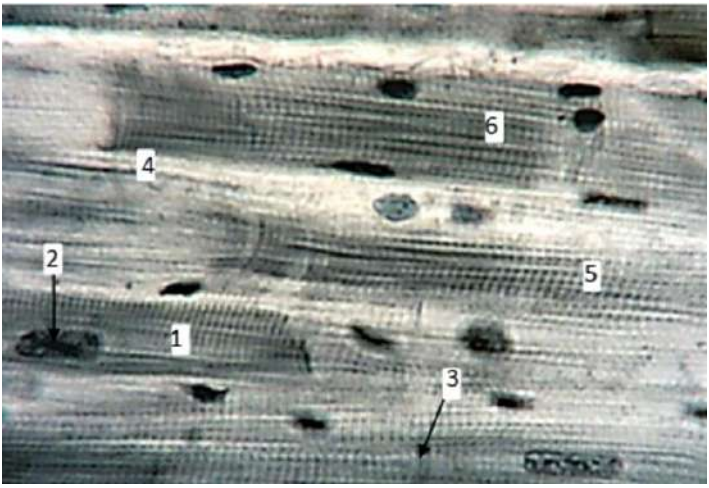

Fig. 3.21. Microscopic structure of the myocardium of the left ventricle of a sexually mature rabbit: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – intermuscular connective tissue; 5 – transverse striations; 6 – longitudinal striations. Heidenhain staining. ×600.

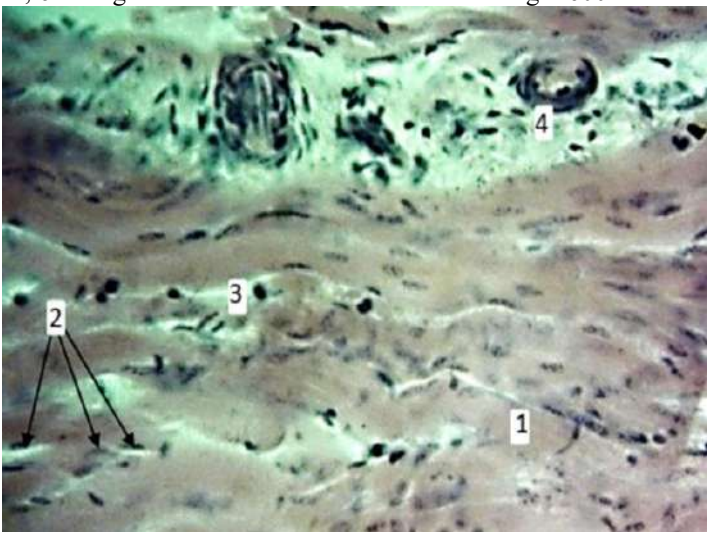

Fig. 3.22. Microscopic structure of the myocardium of the left ventricle of a sexually mature rabbit: 1 – muscle fibers; 2 – cardiomyocyte nuclei; 3 – intermuscular connective tissue; 4 – blood vessels. Hematoxylin and eosin staining. ×280.

The nuclei (one, rarely two) are located in the central part of the sarcoplasm and have an oval, rounded, or elongated (rod-shaped) form. The karyoplasm of cardiomyocytes in sexually mature rabbits contains well-defined nuclear chromatin, which is distributed in the form of small or larger granules throughout the karyoplasm (Fig. 3.23).

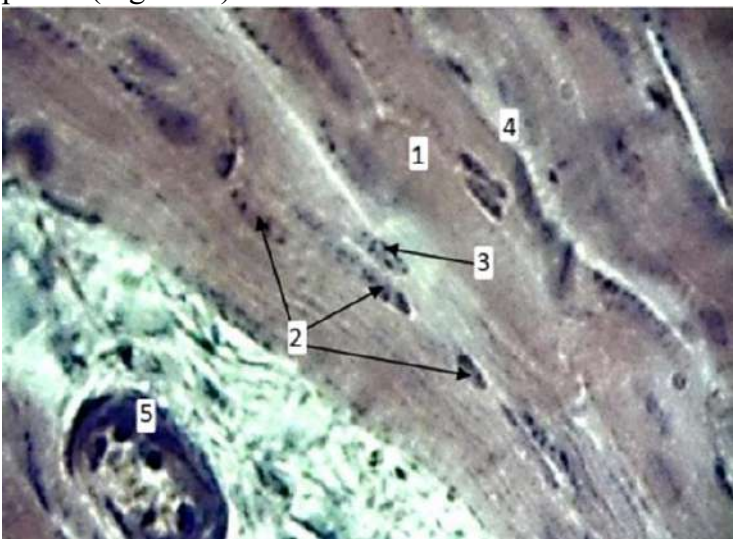

Fig. 3.23. Microscopic structure of the myocardium of the left ventricle of a sexually mature rabbit: 1 – muscle fibers; 2 – cardiomyocyte nuclei; 3 – nuclear chromatin; 4 – intermuscular connective tissue; 5 – blood vessel. Hematoxylin and eosin staining. ×600.

Cardiomyocytes vary in thickness and length. In rabbits, they are closely apposed to one another (Figs. 3.19; 3.20), while in some areas they are arranged in a slightly loose manner.

When stained with hematoxylin and eosin or using Heidenhain's method, the myocardial fibers formed by cardiomyocytes are stained predominantly uniformly. They contain a small number of myofibrils, which are concentrated closer to the fiber periphery. Their transverse striations are

pronounced; however, due to the limited number of myofibrils, the longitudinal and transverse striations of the muscle fibers are weakly expressed.

According to morphometric analysis, cardiomyocytes exhibit variable cytometric characteristics depending on their morphotopography (left ventricle, right ventricle, atria) and, consequently, their functional load. Quantitative values of cardiomyocytes in the left ventricular myocardium are significantly larger than those of the right ventricle: the mean length of left ventricular cardiomyocytes is significantly greater ($p \leq 0.05$) by 1.29 times compared to the right ventricle, measuring 56.14 ± 1.81 μm. Correspondingly, the width of left ventricular cardiomyocytes is 1.14 times larger ($p \leq 0.05$), measuring 8.02 ± 0.112 μm (Table 3.3).

Table 3.3

Histometry of cardiomyocytes in sexually mature rabbits (Oryctolagus cuniculus L., 1758), M ± m, n = 5

Parameter	Cardiomyocyte Length (μm)	Cardiomyocyte Width (μm)	Cardiomyocyte Volume (μm³)	Cardiomyocyte Nuclear Volume (μm³)	Nuclear-to-Cytoplasmic Ratio
Left ventricle	56,14± 1,81	8,02± 0,112	2834,59± 319,99	42,01± 3,12	0,0161± 0,0054
Right ventricle	43,64± 1,38*	7,04± 0,42*	1697,85± 239,06*	40,14± 3,93	0,0242± 0,0048*
Right and left atria	37,02± 1,26	5,92± 0,29	1018,47± 119,66	38,22± 3,98	0,0389± 0,0062

Note: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$ compared with the left ventricle.

Similar morphometric indicators are observed when calculating cardiomyocyte volumes: the largest volume was found for the left ventricle (2834.59±319.99 μm^3), the volume of cardiomyocytes in the right ventricle, compared to the left ventricle, is significantly ($p \leq 0.05$) smaller by 1.67 times and amounts to 1697.85±239.06 μm^3, respectively (Table 3.3; Fig. 3.24).

The volume of cardiomyocyte nuclei has similar values: the volume of the left ventricle nuclei is 42.01 ± 3.12 μm^3, and that of the right ventricle is 40.14 ± 3.93 (Table 3.3; Fig. 3.24).

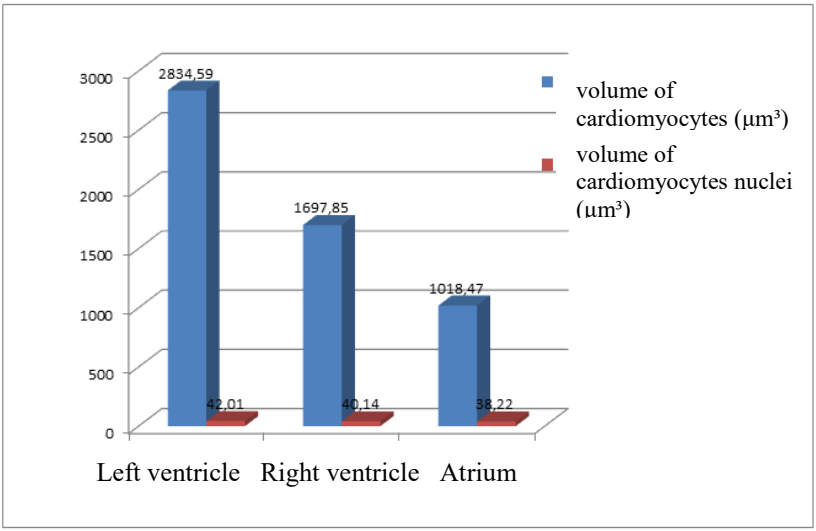

Fig. 3.24. Histometry of cardiomyocytes of the heart myocardium of a sexually mature rabbit.

The ambiguous cytometric parameters of cardiomyocyte volumes and their nuclei in the right and left ventricles (Fig. 3.25) that we have identified form different nuclear-cytoplasmic ratios in them: a lower nuclear-cytoplasmic ratio is characteristic of left ventricular cardiomyocytes (0.0161±0.0054) and significantly

(p≤0.05) 1.5 times higher for cardiomyocytes of the right ventricle (0.0242±0.0048), which indicates the functional activity of cardiomyocytes of the left ventricle.

The smallest cytometric values (length, width, volume) were found in atrial cardiomyocytes (Table 3.3). At the same time, the YCV of atrial cardiomyocytes relative to the left and right ventricles, respectively, was (p≤0.001) 2.42 and 1.62 times (p≤0.05) greater and equal to 0.0389±0.0062 (Table 3.3; Fig. 3.25).

Thus, we associate the ambiguous organometric, cytometric and karyometric characteristics of ventricular and atrial cardiomyocytes that we have identified with the functional activity of the heart: the atria receive blood returning to the heart from the body of animals, and the ventricles pump blood from the heart to the body, performing the greatest load.

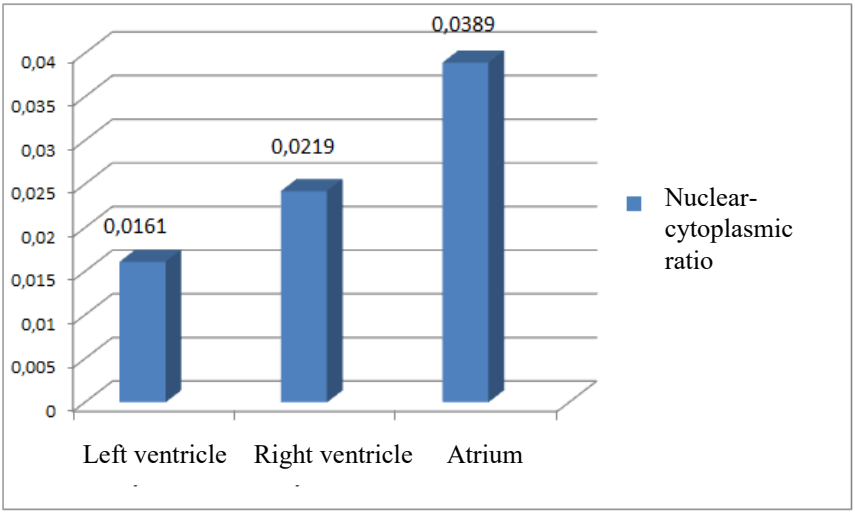

Fig. 3.25. Nuclear-cytoplasmic ratio of cardiomyocytes in the heart myocardium of a sexually mature rabbit.

3.1.2. Morphology of the Heart of a Domestic Dog (Canis lupus familiaris L., 1758)

The heart of a domestic dog, as a representative of the mammalian order, is characterised by a high degree of morphofunctional organisation, which ensures the efficient functioning of the cardiovascular system under conditions of constant warm-blooded metabolism and high metabolic activity. Its structure reflects the general principles of heart organisation in homeothermic animals, in particular the clear differentiation of the chambers, a well-developed valve apparatus and a complex conduction system, which ensures the rhythmicity and coordination of contractions.

The study of the anatomical structure of the heart in dogs is not only of fundamental importance for the comparative anatomy of mammals, but also has significant practical value in veterinary medicine, particularly for the diagnosis, treatment and surgical management of cardiac conditions. It also lays the groundwork for improving clinical examination methods and enhancing the effectiveness of therapeutic measures.

The morphological features of the heart in dogs demonstrate both general patterns common to most homeothermic animals and species-specific features associated with physiological adaptation to the level of motor activity, body size, blood flow intensity and trophic load on the myocardium.

The relevance of research into the morphology of the canine heart is also due to its widespread use in scientific experiments, clinical practice, and its role as a model organism for studying the cardiovascular system in normal and pathological conditions.

The heart in dogs (Fig. 3.26; 3.27) is located in the chest cavity between the lungs, occupying the space between the 3rd and 7th ribs and slightly shifted to the left of the median plane.

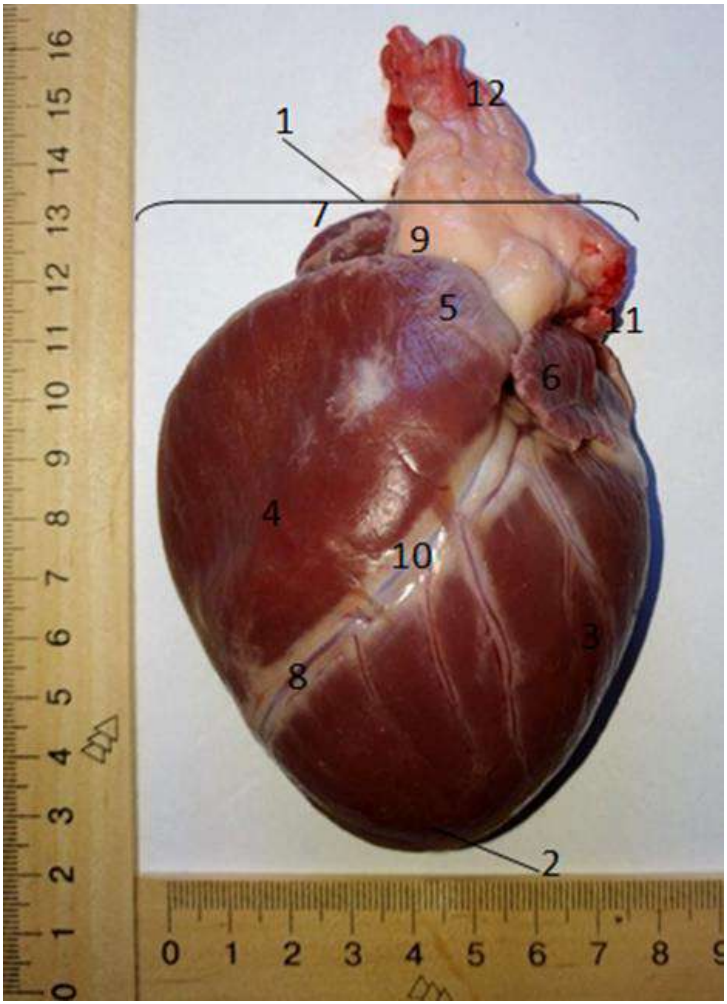

Fig. 3.26. Macroscopic structure of the heart of a sexually mature dog (projection of the heart from the left side): 1 – base of the heart; 2 – apex of the heart; 3 – right ventricle; 4 – left ventricle; 5 – left atrium; 6 – left atrial appendage; 7 – right atrial appendage; 8 – interventricular sulcus; 9 – subepicardial fat; 10 – blood vessels; 11 – pulmonary veins; 12 – aorta. Macro specimen.

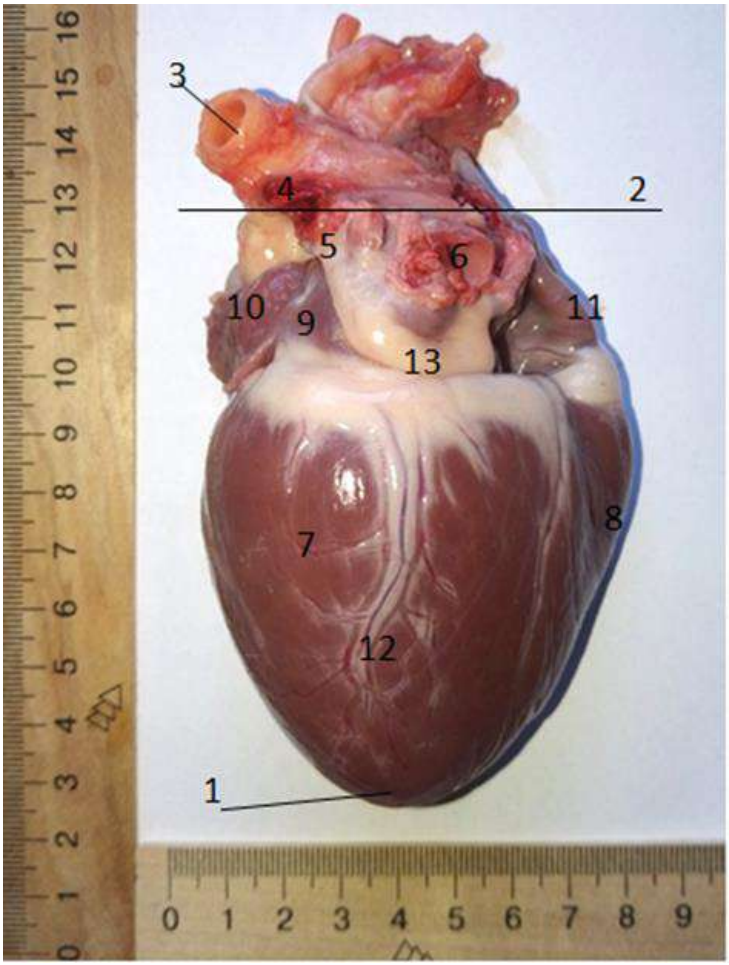

Fig. 3.27. Macroscopic structure of the heart of a sexually mature dog (projection of the heart from the right side): 1 – apex of the heart; 2 – base of the heart; 3 – aorta; 4 – pulmonary artery trunk; 5 – cranial vena cava; 6 – caudal vena cava; 7 – right ventricle; 8 – left ventricle; 9 – right atrium; 10 – right atrial appendage; 11 – left atrium; 12 – subcostal interventricular groove; 13 – subepicardial fat. Macro specimen.

The base of the heart is located at the level of the middle of the first rib, and the apex is in the area of the 6th–7th ribs. The aorta emerges from the left ventricle of the heart, behind the pulmonary trunk. Moving upward and dorsally toward the spine, it forms an arc at the level of the 11th thoracic vertebra.

Externally, the epicardium of the heart is smooth, moist, shiny, white-grey in colour, transparent, without any layers. A small amount of white-grey fat is noted, located mainly in the coronary sulcus and near the large vessels. The epicardium adheres tightly to the myocardium, forming a serous membrane that allows the heart to slide freely in the pericardial cavity during contractions.

The myocardium of the heart is elastic in consistency, pale red in colour, with a well-defined fibre pattern on the surface and on the cut.

The heart of dogs has an expanded base directed dorsocranially and a narrowed apex directed ventrocaually (Fig. 3.26; 3.27).

Table 3.4

Linear parameters of the heart of a sexually mature dog, (Canis lupus familiaris L., 1758), M ± m, n = 5

Parameter	Values
1. Heart height (cm)	11,09 ±0,04
2. Heart width (cm)	7,6±0,02
3. Heart thickness (cm)	4,8±0,01
4. Heart circumference (cm)	17,7±0,08
5. Heart development (shape) index (%)	145,9±6,56
6. Mean ventricular wall thickness (mm)	13,24±0,21
7. Left ventricular wall thickness (mm)	15,92±0,34
8. Right ventricular wall thickness (mm)	10,47±0,11
9. Mean atrial wall thickness (mm)	4,01±0,02
10. Left atrial wall thickness (mm)	4,37±0,08
11. Right atrial wall thickness (mm)	3,32±0,05

According to our research, the absolute weight of a dog's heart is 167.58±9.46 g, the relative weight is 0.72 ± 0.005 %, and the average weight of the heart without epicardial fat is 154.22±8.04 g. At the same time, the height of the heart is 11.09±0.04 cm, width – 7.6±0.02 cm, thickness – 4.8±0.01, circumference – 17.7±0.08 cm (Table 3.4). The heart development index is 145.9±6.56%. According to our analysis of the linear morphological measurements, the hearts of the sexually mature dogs we studied are more often rounded (elliptical) in shape, of the enlarged-shortened type (Fig. 3.26; 3.27).

According to the results of organometric studies, the mass of the left ventricle of the dog's heart is 76.24 ±1.02 g, and the mass of the right ventricle is 43.59±0.62 g. The average mass of both ventricles (right and left) is 120.26 ±1.98 g, and the mass of the atria is 33.77±0.48 g. At the same time, the ratio of the mass of the ventricles to the net mass of the heart is 1:0.78, respectively, the ratio of the mass of the atria to the net mass of the heart is 1:0.22, and the ratio of the mass of the atria to the mass of the ventricles is 1:0.28 (Table 3.5).

The thickness of the heart ventricle walls varies depending on their morphofunctional activity: the thickness of the left ventricle wall (15.92±0.34 mm) is 1.52 times ($p \leq 0.01$) greater (10.47±0.11 mm) than that of the right ventricle. The wall thickness of the atria is 4.01±0.02 mm (Table 3.5).

The wall of a dog's heart consists of three layers: the inner layer (endocardium), the middle layer (myocardium) and the outer layer (epicardium), of which the muscular layer is the most developed.

The myocardium of the atria consists of two layers: the outer layer, which is common to both atria, and the deep layer. The myocardium of the ventricles consists of five layers: the outer and inner layers, in which the muscle fibres are obliquely

longitudinal, then the outer and inner deeper layers and the deepest layer, whose muscle fibres are arranged in a figure-eight pattern. Due to this structure of the ventricular myocardium and its functional activity, its walls are significantly thicker than the walls of the atria.

The histoarchitectonics of the myocardium is formed by transversely striated muscle fibres, between which there is intermuscular connective tissue (Fig. 3.28). Myocardial muscle fibres vary in width (small, medium, large) and length, and they usually fit tightly together (Fig. 3.29).

Table 3.5

Morphometry of the heart, ventricles and atria of a sexually mature dog (Canis lupus familiaris L., 1758), M ± m, n = 5

Parameter	AM (g)	RM (%)
1. Left atrium	24,2±2,88	15,7±1,86
2. Right atrium	9,6±2,01	6,23±0,94
3. Right and left atria (together)	33,8±0,48	21,93±2,14
4. Left ventricle	76,2±1,02	49,45±2,86
5. Right ventricle	43,6±0,62	29,29±1,79
6. Left and right ventricles (together)	120,3±1,98	78,07±4,68
7. Heart mass (without epicardial fat)	154,1±8,04	100
8. Ratio of ventricular mass to net heart mass	1:0,78	
9. Ratio of atrial mass to net heart mass	1:0,21	
10. Ratio of atrial myocardium mass to ventricular myocardium mass	1:0,28	

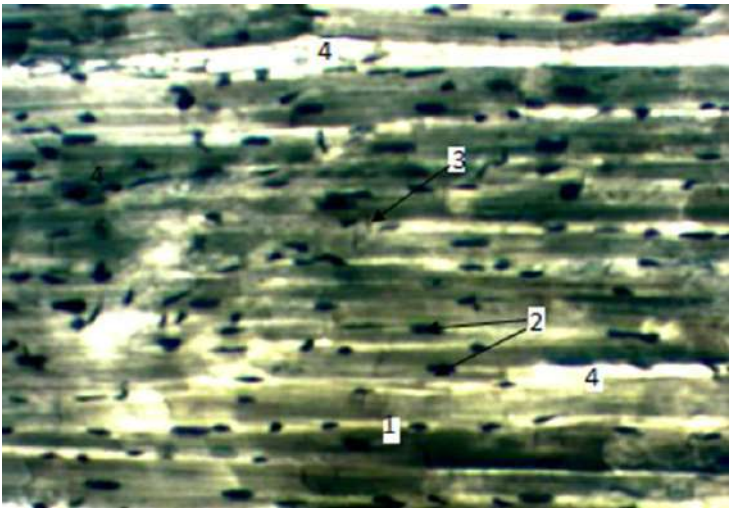

Fig. 3.28. Microscopic structure of the right ventricular myocardium of a sexually mature dog: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – intermuscular connective tissue. Notes: Stained using the Heidenhain method. X 280.

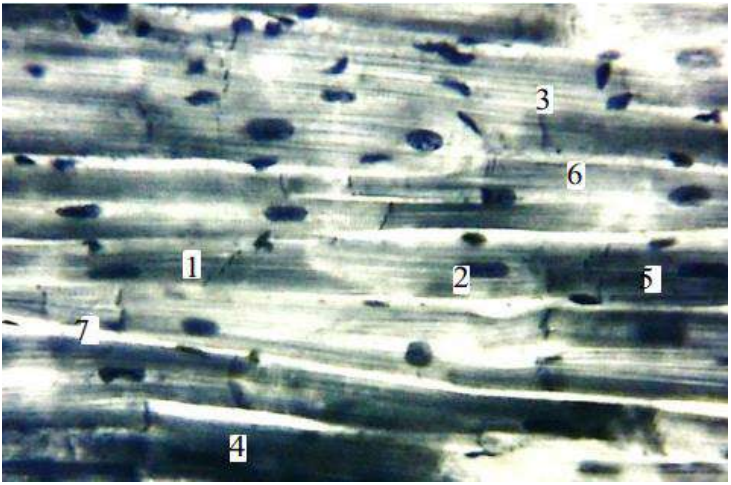

Fig. 3.29. Histological section of the left ventricular myocardium of a sexually mature dog: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – thick muscle fibre; 5 – medium-thickness muscle fibre; 6 – thin muscle fibre; 7 – intermuscular connective tissue. Stained using the Haugen method. X 600.

In certain areas, as seen in a longitudinal section, the fibres are interconnected by anastomoses to form a single morphofunctional system, which ensures the coordinated transmission of impulses and the coordination of myocardial contractions (Fig. 3.30).

The muscle fibres of the myocardium are formed by contractile myocytes – cardiomyocytes, which, when stained using the Heidenhain method, appear as dark transverse stripes (Fig. 3.31). In such cells, the sarcolemma, sarcoplasm and oval-shaped nuclei located in the central part of the cardiomyocytes are clearly differentiated. Transverse (Fig. 3.31) and longitudinal (Fig. 3.32) striations are clearly visible in the sarcoplasm of cardiomyocytes.

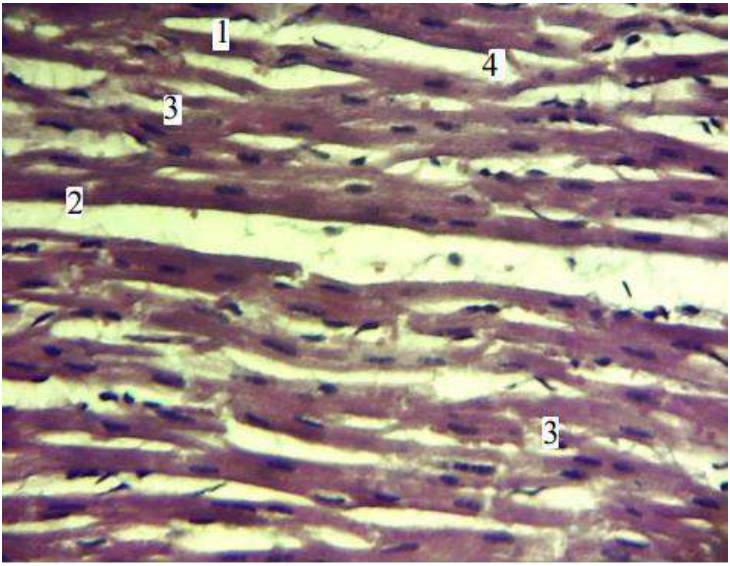

Fig. 3.30. Microscopic structure of the right ventricular myocardium of a sexually mature dog: 1 – muscle fibres; 2 – intermuscular connective tissue; 3 – cardiomyocyte nuclei; 4 – anastomoses. Haematoxylin and eosin. X 120.

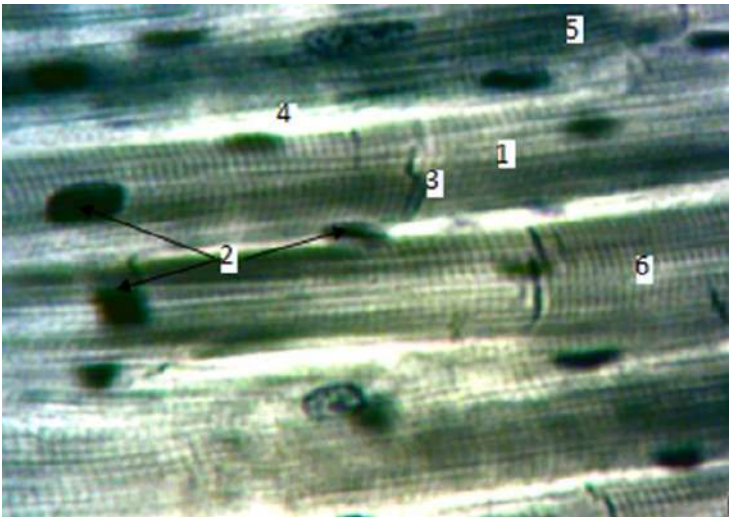

Fig. 3.31. Histological section of the left ventricular myocardium of a sexually mature dog: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – transverse striations. Stained using the Haugen method. X 600.

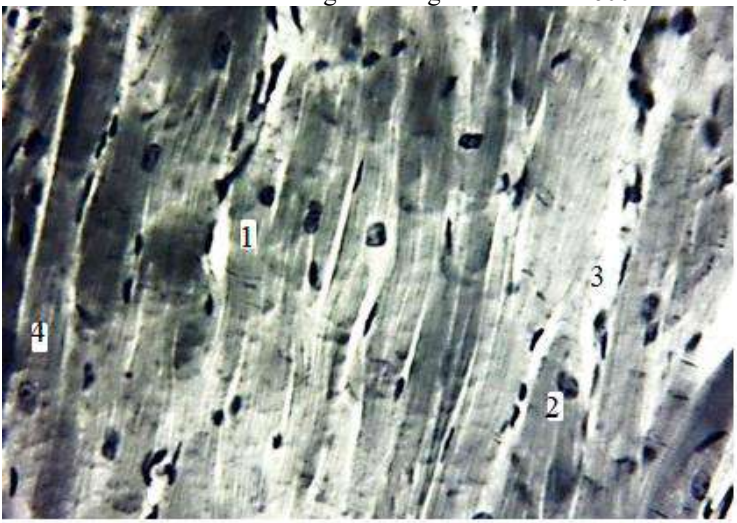

Fig. 3.32. Histological section of the left ventricular myocardium of a sexually mature dog: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intermuscular connective tissue; 4 – longitudinal striations. Stained using the Haugen method. X 400.

According to the results of our morphometric studies, cardiomyocytes of the left and right ventricles and cardiomyocytes of the atria, depending on their morphotopography and, therefore, their functional load, have ambiguous cytometric parameters. Our morphometric analysis of myocardial microstructures shows that the quantitative characteristics of cardiomyocytes in the left ventricle of a dog's heart are significantly greater than those in the right ventricle. Thus, the length and width of cardiomyocytes in the left ventricle are almost 1.1 times greater than those in the right ventricle and equal to 46.06±1.12 μm (length) and 9.02±0.39 μm (width), respectively (Table 3.6).

Table 3.6

Histometric parameters of cardiomyocytes of sexually mature dogs (Canis lupus familiaris L., 1758), M ± m, n = 5

Parameter	Cardiomyocyte Length (μm)	Cardiomyocyte Width (μm)	Cardiomyocyte Volume (μm³)	Cardiomyocyte Nuclear Volume (μm³)	Nuclear-to-Cytoplasmic Ratio
Left ventricle	46,06± 1,12	9,02± 0,39	2941,76± 127,44	64,58 ±5,09	0,0224± 0,0076
Right ventricle	41,47± 1,24	8,29± 0,42	2237,24± 103,02*	59,97± 5,83	0,0275± 0,0081*
Atria	39,06± 1,35*	7,19± 0,49*	1496,92± 98,02**	53,06 ± 6,02*	0,0367± 0,0105**

Note: * p≤0.05; ** p≤0.01; *** p≤0.001 relative to the left.

We also found similar changes in a morphometric study of cardiomyocyte volumes and their nuclei: the largest cardiomyocyte volume was observed in the left ventricle (2941.76±127.44 μm^3), while in the right ventricle, this indicator

is significantly ($p \leq 0.05$) 1.31 times smaller and equals 2237.24±103.02 μm^3 (Table 3.6; Fig. 3.33).

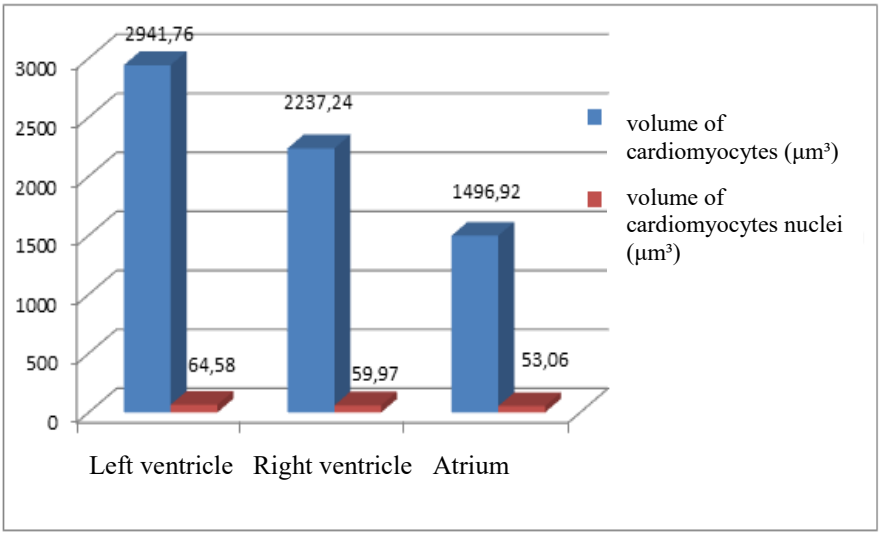

Fig. 3.33. Histometry of cardiomyocytes in the heart muscle of a domestic dog.

Similar results of morphometric parameters were found when determining the volume of cardiomyocyte nuclei: the average volume of cardiomyocyte nuclei in the left ventricle is 64.58±5.09 μm^3, and in the right ventricle – 59.97±5.83 μm^3 (Table 3.6; Fig. 3.33).

According to these ambiguous quantitative cytometric characteristics of cardiomyocytes for the ventricles of the dog heart, different nuclear-cytoplasmic ratios were formed for them: the smallest nuclear-cytoplasmic ratio was characteristic of left ventricular cardiomyocytes (0.0224±0.0076) and significantly higher for cardiomyocytes of the right ventricle (0.0275±0.0081), which indicated their morphofunctional activity (Table 3.6; Fig. 3.34).

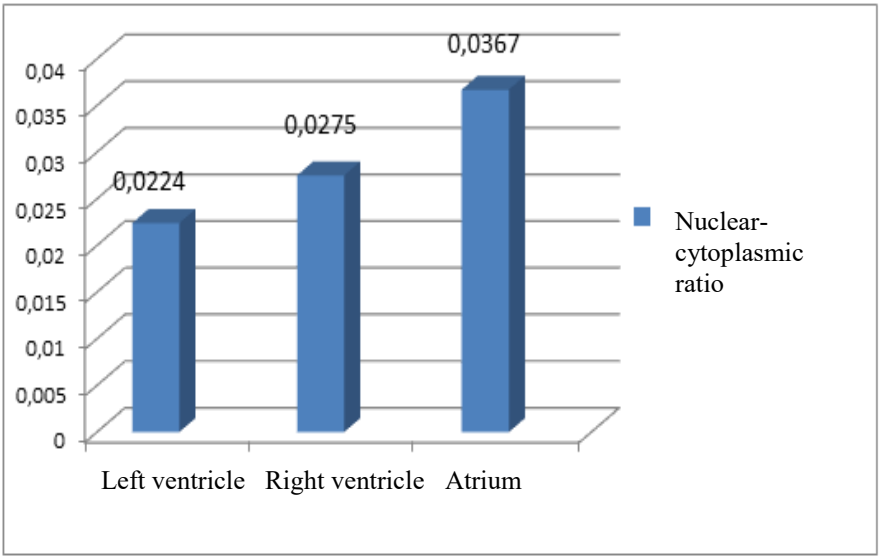

Fig. 3.34. Nuclear-cytoplasmic ratio of cardiomyocytes in the heart myocardium of a domestic dog.

Significantly smaller cytometric parameters (length, width, cell volume, nucleus volume) were characteristic of atrial cardiomyocytes, and therefore, such cardiomyocytes had the highest nuclear-cytoplasmic ratio (0.0367±0.0105) (Table 3.6; Fig. 3.34).

We attribute these inconsistent morphometric measurements of cardiomyocytes in the left and right ventricles and atria of the heart to the morphofunctional characteristics of the heart's operation: the atria receive blood returning to the heart from the animal's body, performing a significantly lighter workload, whereas the ventricles pump blood from the heart to the organs and tissues, ensuring systemic circulation and undergoing significantly greater functional stress.

3.1.3. Morphology of the Heart of a Domestic Pig (*Sus scrofa, forma domestica L.*, 1758)

Among farm animals, the domestic pig (Sus scrofa domesticus) is the subject of numerous anatomical, physiological, and medical-biological studies due to its high economic value and the similarity of certain morphofunctional indicators to the human body. The study of the morphology of the pig's heart makes it possible to identify general patterns in the structure of the cardiovascular system of mammals, as well as to reveal species and individual characteristics determined by the intensity of growth, conditions of maintenance, level of physiological stress and adaptive mechanisms. The data obtained are important for veterinary medicine, comparative morphology, and experimental biology.

The pig's heart is relatively large, ellipsoidal-conical in shape, with an expanded base and a pointed (narrowed) apex (Fig. 3.35; 3.36). The heart is located in the pericardium, an external connective tissue membrane (tight sac) that surrounds the heart on all sides.

Topographically, the heart is located in the chest cavity between the right and left lungs, cranially from the diaphragm and slightly shifted to the left of the midline. Its enlarged base (the site of attachment of the large vessels through which blood enters the lungs and organs of the circulatory system) is located at the level of the shoulder joint (at the level of the middle of the first rib) and is directed dorsocranially and to the right. The pointed apex of the heart is located in the 5th–6th intercostal space, near the sternum at the junction of the 7th rib and its cartilage. It is directed ventrocaudally and to the left, without reaching the diaphragm and sternum, to which it is connected by the diaphragmatic-pericardial and sternum-pericardial ligaments. The cranial edge of

the heart lies at the level of the third rib, and the caudal edge at the level of the sixth rib.

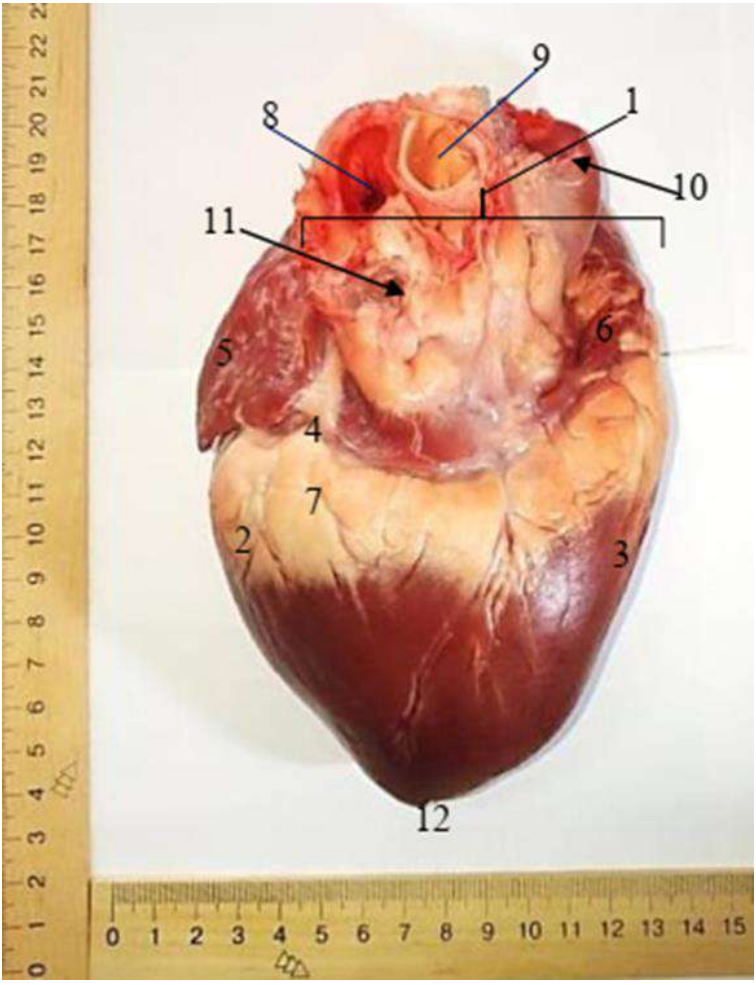

Fig. 3.35. Macroscopic structure of the heart of a sexually mature pig (caudal projection): 1 – base of the heart; 2 – left ventricle; 3 – right ventricle; 4 – left atrium; 5 – left heart ear; 6 – right atrium; 7 – subepicardial fat; 8 – pulmonary artery 9 – aorta; 10 – caudal vena cava; 11 – pulmonary veins; 12 – apex of the heart. Macro specimen.

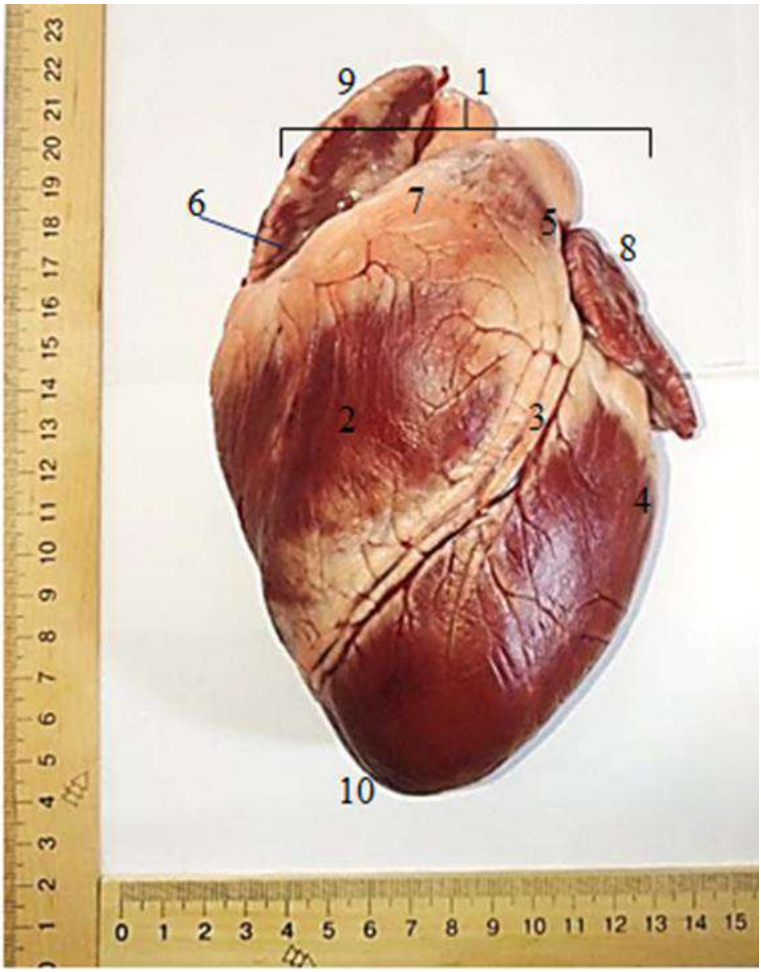

Fig. 3.36. Macroscopic structure of the heart of a sexually mature pig (projection of the heart from the right side): 1 – base of the heart; 2 – left ventricle; 3 – subaortic interventricular groove; 4 – right ventricle; 5 – right atrium; 6 – left atrium; 7 – subepicardial fat; 8 – right atrial appendage; 9 – left atrial appendage; 10 – apex of the heart. Macroscopic specimen.

On the surface of the pig's heart, there are clearly defined interventricular external grooves (right and left), and inside, a thick impermeable muscle wall (septum) separates both the ventricles from each other and the atria and blood vessels into left and right halves, which are not connected to each other (Fig. 3.35; 3.36).

In the area of transition of the interventricular groove from the cranial to the caudal direction, closer to the right edge of the pig's heart, there is a cardiac notch.

Each half of the heart is externally separated by a coronary groove, which is located across the heart, closer to its base, is divided (left and right) into two connected chambers – the thin-walled atrium and the thick-walled ventricle, which are separated from each other by a valve that ensures blood flow in only one direction – from the atrium to the ventricle.

The right and left atria are located at the widest base of the organ. There they form sac-like protrusions – the large and clearly defined cardiac ears of the same name (Fig. 3.36). The latter are topographically located in the cranial direction and are located to the right and left of the pulmonary artery trunk and aorta.

The ventricles occupy the main lower part of the heart, which are externally separated from each other by the interventricular subapical and apical sulci. The latter merge on the cranial surface of the heart, without reaching its apex, separating the right ventricle from the left ventricle. The narrowed apex of the heart belongs to the LV, which is located on the left in the caudal direction. The right ventricle is located on the right in the cranial direction. The interventricular grooves have a similar arrangement: the subxiphoid groove is in the caudal direction, and the conal groove is in the cranial direction. In the upper third, the left and right ventricles of the heart are more pronounced, more voluminous, and taper conically toward the apex (Fig. 3.35; 3.36).

Organometric studies of the heart of a sexually mature pig have established that its AM is 487.4 ± 8.12 g, BM is 0.29 ± 0.004%, and the weight of the heart without epicardial fat (net weight) is 461.4 ± 8.01 g (Table 3.7).

The height of the heart is 15.9 ± 0.07 cm, the width at the base is 10.3 ± 0.06 cm, the thickness is 6.4 ± 0.05 cm, and the circumference is 26.5 ± 0.12 cm. The pig's heart development index is 155.06±6.32%, therefore, this heart is classified as enlarged-elongated (cone-shaped) (Fig. 3.53; 3.36; Table 3.7).

Table 3.7

Linear parameters of the heart of a sexually mature pig (Sus scrofa, forma domestica L., 1758), M ± m, n = 5

Parameters	Numerical values
1. Heart height (cm)	15,9±0,07
2. Heart width (cm)	10,3±0,06
3. Heart thickness (cm)	6,4±0,05
4. Heart circumference (cm)	26,5±0,12
5. Cardiac development (shape) index (%)	155,06±6,32
6. Mean ventricular wall thickness (mm)	20,55±0,24
7. Left ventricular wall thickness (mm)	26,7±0,51
8. Right ventricular wall thickness (mm)	14,4±0,32
9. Mean atrial wall thickness (mm)	6,93±0,09
10. Left atrial wall thickness (mm)	7,81±0,06
11. Right atrial wall thickness (mm)	6,02±0,04

According to the results of linear measurements, the wall of the left ventricle of a pig (26.7±0.51 mm) is almost twice as thick as that of the right ventricle (14.4±0.32 mm), the wall of which is thin-walled and less distinctly flattened in pigs. The thickness of the atrial wall is the smallest: PP – 6.02±0.04 mm, LP – 7.81±0.06 mm (Table 3.7).

The linear parameters of the walls of the ventricles and atria of the pig's heart correlate with their mass indicators. Moreover, there is a certain dependence between the thickness of the walls of the ventricles and atria and their absolute and relative mass, which emphasises the connection between the linear dimensions of the heart and its anatomical mass (AM). This indicates the harmony of the morphological organisation of the heart and the functional correspondence between structural indicators and the mechanical load on each of the chambers. Thus, the morphometric parameters of the heart can be used as indicative criteria in assessing age-related, physiological or pathological changes in the cardiac anatomy of mammals.

Thus, according to the morphometry of the anatomical structures of the heart, the left and right ventricles are more voluminous in terms of absolute and relative mass. The largest AM (250.9±5.37 g) and VM (54.38±3.18 %) are characteristic of the LV, whichs the greatest load in the heart. The difference between the absolute mass of the left and right ventricles is 138.1g. The average AM of both ventricles is 363.7±11.14 g (78.83±5.92%) (Table 3.8).

Lower values are characteristic of the left (59.6±2.16 g; 12.91±0.09%) and right (38.1±1.92 g; 8.26±0.11%) atria. The average absolute mass of the pig's atria is 97.7±5.49 g (21.17±2.01%) (Table 3.8).

Based on this, the absolute mass of the ventricles is significantly ($P < 0.001$) 3.7 times greater than the absolute mass of the atria. Therefore, the ratio of the absolute mass of the ventricles of the pig's heart to the absolute mass of the heart without epicardial fat is 1:0.79, respectively, the ratio of the absolute mass of the atria is 1:0.21, and the ratio of the absolute mass of the heart atria myocardium to the absolute mass of the ventricles myocardium is 1:0.27 (Table 3.8).

Table 3.8

Morphometry of the heart, ventricles and atria of a sexually mature pig (Sus scrofa, forma domestica L., 1758), M ± m, n = 5

Parameters	Absolute mass (g)	Relative mass (%)
1. Heart	487,4 ±8,12	0,29±0,004
2. Left atrium	59,6±2,16	12,91±0,09
3. Right atrium	38,1±1,92	8,26±0,11
4. Left and right atria (total)	97,7±5,49	21,17±2,01
5. Left ventricle	250,9±5,37	54,38±3,18
6. Right ventricle	112,8±4,03	24,45±1,62
7. Left and right ventricles (total)	363,7±11,14	78,83±5,92
8. Heart mass (without epicardial fat)	461,4±8,01	100
9. Ratio of ventricular mass to net heart mass	1:0,79	
10. Ratio of atrial mass to net heart mass	1:0,21	
11. Ratio of atrial myocardium mass to ventricular myocardium mass	1:0,27	

The heart wall is composed of the endocardium (inner lining of the heart), myocardium (middle muscle layer) and epicardium (outer lining of the heart).

The outer lining of the heart (epicardium) is an important anatomical and functional element of the heart wall. It is formed by fibrous connective tissue (reducing friction between the heart and surrounding tissues), which provides strength and elasticity to the membrane, and is also covered by mesothelium (a single layer of flat epithelium) that lines the surface of the epicardium and

produces serous fluid. The fibrous connective tissue of the epicardium contains collagen and elastic fibres that provide mechanical support to the heart, as well as blood vessels and nerves that supply the heart muscle (myocardium) and help regulate cardiac activity.

The epicardium plays a key role in the functioning of the cardiovascular system, particularly in maintaining cardiac homeostasis and its adaptation to physiological and pathological stresses.

The endocardium is formed from the endothelial, subendothelial, muscular-elastic and connective tissue layers. The endothelial layer of the endocardium is located on the basement membrane, the subendothelial layer is formed by a large number of poorly differentiated cells, the muscular-elastic layer is represented by smooth muscle cells, and the connective tissue layer is formed by fibrous connective tissue consisting of thick collagen, elastic and reticular fibres.

The middle layer (myocardium) is the main, most powerful layer of the heart wall of its ventricles and atria. The wall of the myocardium of the heart ventricles consists of outer and inner layers (whose muscle fibres are obliquely longitudinal), outer and inner deeper layers, and the deepest layer, whose fibres are arranged in a figure-eight pattern. The myocardium consists mainly of cardiomyocytes (specialised muscle cells) that provide rhythmic contractions of the heart.

The myocardium of the atrial wall consists of two layers: the outer and the deep. The first (outer) layer is common to both atria, and its muscle fibres run transversely from the right to the left atrial appendage. The muscle fibres of the second (deep) layer of the myocardium of the right and left atria are arranged longitudinally. In addition, circular bundles of muscle fibres are found in the area of the venous openings of the heart myocardium.

They probably play a role in regulating venous blood flow during the atrial contraction phase. This morpho-functional organisation of the myocardium ensures the coordinated work of the atria and is an important element of the haemodynamics of the mammalian heart, particularly under conditions of intense physiological stress.

Cardiomyocytes form an extensive three-dimensional network through numerous intercellular connections, in particular intercalated discs, which provide both mechanical and electrical communication between cells. The presence of desmosomes and gap junctions facilitates the rapid propagation of excitation and the coordination of contractions, enabling the myocardium to function as a single syncytium.

The variety of cardiomyocyte sizes enables the heart to adapt to changing functional conditions, particularly when there are fluctuations in circulating blood volume or vascular resistance. An increase in cell size, as well as changes in their ultrastructure, reflect processes of functional adaptation and myocardial remodelling in response to increased workload. This ensures that optimal levels of contractile activity and cardiac output are maintained in various physiological and pathological conditions.

The microscopic structure of the myocardial wall is formed by cardiac muscle fibres, which are composed of contractile (typical) cells called cardiomyocytes. The latter have a rectangular shape in longitudinal section and a rounded shape in transverse section (Fig. 3.37). Between the muscle fibres, there are layers of loose connective tissue (intermuscular connective tissue), where a significant number of vessels and nerves are located (Fig. 3.38).

A distinctive feature of the structure of cardiomyocytes is the presence of intercellular discs – specialised contacts between neighbouring cells. They ensure electrical synchronisation (thanks to tight contacts and channels, ions are rapidly transmitted between cells, ensuring effective impulse propagation) and

mechanical strength (desmosomes and adhesive contacts allow cardiomyocytes to withstand stress during heart contraction).

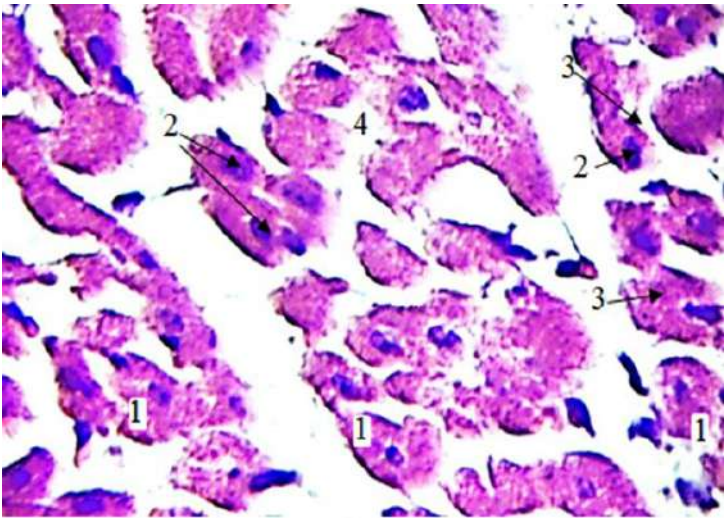

Fig. 3.37. Microscopic structure of the left ventricular myocardium of a sexually mature pig (cross section): 1 – round cardiomyocytes; 2 – nuclei; 3 – sarcoplasm; 4 – intermuscular connective tissue. Haematoxylin and eosin. x 400.

Muscle fibres (cardiomyocytes) vary in length and width, which allows them to adapt to the functional needs of the heart. Thus, the largest length (64.08±2.02 μm) and width (11.04±0.132 μm) are characteristic of left ventricular cardiomyocytes, while the smallest are characteristic of atrial cardiomyocytes, respectively 55.49±1.98 μm and 8.25±0.182 μm, respectively (Fig. 3.39; Table 3.9). In some places, myocardial muscle fibres are connected to each other by anastomoses (Fig. 3.40), forming a net-like structure (Fig. 3.41), which is clearly visible on a longitudinal section of muscle tissue. This structure of the myocardium promotes rapid and simultaneous contraction of the heart muscle.

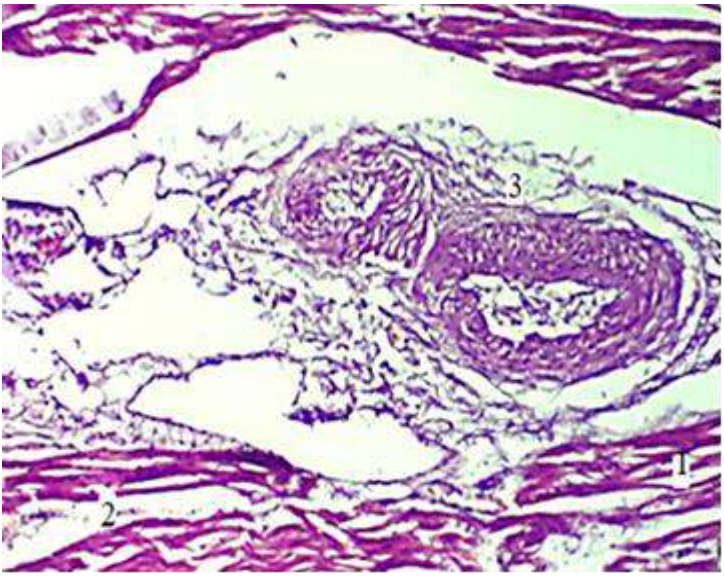

Fig. 3.38. Microscopic structure of the left ventricular myocardium of a sexually mature pig: 1 – muscle fibres; 2 – intermuscular connective tissue; 3 – blood vessels. Haematoxylin and eosin. x 56.

When staining heart muscle histological preparations using the Hodenheim method, the sarcoplasm of cardiomyocytes contains clearly defined uniform striations, which is a characteristic feature of this staining method (Fig. 3.42). It allows for detailed examination of the structure of the myocardium, in particular, to reveal the difference between light and dark areas, which is important for studying the functional organisation of muscle fibres. Such striation is formed as a result of the alternation of actin and myosin proteins, which together form a complex muscle fibre protein (actomyosin) – the actomyosin complex (actomyosin system), which is a component of contractile (typical) cells – cardiomyocytes, determining their contractile ability.

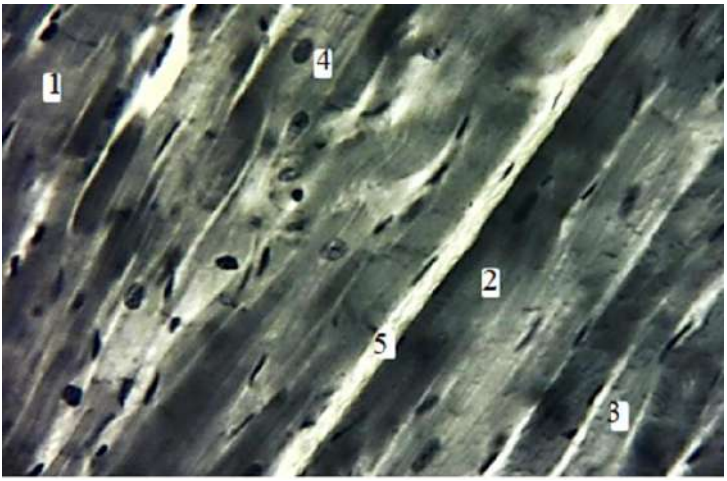

Fig. 3.39. Microscopic structure of the left ventricular myocardium of a sexually mature pig: 1 – thick muscle fibre; 2 – medium-thick muscle fibre; 3 – thin muscle fibre; 4 – cardiomyocyte nuclei; 5 – intermuscular connective tissue. Stained using the Haemigyne method. ×280.

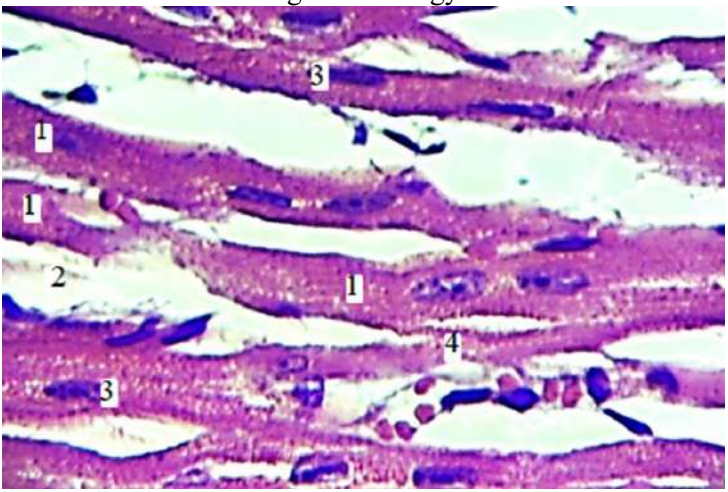

Fig. 3.40. Microscopic structure of the right ventricular myocardium of a sexually mature pig: 1 – muscle fibres; 2 – intermuscular connective tissue; 3 – muscle fibre nuclei; 4 – anastomoses. Haematoxylin and eosin. x 600.

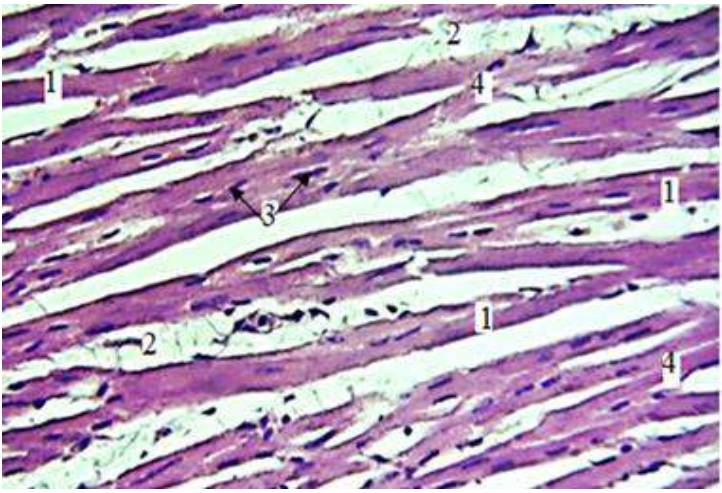

Fig. 3.41. Microscopic structure of the left ventricular myocardium of a sexually mature pig: 1 – muscle fibres in the form of a reticular structure; 2 – intermuscular connective tissue; 3 – muscle fibre nuclei; 4 – anastomoses. Haematoxylin and eosin. x 280.

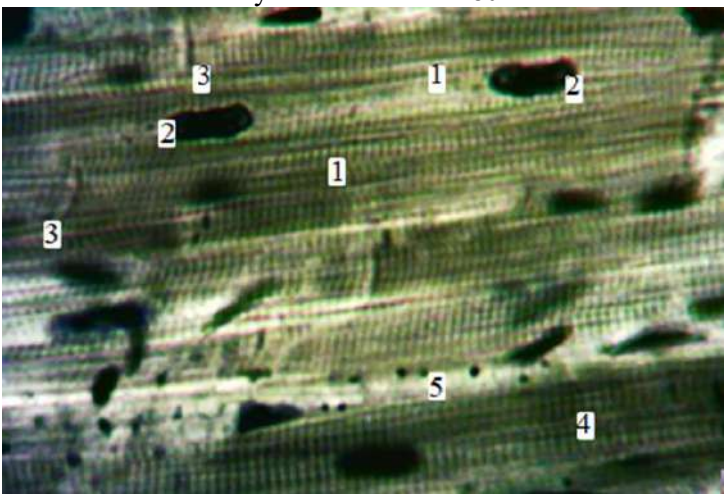

Fig. 3.42. Microscopic structure of the left ventricular myocardium of a sexually mature pig: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – transverse striations; 5 – intermuscular connective tissue. Stained using the Heidenhain method. x 600.

Two types of protein filaments–actin (thin) and myosin (thicker) – form sarcomeres, which, by linking together in series, form myofibrils. The sarcomere is the basic structural and functional unit of the contractile apparatus of the muscle cell, within which the interaction between actin and myosin filaments takes place. Myofibrils, in turn, occupy a significant portion of the sarcoplasm of cardiomyocytes and are arranged in an orderly fashion along the longitudinal axis of the cell.

This clear organisation gives rise to the characteristic transverse striation of cardiac muscle tissue, which results from the alternation of light and dark bands, corresponding to the arrangement of filaments within the sarcomeres (Fig. 3.43; 3.44).

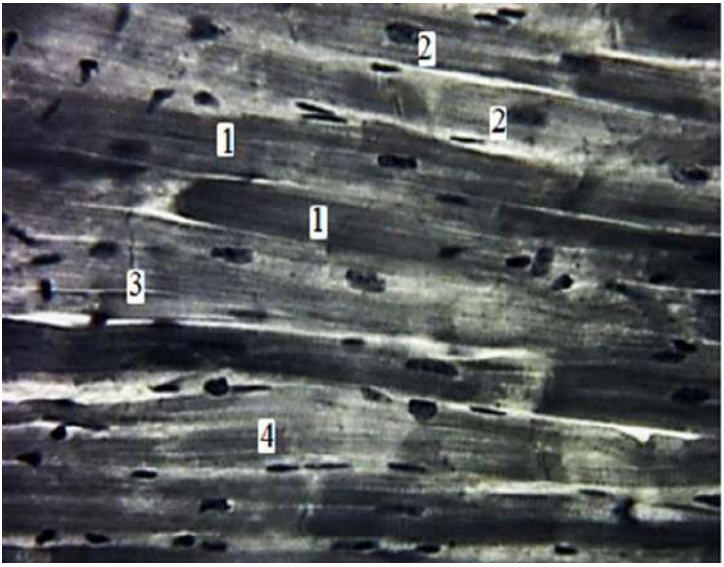

Fig. 3.43. Microscopic structure of the right ventricular myocardium of a sexually mature pig: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – longitudinal striations. Stained using the Heidenhain method. x 600

The coordinated interaction of these structures ensures the effective contraction of cardiomyocytes and forms the morphological basis of the heart's pumping function.

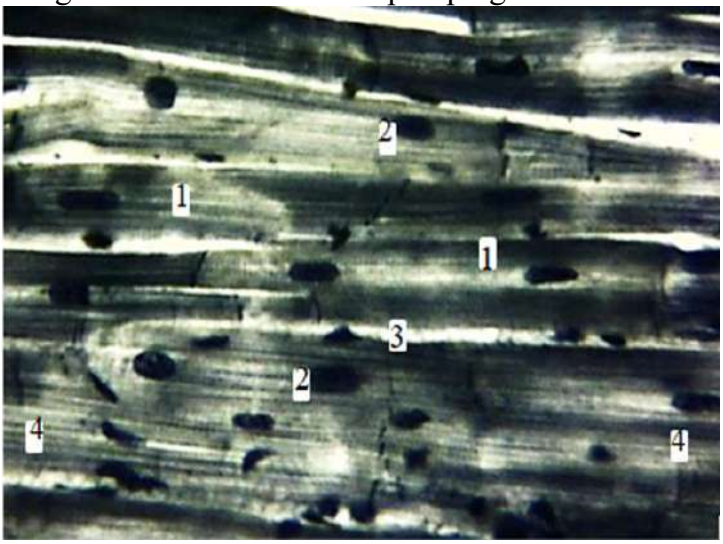

Fig. 3.44. Microscopic structure of the left ventricular myocardium of a sexually mature pig: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – longitudinal striations. Stained using the Heidenhain method. x 600.

The coordinated interaction of actin and myosin filaments during contraction underlies the sliding mechanism, which ensures the shortening of sarcomeres and, consequently, the contraction of muscle fibres. This organisation of the contractile apparatus ensures the rhythmicity and coordination of myocardial function, which are essential for maintaining the heart's continuous pumping action and stable haemodynamics. The high degree of orderliness of myofilaments facilitates the efficient conversion of chemical energy into mechanical energy, which is a key condition for the functioning of cardiomyocytes.

In histological examination, the nuclei of cardiomyocytes, which are located in the central part of the sarcoplasm, stain most intensely. The nuclei are predominantly oval or elongated in shape, with clearly defined contours and a well-defined nuclear envelope. The nucleoplasm contains one or more nucleoli, indicating high functional activity of the cells, as well as fine-grained chromatin, evenly distributed within the nucleus. This organisation of the nuclear apparatus reflects the intense processes of protein synthesis and metabolic activity necessary to maintain the structural integrity and contractile capacity of the myocardium.

Table 3.9

Histometric parameters of cardiomyocytes of sexually mature pigs (Sus scrofa, forma domestica L., 1758), M ± m, n = 5

Parameters	Cardiomyocyte length (μm)	Cardiomyocyte width (μm)	Cardiomyocyte volume (μm³)	Nuclei volume of cardiomyocytes (μm³)	Nuclear-cytoplasmic ratio
Left ventricle	64,08±2,02	11,04±0,132	6130,98± 922,18	77,16± 2,01	0,0127± 0,0056
Right ventricle	59,15±2,12	9,04±0,143	3794,56± 489,87	76,02± 2,43	0,0204± 0,0068
Atria	55,49±1,98	8,25±0,182	2964,20± 412,02	75,97± 3,24	0,0263± 0,0097

Note: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$ relative to the left.

According to cytomorphometry, the mean volume of left ventricular cardiomyocytes in pigs was 6130.98 ± 922.18 μm³. The volume of right ventricular myocardial cardiomyocytes in pigs is 1.6 times greater (3794.56 ± 489.87 μm³) than that of the

left ventricle. The mean values for the volume of cardiomyocytes in the atrial myocardium of the pig's heart are the smallest (2964.20 ± 412.02 μm³), and 2.07 times smaller than those of left ventricular cardiomyocytes and 1.3 times smaller than those of right ventricular cardiomyocytes (Table 3.9; Fig. 3.45).

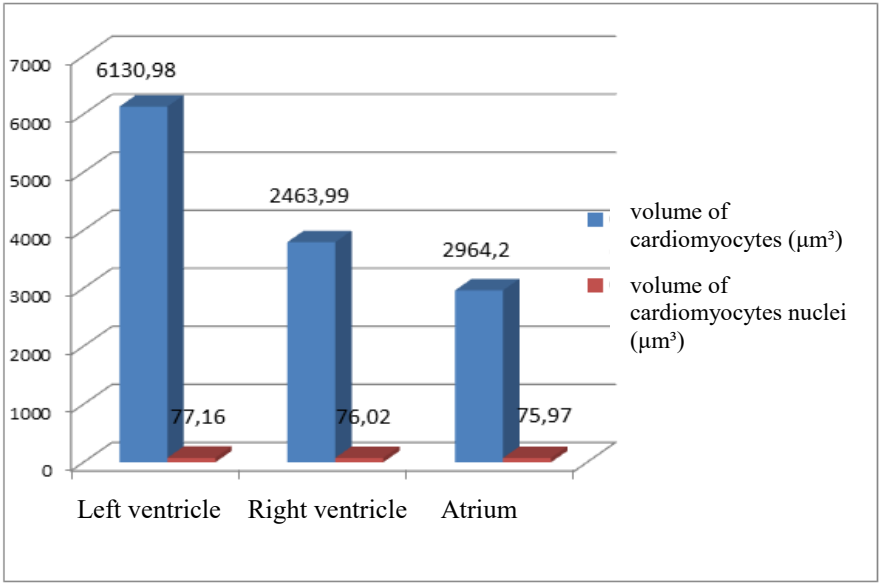

Fig. 3.45. Histometric parameters of cardiomyocytes of the heart myocardium of a sexually mature pig.

The volume indices of LV, RV and atrial cardiomyocytes are similar, amounting to 77.16±2.01 μm^3, 76.02±2.43 μm^3 and 76.02±2.43 μm^3, respectively (Table 3.9; Fig. 3.45).

Based on the average values of cardiomyocyte volume and their nuclei, it was established that the YCV in LV cardiomyocytes is at least 0.0127±0.0056. Meanwhile, the YCV of right ventricular cardiomyocytes (0.0204±0.0068) is 1.6 times greater than that of the left ventricle. The largest YCV value is

characteristic of atrial cardiomyocytes and, accordingly, equals 0.0263±0.0097, which is 2.07 times higher than that of LV cardiomyocytes and 1.29 times higher than that of right ventricular cardiomyocytes (Table 3.9; Fig. 3.46).

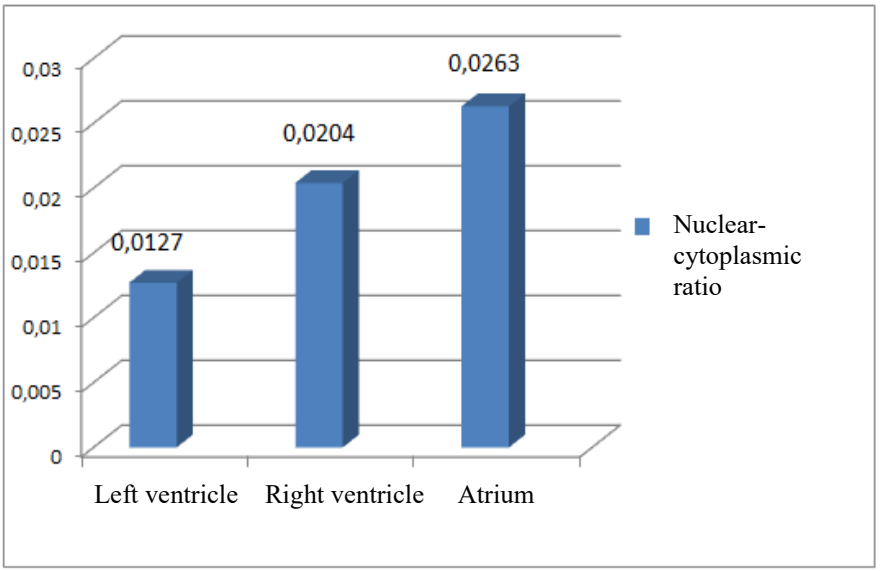

Fig. 3.46. Nuclear-cytoplasmic ratio of cardiomyocytes in the heart myocardium of a sexually mature pig.

Thus, when analysing the processes of nuclear-cytoplasmic ratio formation in cardiomyocytes of the pig heart myocardium, specific features of the NCR in different parts of the heart were established, which is due to their morphofunctional specialisation and load.

According to the results of our studies, the lowest NCR index was found in the cardiomyocytes of the left ventricle (LV), where the greatest functional load is concentrated due to its participation in ensuring systemic blood flow.

Right ventricular cardiomyocytes have a higher YACV because they function under lower pressure, serving the pulmonary circulation. The highest YCV index was recorded in atrial cardiomyocytes, which are smaller in size, have less mechanical load and play a supporting role in maintaining blood flow.

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These data indicate that the nuclear-cytoplasmic ratio is directly dependent on the amount of cytoplasmic mass required for contractile activity of cells and inversely proportional to functional load. Therefore, the nuclear-cytoplasmic ratio index can be considered as one of the morphological markers of the functional state of myocardial cells in different anatomical parts of the heart.

The results obtained are important for understanding the physiological adaptation of the heart to load and can be used as a basis for further research in the field of experimental morphology, cardiology, and veterinary pathology.

3.1.4. Morphology of the Heart of Domestic Sheep (*Ovis aries L.,* 1758)

The domestic sheep (Ovis aries L., 1758) belongs to the class Mammalia, order Artiodactyla, family Bovidae, and is one of the oldest domesticated species of farm animals. Over a long period of selection, numerous breeds have been formed, differing in their productive qualities, constitutional characteristics and adaptive abilities to different climatic conditions. As a typical representative of ruminants, sheep are characterised by specific metabolic features, high digestive intensity and a significant functional load on the circulatory system, which ensures the transport of nutrients and metabolites.

The physiological characteristics of the sheep's body, in particular the level of metabolic activity, the nature of motor activity and adaptation to the conditions of keeping, determine certain morphofunctional characteristics of the cardiovascular system. The study of the anatomical structure of the heart of this species is important both for comparative morphology and for practical veterinary medicine, as it allows us to establish the species-specific features of the organ and their connection with the functional parameters of blood circulation.

The heart of a domestic sheep is an important organ that ensures effective blood circulation and maintains the body's vital functions.

Studying the morphological features of this animal's heart is important not only for fundamental veterinary anatomy, but also for the practical needs of diagnosing and treating cardiovascular diseases.

The structural features of the sheep's heart reflect the adaptive mechanisms that ensure its functioning in the context of species, body size and physiological activity.

The heart of sheep has a conical shape with a broad base and a narrow apex (Fig. 3.47; 3.48).

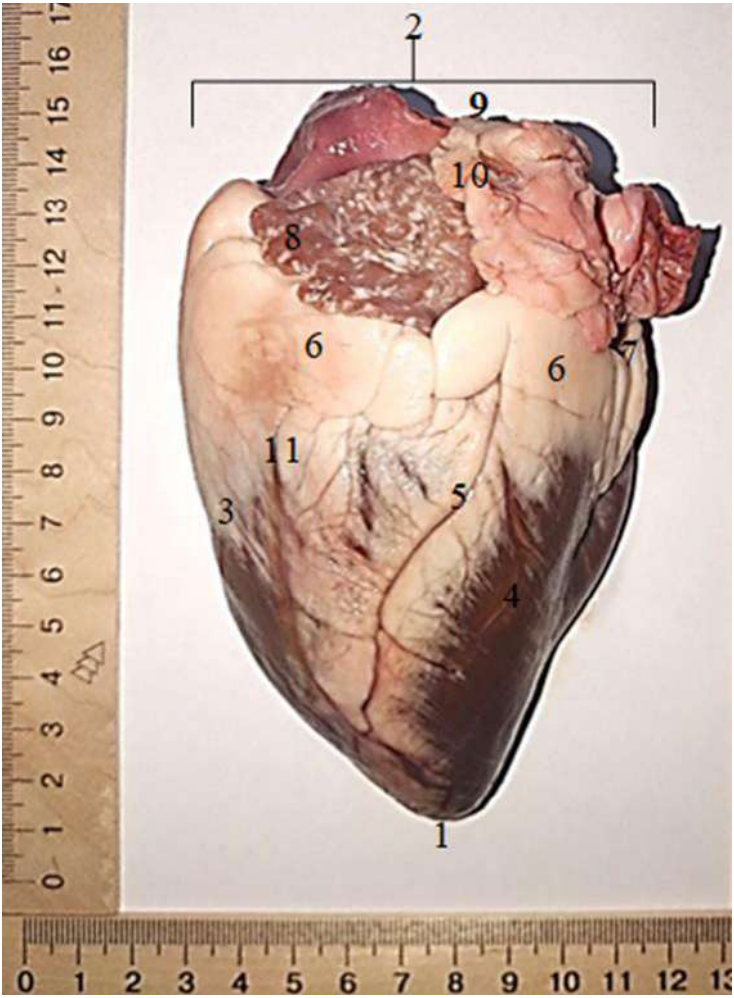

Fig. 3.47. Macroscopic structure of the heart of a sexually mature sheep (projection of the heart from the left side): 1 – apex of the heart; 2 – base of the heart; 3 – right ventricle; 4 – left ventricle; 5 – interventricular sulcus; 6 – subepicardial fat; 7 – left atrium; 8 – left atrial appendage; 9 – right atrial appendage; 10 – pulmonary trunk; 11 – blood vessels. Macro preparation.

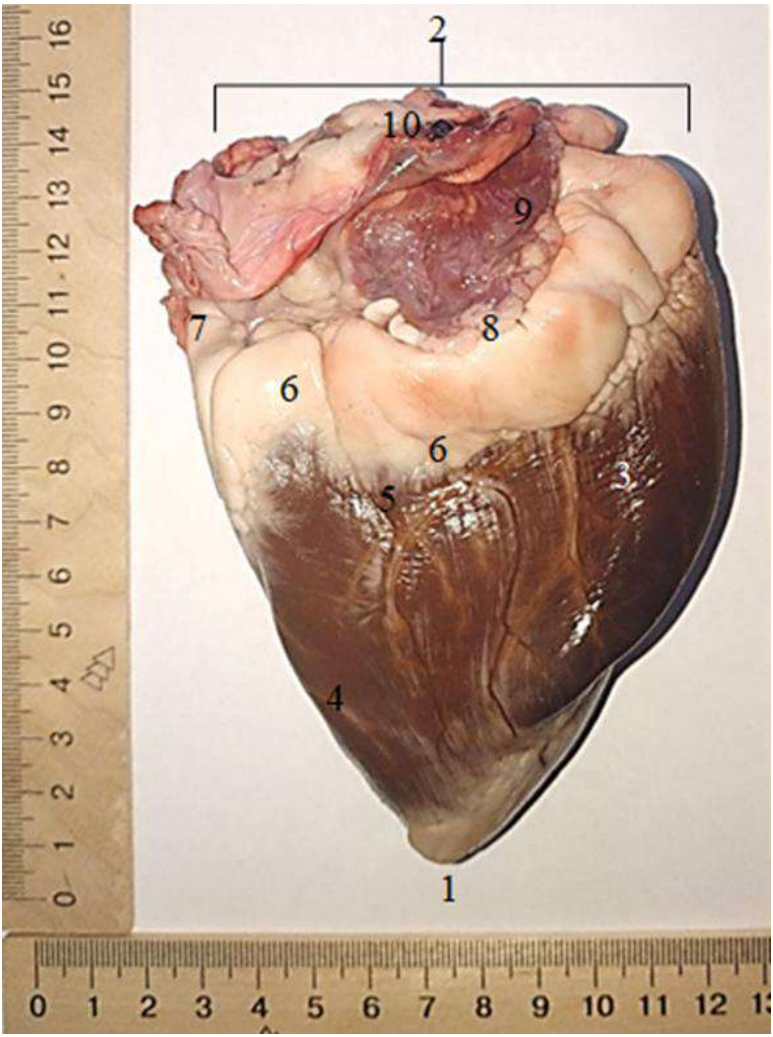

Fig. 3.48. Macroscopic structure of the heart of a sexually mature sheep (projection of the heart from the right side): 1 – apex of the heart; 2 – base of the heart; 3 – right ventricle; 4 – left ventricle; 5 – subcostal interventricular groove; 6 – subepicardial fat; 7 – left atrium; 8 – right atrium; 9 – right atrial appendage; 10 – pulmonary trunk. Macro specimen.

The heart is located in the mediastinum of the thoracic cavity between both lungs, in the area between the third and sixth ribs: cranially it reaches the third rib, caudally – the sixth rib. Relative to the mid-sagittal plane, the heart is displaced 5/7 to the left, adjacent to the left chest wall between the third and fourth ribs. This location provides optimal conditions for its protection and functioning in conditions of chest mobility during breathing and physical activity of the animal. In addition, the anatomical features of the heart's position meet the needs of the circulatory system, maintaining effective blood circulation in the ram's body.

The base of the heart has a craniocaudal orientation and is located at the level of the middle of the first and second ribs.

The apex of the heart is directed caudoventrally and is located opposite the fifth costal cartilage, or caudally from it, not reaching the sternum by two centimetres, and cranially from the diaphragm – from two to five centimetres. The cardiac sulcus, which separates the atria from the ventricles, is clearly defined.

The heart is contained in a thin but dense sac – the pericardium. The latter surrounds the organ on all sides, thus forming a closed serous sac, which is attached to the sternum by two ligaments in the area of the sixth costal

Externally, the heart of sexually mature sheep is divided into left and right halves by the left (paraconal) and right (subsynosial) interventricular external grooves and the septum inside, which are not connected to each other. Externally, each half of the heart is divided (left and right) into the atrium and ventricle by a transverse coronary sulcus that runs across the heart, closer to its base. The atria and ventricles of the same name (right and left) are connected to each other by atrioventricular openings (Fig. 3.47; 3.48).

The right and left atria are located at the very base of the heart, where they form sac-like protrusions – the right and left

cardiac ears, which are directed in the cranial direction and are located on the right and left, respectively, from the trunk of the pulmonary arteries and aorta (Fig. 3.47; 3.48).

The ventricles occupy the main part of the heart. Externally, they are separated from each other by the interventricular subapical and apical sulci, which join on the cranial surface of the heart without reaching its apex, separating the right ventricle from the left. The apex of the heart in sheep refers to the left ventricle, which is located on the left in the caudal direction. The right ventricle of the heart, accordingly, is located on the right in the cranial direction. The interventricular grooves have a similar location (subcostal – in the caudal direction, subconical – in the cranial direction) (Fig. 3.47; 3.48).

Table 3.10

Linear parameters of the heart of a sexually mature sheep (Ovis aries L., 1758), M ± m, n = 5

Parameter	Numerical Value
1. Heart height (cm)	13,1 ± 0,4
2. Heart width (cm)	9,0 ± 0,3
3. Heart thickness (cm)	5,6±0,02
4. Heart circumference (cm)	22,2 ± 0,6
5. Cardiac development (shape) index (%)	145,5 ± 4,02
6. Mean ventricular wall thickness (mm)	12,42 ± 0,17
7. Left ventricular wall thickness (mm)	16,2 ± 0,22
8. Right ventricular wall thickness (mm)	8,04 ± 0,11
9. Mean atrial wall thickness (mm)	6,62 ± 0,43
10. Left atrial wall thickness (mm)	7,05 ± 0,09
11. Right atrial wall thickness (mm)	5,06 ± 0,07

According to our morphometric analysis of linear parameters, the heart development index of sheep is

145.5±4.02%, which means that the heart of this animal species is of the enlarged-shortened type (Table 3.10).

The most developed anatomical structures of the heart are its left and right ventricles, followed by the left and right atria, which correlates with the linear indicators of their wall thickness and their absolute and relative mass in relation to the pure mass of the heart (without epicardial fat) (Tables 3.10; 3.11).

According to our research, the absolute weight of the heart of sexually mature sheep is 208.4±9.82 g, and the relative weight is 0.44±0.007%. The net weight of the heart (without epicardial fat) is 175.0±8.17 g. The height of the heart is 13.1±0.4 cm, width – 9.0±0.3 cm, thickness – 5.6±0.02, circumference – 22.2±0.6 cm (Table 3.10).

Table 3.11

Morphometry of the heart, ventricles and atria of sexually mature sheep (Ovis aries L., 1758), M ± m, n = 5

Parameters	AM (g)	VM (%)
1. Left atrium	27,9 ± 3,31	15,94 ± 1,49
2. Right atrium	11,2 ± 2,02	6,4 ± 0,82
3. Right and left atria (together)	39,1 ± 4,64	22,34 ± 2,02
4. Left ventricle	90,3 ± 5,21	51,6 ± 3,06
5. Right ventricle	45,6 ± 3,04	26,06 ± 1,32
6. Left and right ventricles (together)	135,9 ±7,16	77,66 ± 4,36
7. Heart weight (without epicardial fat)	175,0 ± 8,17	100
8. Ratio of ventricular mass to net heart mass	1 : 0,78	
9. Ratio of atrial mass to net heart mass	1 : 0,22	
10. Ratio of atrial myocardial mass to ventricular myocardial mass	1 : 0,29	

Thus, the wall thickness of the left ventricle is 2.01 times greater than that of the right ventricle ($P < 0.01$) and amounts to 16.2±0.22 mm, while that of the right ventricle is 8.04±0.11 mm. The wall thickness of the atria is 6.62±0.43 mm, with the left atrium measuring 7.05±0.09 mm and the right atrium measuring 5.06±0.07 mm (Table 3.10).

With these linear parameters of the heart components, the average mass of the left atrium is 27.9±3.31 g (15.94±1.49%), the average mass of the right atrium relative to the left is significantly ($P < 0.01$) 2.5 times smaller and equals 11.2±2.02 g (6.4±0.82%). The average mass of the atria of sheep is 39.1±4.64 g (22.34±2.02%), (Table 3.11).

The mass of the left ventricle is the largest and amounts to 90.3±5.21 g (51.6±3.06%), the mass of the right ventricle is intermediate and equals 45.6±3.04 g (26.06±1.32%), the average mass of both ventricles is 135.9 ± 7.16 g (77.66±4.36%). Therefore, the mass of the ventricles of sheep hearts is significantly ($P < 0.001$) 3.5 times greater than the mass of the atria. Accordingly, the ratio of the mass of the ventricles of sexually mature sheep to its pure (without epicardial fat) mass is 1:0.78, the ratio of the mass of the atria to its pure mass is 1:0.22, and the ratio of the mass of the atrial myocardium to the mass of the ventricular myocardium is 1:0.29 (Table 3.11).

The wall of the sheep heart is formed by the inner (endocardium), middle (myocardium), and outer (epicardium) membranes. The main structural component of the wall of the ventricles and atria is the myocardium, the muscular membrane.

Based on the analysis of histological preparations of the myocardium of the ventricular walls (left and right) stained with hematoxylin and eosin, five layers are differentiated: the outer and inner layers (whose muscle fibers have an oblique longitudinal

direction), then the outer and inner deeper layers, and the deepest layer, whose fibers have a figure-eight orientation.

The myocardium of the atrial wall is formed by only two layers of muscle membrane–the outer (common to both atria) and the deep.

The muscle fibers of the outer layer of the myocardium are arranged transversely from the right to the left atrium. The muscle fibers of the deep layer of the myocardium of the right and left atria are arranged longitudinally. However, in the area of the venous openings of the myocardium, circular bundles of muscle fibers are formed. Due to the more intensive development of the ventricular myocardium relative to the atria, the walls of the ventricles are much thicker than the walls of the atria, which is associated with their functional activity (effective and powerful contraction).

The heart's ventricles perform the main work of pumping blood through the vessels of the systemic and pulmonary circulatory systems. The left ventricle pumps blood into the aorta, from where it is distributed to all organs and tissues, whilst the right ventricle directs blood to the lungs to be oxygenated.

The histoarchitectonics of the myocardial wall of the ventricles and atria is formed by cardiac striated muscle tissue, which is represented by cardiomyocytes that form muscle fibers, and intermuscular layers of loose fibrous connective tissue containing blood and lymphatic vessels and nerves (Fig. 3.49; 3.50).

Striated muscle fibers are composed of cardiac myocytes (cardiomyocytes), which take on different colors (Fig. 3.51).

Cardiac myocytes in the structure of the myocardium form a network of thin and thicker striated muscle fibers, between which there is a slit space filled with intermuscular connective tissue.

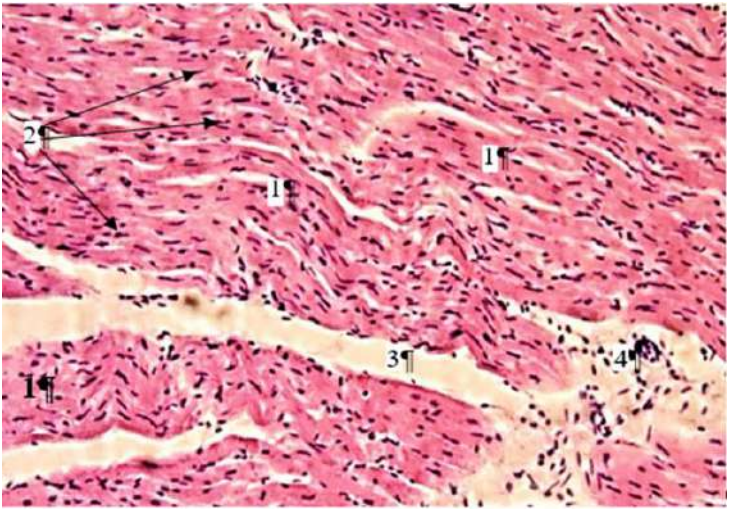

Fig. 3.49. Microscopic structure of the left ventricular myocardium of a sexually mature sheep: 1 – muscle fibers (longitudinal section); 2 – nuclei; 3 – intermuscular connective tissue; 4 – microcirculatory vessel. Hematoxylin and eosin. x 120.

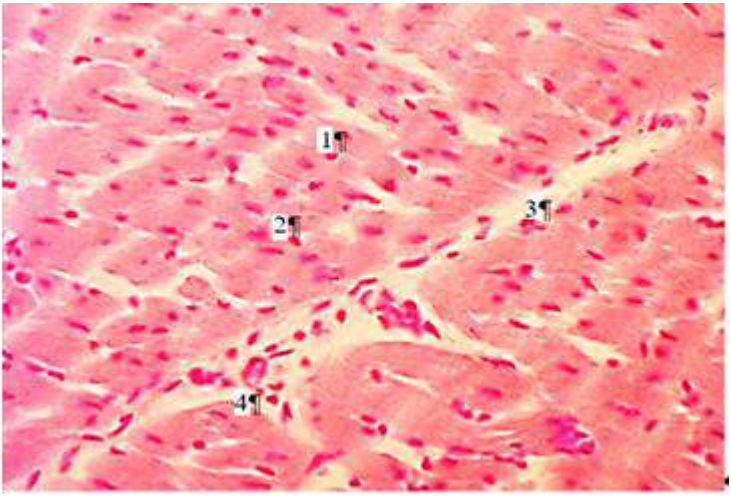

Fig. 3.50. Microscopic structure of the left ventricular myocardium of a sexually mature sheep: 1 – muscle fibers (cross section); 2 – nuclei; 3 – intermuscular connective tissue; 4 – microcirculatory vessel. Hematoxylin and eosin. x 280.

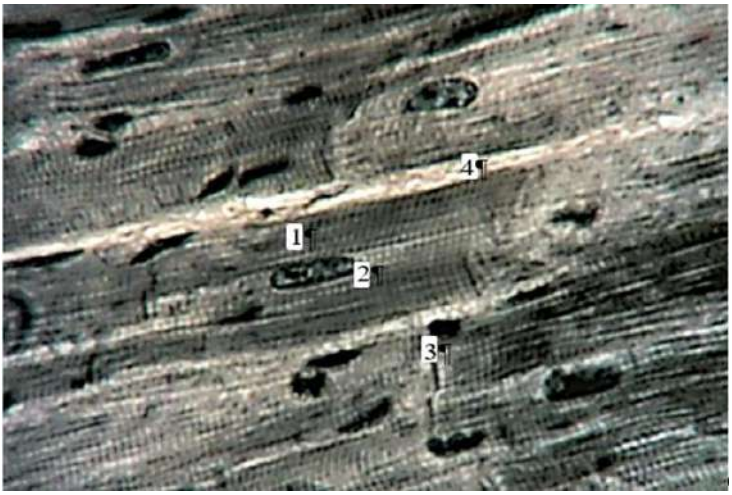

Fig. 3.51. Microscopic structure of the left ventricular myocardium of a sexually mature sheep: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – intermuscular connective tissue. Stained using the Heidenhain method. x 600.

Parallel myocardial muscle fibers formed by cardiomyocytes connect to each other through anastomoses, forming a mesh-like structure that constitutes the heart's contractile system.

In the center of the sarcoplasm of cardiomyocytes, there is one, rarely two, oval or elongated nuclei, which are unevenly distributed. Nuclear chromatin in the form of small or larger grains is found throughout the perimeter of the karyoplasm (Fig. 3.51).

When stained using the Haematoxylin and Eosin method, cardiomyocytes in the fiber structure are arranged in a chain, connected to each other by intercalated discs (Fig. 3.52). When staining histosections with hematoxylin and eosin, cardiomyocytes in the muscle tissue of the heart form histostructures similar to the muscle fibers of somatic muscle tissue.

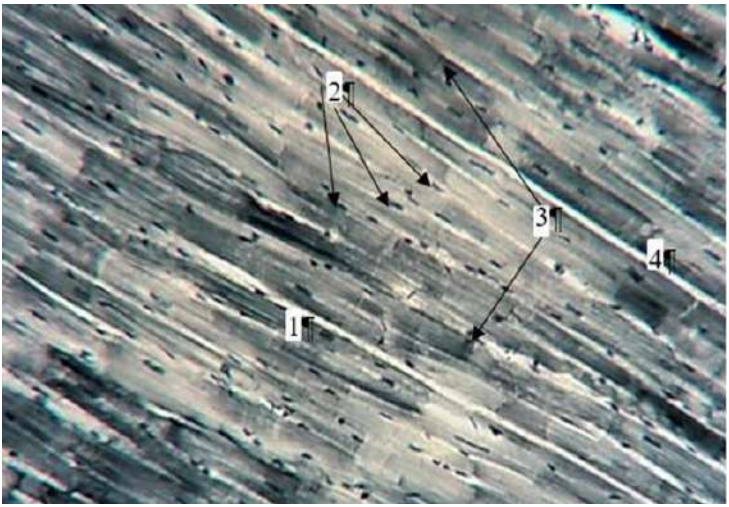

Fig. 3.52. Microscopic structure of the left ventricular myocardium of a sexually mature sheep: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – intermuscular connective tissue. Stained using the Heidenhain method. x 280.

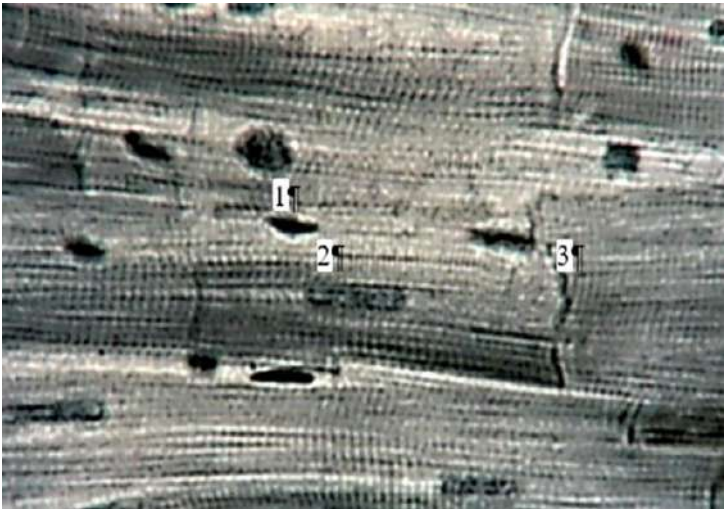

Fig. 3.53. Microscopic structure of the left ventricular myocardium of a sexually mature sheep: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – intermuscular connective tissue. Stained using the Heidenhain method. x 600.

This connection between cardiomyocytes in muscle fibers via intercalated discs provides support for the contractile elements of heart cells (myofilaments) and uniform contraction of the myocardium, thereby forming a functional syncytium.

Intercalated discs contain specialized structures such as desmosomes and voluminous tight junctions, which provide mechanical strength and coordination between cardiomyocytes. This allows cardiomyocytes to work synchronously, since all myocardial cells must contract simultaneously for effective blood circulation.

Under light microscopy of histological sections stained using the H&E method, cardiomyocytes appear as dark rectangular bands in longitudinal sections (Fig. 3.53) and as rounded bands in transverse sections (Fig. 3.54), indicating their cylindrical shape.

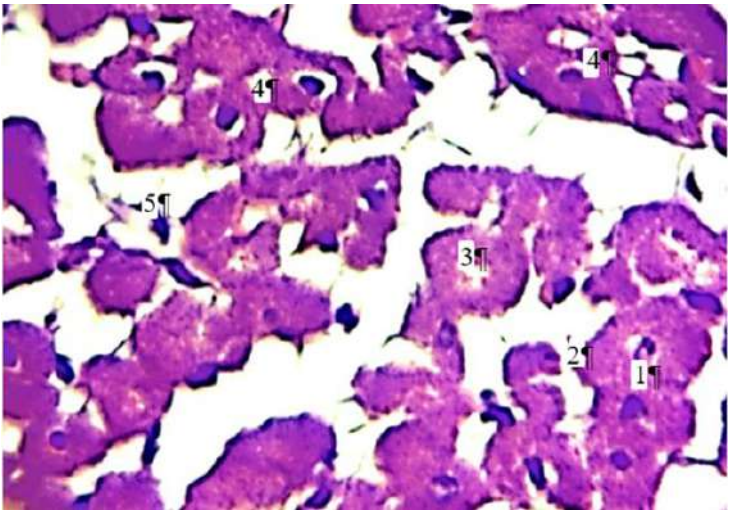

Fig. 3.54. Microscopic structure of the right ventricular myocardium of a sexually mature sheep: 1 – cardiomyocytes (cross section); 2 – sarcolemma; 3 – sarcoplasm; 4 – cardiomyocyte nuclei; 5 – intermuscular connective tissue. Hematoxylin and eosin. x 400.

In cardiomyocytes, the sarcolemma, sarcoplasm, myofibrils, and nuclei are clearly differentiated. Transverse striations, which are caused by the regular arrangement of myofibrils, and longitudinal striations, which are associated with actin and myosin proteins, are particularly pronounced (Fig. 3.55).

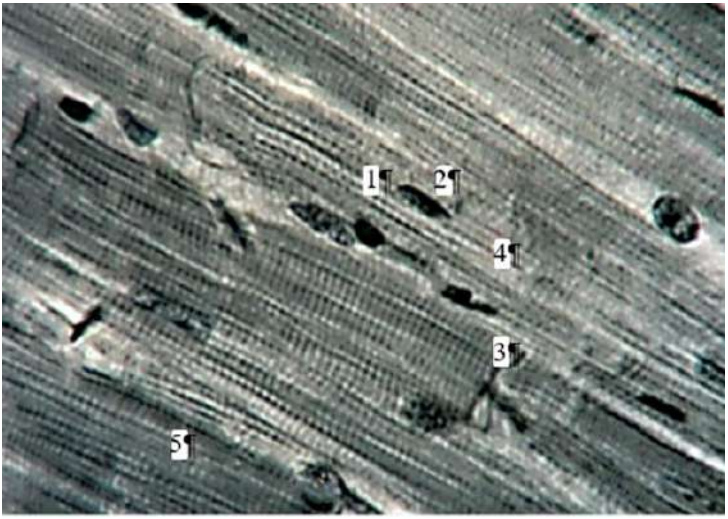

Fig. 3.55. Microscopic structure of the left ventricular myocardium of a sexually mature sheep: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – transverse striations; 5 – longitudinal striations. Stained using the Heidenhain method. x 600.

In addition, there is a high density of capillary network between cardiomyocytes, which ensures effective gas exchange and metabolic nutrition of the myocardium. This structure meets the functional needs of the sheep's heart, allowing it to maintain intense contractile activity for a long time.

Myofibrils (specialized organelles) on a longitudinal section of cardiomyocytes, under a light microscope, appear as longitudinally oriented, parallel to each other, thin threads that are as long as the cardiomyocytes (muscle fibers) themselves (Fig.

3.55). (Fig. 3.55). In most cases, myofibrils are located around the entire perimeter of the sarcoplasm, which is noticeable in a cross section of cardiomyocytes, where they appear as several dozen dots in a single cardiomyocyte (Fig. 3.56). Specialized organelles, often connected by anastomoses, pass from one fiber to another, thus ensuring the common contractile function of the heart myocardium.

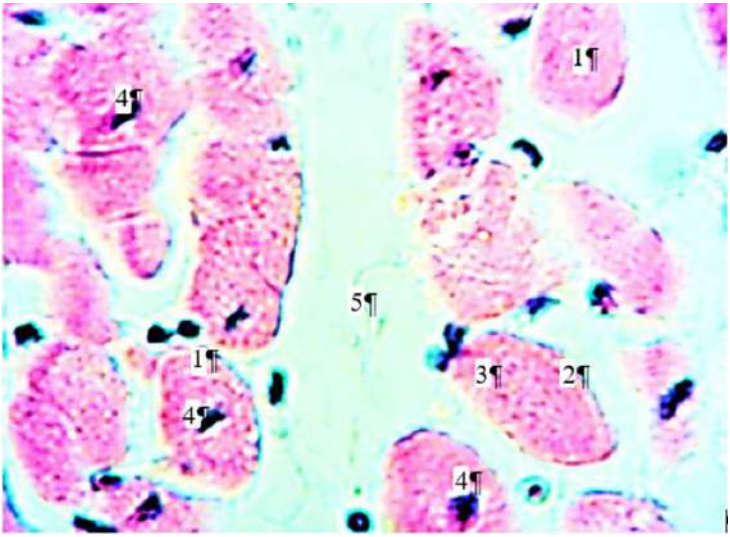

Fig. 3.56. Microscopic structure of the left ventricular myocardium of a sexually mature sheep: 1 – cardiomyocytes (cross section); 2 – sarcolemma; 3 – sarcoplasm; 4 – cardiomyocyte nuclei; 5 – intermuscular connective tissue. Hematoxylin and eosin. x 600.

Myofibrils, which are densely packed in the fiber structure and located closer to its periphery, are connected to other fibers by anastomoses. With low myofibril density, the longitudinal striations of muscle tissue are clearly visible, while the transverse striations are relatively weak. Thicker muscle fibers absorb dye much less effectively, so their transverse striations are weakly

expressed, and myofibrils take on a refined appearance. In thin muscle fibers, myofibrils are more densely packed.

According to the results of our histometry, cardiomyocytes that form muscle fibers, depending on their morphotopography (right, left ventricles, atria), are characterized by ambiguous cytometric parameters (Table 3.12).

Table 3.12

Histometric parameters of cardiomyocytes of sexually mature sheep (Ovis aries L., 1758), M ± m, n = 5

Parameter	Cardiomyocyte Length (μm)	Cardiomyocyte Width (μm)	Cardiomyocyte Volume (μm³)	Cardiomyocyte Nuclear Volume (μm³)	Nuclear-to-Cytoplasmic Ratio
Left ventricle	62,92±1,84	8,98±0,64	3982,99± 423,96	53,42± 5,18	0,0136± 0,0062
Right ventricle	49,52±1,62*	7,96±0,56*	2463,02± 318,04*	52,85± 4,33	0,0219± 0,0079**
Atria	42,04±1,27**	6,07±0,38*	1215,93± 176,94**	50,16± 4,57	0,0430± 0,0096***

Note: *P < 0.05; **P < 0.01; ***P < 0.001 compared to the left ventricle.

Quantitative indicators of contractile myocytes of the left ventricle of the heart myocardium in sheep are higher than those in the right ventricle: the average length of cardiomyocytes in the left ventricle is significantly (P < 0.05) 1.27 times greater than that of the right ventricle and equals 62.92±1.84 μm, while the width of cardiomyocytes is, respectively, (P < 0.05) 1.13 times greater and equals 8.98±0.64 μm (Table 3.12).

We found similar morphometric characteristics when calculating cardiomyocyte volumes: the largest cardiomyocyte

volume is characteristic of the left ventricle (3982.99± 423.96 μm^3), the volume of cardiomyocytes in the right ventricle, compared to the left, is significantly (P < 0.05) smaller by 1.62 times and equals, respectively, 2463.02±318.04 μm^3 (Table 3.12; Fig. 3.57).

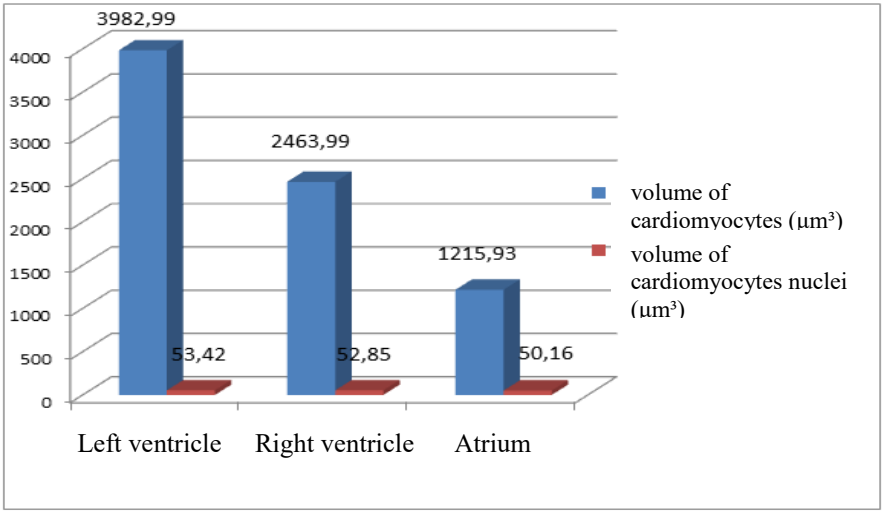

Fig. 3.57. Histometric parameters of cardiomyocytes in the heart myocardium of sexually mature sheep.

We also found similar morphometric characteristics when calculating cardiomyocyte volumes: the largest cardiomyocyte volume is characteristic of the left ventricle (3982.99±423.96 μm^3), the volume of cardiomyocytes in the right ventricle, compared to the left, is significantly (P < 0.05) smaller by 1.62 times and equals, respectively, 2463.02±318.04 μm^3 (Table 3.12; Fig. 3.57).

Similar changes in cytometric parameters are also found when determining the volume of cardiomyocyte nuclei: a larger volume of cardiomyocyte nuclei is characteristic of the left ventricle (53.42±5.18 μm^3), and a slightly smaller volume is

characteristic of the right ventricle (52.85±4.33 μm^3) (Table 3.12; Fig. 3.58).

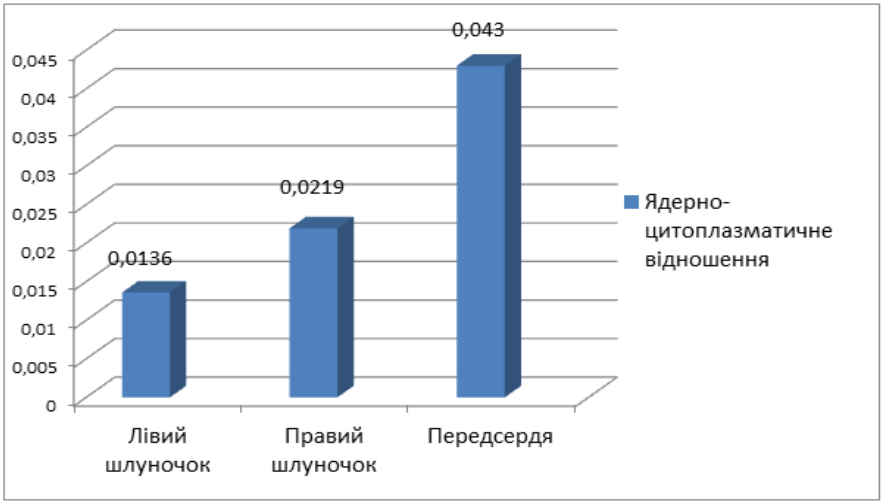

Fig. 3.58. Nuclear-cytoplasmic ratio of cardiomyocytes in the heart myocardium of sexually mature sheep.

The ambiguous morphometric parameters of cardiomyocyte volumes and their nuclei in the right and left ventricles of the heart lead to different nuclear-cytoplasmic ratios: the lowest nuclear-cytoplasmic ratio is characteristic of left ventricular cardiomyocytes (0.0136±0.0062) and is significantly ($P < 0.01$) 1.61 times higher for cardiomyocytes of the right ventricle (0.0219±0.0079), which indicates the morphofunctional activity of cardiomyocytes of the left ventricle (Fig. 3.58). The decrease in the nuclear-cytoplasmic ratio in left ventricular cells may be associated with an increase in the volume of cytoplasm saturated with contractile elements and mitochondria, which ensure a high level of energy metabolism. This structural organisation reflects the more intense functional load on this part of the heart, caused by the need to maintain systemic blood circulation.

Thus, the ambiguous cytometric parameters of atrial cardiomyocytes relative to the ventricles of the heart that we have identified indicate a lower morphofunctional load on the contractile myocytes of the atria compared to the cardiomyocytes of the ventricles, whose action we associate with the morphofunctional activity of the heart: the atria receive blood returning to the heart from the body of animals, while the ventricles pump blood from the heart to the body, performing the greatest load.

These functional differences determine the formation of specific morphological characteristics of atrial and ventricular myocardial cells. Ventricular cardiomyocytes are characterised by greater thickness, increased cytoplasmic volume, and a well-developed contractile apparatus and mitochondrial complex, which ensures their ability to withstand significant mechanical and electrophysiological loads associated with blood ejection into the systemic and pulmonary circulatory systems. This structural organisation helps maintain a high level of contractile activity and haemodynamic stability under conditions of constant functional stress.

In contrast, atrial myocardial cells are characterised by relatively lower mass, thinner myofibrils and less pronounced development of the energy apparatus, which corresponds to their role in the filling phase of the heart and the movement of blood to the ventricles. The established cytometric differences reflect the patterns of morphofunctional specialisation of different parts of the heart and indicate a close relationship between the structural organisation of cardiomyocytes and the nature of their functional load. Such differentiation of cell composition is an important condition for the coordinated and effective work of the heart as a whole organ.

3.1.5. Morphology of the Heart of Cattle (*Bos Taurus taurus L.,* 1758 – domestic bull)

The study of morphological features of the heart of cattle is important for modern veterinary morphology, clinical diagnostics and comparative anatomy, since this species is not only economically significant, but also biologically indicative for studying the patterns of structural and functional organisation of organs in large mammals. Analysis of the anatomical and histological characteristics of the heart allows us to establish the relationship between body weight, metabolic rate and haemodynamic characteristics.

The domestic bull (Bos taurus taurus L., 1758) is a member of the cattle genus, one of the most important agricultural species, bred for meat, milk and other livestock products. As an animal large in mass and body volume, the bull needs a powerful circulatory system capable of transporting significant volumes of blood, maintaining stable blood pressure and effective gas exchange in tissues.

The morphological features of the heart in cattle reflect a high degree of adaptation to physiological stress and have pronounced species characteristics that are important for anatomical analysis, veterinary practice and comparative morphology. The large body size, intensive digestive processes in the multi-chambered stomach, active muscle activity, and the need for thermoregulation determine the corresponding structural features of the myocardium and vascular bed.

The heart of cattle, as representatives of cloven-hoofed ruminants, is characterised by a well-developed anatomical (Fig. 3.59; 3.60) and histological organisation, which ensures a reliable blood supply in accordance with the specifics of the digestive, respiratory and musculoskeletal systems.

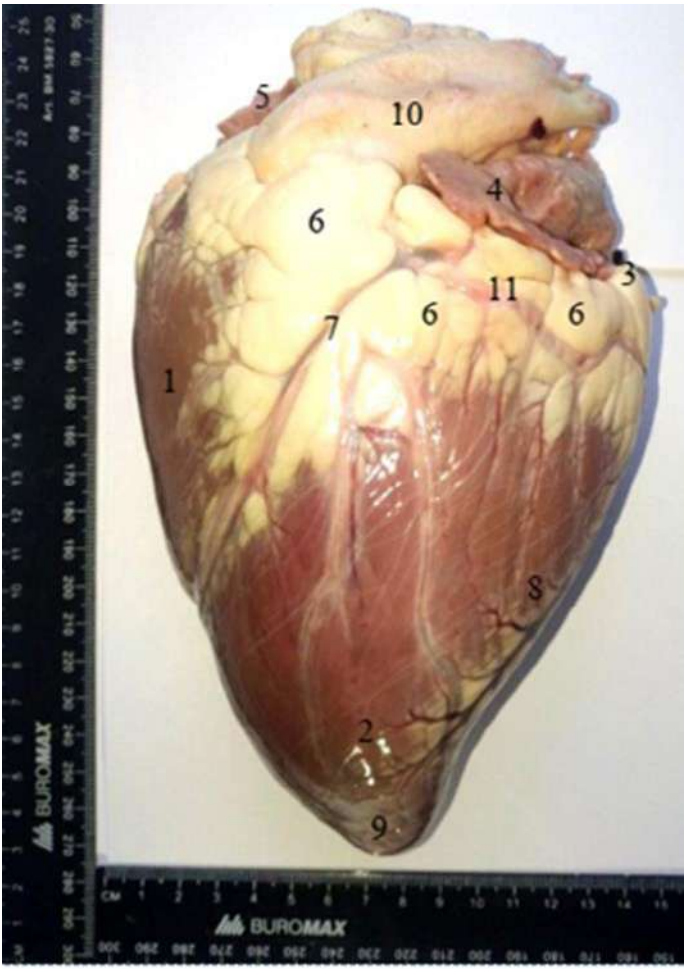

Fig. 3.59. Macroscopic structure of the heart of sexually mature cattle (projection of the heart from the left side): 1 – right ventricle; 2 – left ventricle; 3 – left atrium; 4 – left auricle; 5 – right auricle; 6 – subepicardial fat; 7 – conal interventricular sulcus; 8 – median interventricular sulcus; 9 – apex of the heart; 10 – pulmonary trunk; 11 – left unpaired vein. Macro specimen.

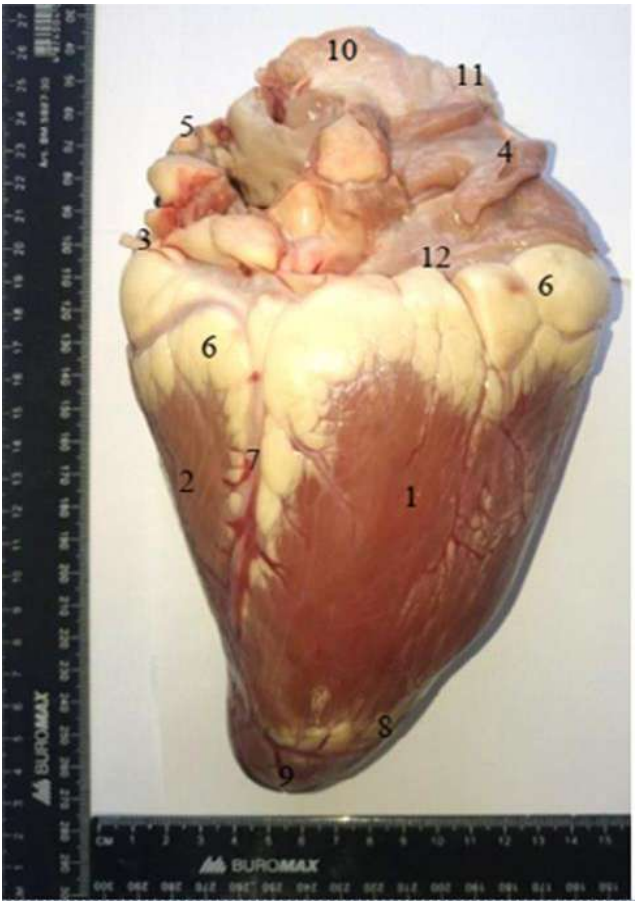

Fig. 3.60. Macroscopic structure of the heart of sexually mature cattle (projection of the heart from the right side): 1 – right ventricle; 2 – left ventricle; 3 – left atrium; 4 – right auricle; 5 – pulmonary veins; 6 – subepicardial fat; 7 – subaortic interventricular groove; 8 – apical interventricular groove; 9 – apex of the heart; 10 – aorta; 11 – brachiocephalic trunk; 12 – right atrium. Macro preparation.

The morphological features of this organ reflect the general patterns characteristic of mammals, but also have pronounced species differences due to the significant body weight, circulating

blood volume and high requirements for maintaining stable haemodynamics. These features indicate a close relationship between the structural organisation of the heart and the functional needs of the body, which determines its adaptive potential.

The heart of large cattle (Fig. 3.59; 3.60) is located in the chest cavity between both lungs, in front of the diaphragm and shifted to the left. In the area of the 3rd and 4th ribs, the heart is adjacent to the left chest wall. The apex of the heart lies in the area of the 5th costal cartilage. Its absolute mass is 2143.27 ± 38.76 g, and its relative mass is 0.43 ± 0.006%.

The heart of large horned cattle is cone-shaped (Fig. 3.59; 3.60). Its base is dorsal, and its apex is ventral. Internally, the heart cavity is divided by a septum into left and right halves, which are divided, respectively, into atria and ventricles. The atria and ventricles are connected to each other by the atrioventricular opening. The atria are usually located at the very base of the heart. Externally, the atria are separated from the ventricles by a transverse coronary sulcus, which is well visualised.

The right and left atria at the base of the heart form sac-like protrusions – the right and left cardiac ears, which are directed in the cranial direction and located to the right and left, respectively, of the pulmonary artery trunk and aorta. The ventricles occupy the dominant part of the heart and are separated externally by the interventricular and subaortic sulci, which connect on the cranial surface of the heart without reaching the apex and separate the right ventricle from the left. The apex of the heart in cattle refers to the left ventricle. The left ventricle is located on the left and caudally, while the right ventricle is located cranially and on the right. The interventricular sulci are similarly located (subcostal – caudally, bicuspid – cranially) (Fig. 3.59; 3.60).

The net weight of the heart, excluding epicardial fat, in cattle is 1936.26±41.12 g. The height of the heart is 23.08±0.11

cm, width – 13.9±0.18 cm, thickness – 8.1±0.12 cm, circumference – 38.08±0.9 cm. At the same time, the heart development (shape) index in cattle is 166.04±5.14 %, therefore the heart is defined as an elongated-narrowed (cone-shaped) type (Fig. 3.59; 3.60; Table 3.13).

According to the analysis of linear indicators, the wall thickness of the left ventricle is 1.98 times greater than that of the right ventricle ($p \leq 0.01$) and is 36.54±0.64 mm, while that of the right ventricle is 18.46±0.52 mm. The wall thickness of the atria is 7.69±0.23 mm (Table 3.13).

Table 3.13

Linear parameters of the heart of sexually mature cattle (*Bos Taurus taurus L.,* 1758), M ± m, n = 5

Parameter	Numerical Value
1. Heart height (cm)	23,08 ±0,11
2. Heart width (cm)	13,9±0,18
3. Heart thickness (cm)	8,1±0,12
4. Heart circumference (cm)	38,08±0,9
5. Cardiac development (shape) index (%)	166,04±5,14
6. Mean ventricular wall thickness (mm)	27,68± 0,36
7. Left ventricular wall thickness (mm)	36,54 ± 0,64
8. Right ventricular wall thickness (mm)	18,46 ± 0,52
9. Mean atrial wall thickness (mm)	7,69 ± 0,23
10. Left atrial wall thickness (mm)	8,24±0,12
11. Right atrial wall thickness (mm)	7,22±0,09

According to morphometric results, the thickness of the heart ventricle walls is closely related to the mass of the left and right ventricles themselves. Thus, the mass of the left ventricle is 978.54±19.52 g (50.87±1.32%), and the mass of the right ventricle is 554.17±14.21 g (28.62±0.64%). The average mass of

both ventricles (right and left) is 1539.08±49.74 g (79.49±2.18%). At the same time, the mass of the atria is 397.18±11.21 g (20.51±0.42%): left – 255.02±8.04 (13.17±0.21%), right – 142.16±6.72 g (7.34±0.09%). Accordingly, the ratio of the mass of the ventricles to its pure (without epicardial fat) mass is 1:0.8, the ratio of the mass of the atria to the pure mass of the heart is 1:0.2, and the ratio of the mass of the atrial myocardium to the mass of the ventricular myocardium is 1:0.26 (Table 3.14).

Table 3.14

Morphometry of the heart, ventricles and atria of sexually mature cattle (*Bos Taurus taurus L.,* 1758), M ± m, n = 5

Parameters	AM (g)	VM (%)
1. Left atrium	255,02±8,04	13,17±0,21
2. Right atrium	142,16±6,72	7,34±0,09
3. Right and left atria (together)	397,18±11,21	20,51±0,42
4. Left ventricle	984,91±19,52	50,87±1,32
5. Right ventricle	554,17±14,21	28,62±0,64
6. Left and right ventricles (together)	1539,08±49,74	79,49±2,18
7. Heart weight (without epicardial fat)	1936,26±41,12	100
8. Ratio of ventricular mass to net heart mass	1:0,8	
9. Ratio of atrial mass to net heart mass	1:0,2	
10. Ratio of atrial myocardial mass to ventricular myocardial mass	1:0,26	

The wall of the heart is formed by three layers: the inner layer – the endocardium, the middle layer – the myocardium, and the outer layer – the epicardium. Each of them has characteristic

structural features and performs specific functions in ensuring the activity of the organ. The endocardium is represented by a layer of endothelium with subendothelial connective tissue that lines the heart cavities and forms the valve apparatus, ensuring the smoothness of the inner surface and optimal conditions for blood flow.

The middle layer is the myocardium, a striated cardiac muscle tissue that forms the bulk of the heart wall and determines its contractile capacity. Cardiomyocytes are organised into a complex system of muscle fibres that ensures rhythmic and coordinated contractions. The outer layer, the epicardium, is formed by connective tissue covered with mesothelium and is the visceral layer of the serous pericardial membrane; it performs a protective function and participates in the trophic supply of the myocardium.

The dominant mass of the heart wall is formed by the muscular membrane – the myocardium, the thickness of which varies depending on the functional load of individual heart chambers, reflecting their morphofunctional specialisation.

The myocardium of the atria is formed by two layers: the outer layer (common to both atria) and the deep layer. The muscle fibres of the outer layer of the myocardium run transversely from one ear to the other. The deep layer of the myocardium in the right and left atria has a longitudinal direction. At the same time, circular bundles of fibres are found in the area of the venous openings.

The walls of the ventricles of the myocardium are thicker than the walls of the atria, which is related to their functional activity. At the same time, the ventricular myocardium is formed by five layers: the outer and inner layers, whose muscle fibres have an oblique longitudinal direction, then the outer and inner deeper layers and the deepest layer.

The microscopic structure of the heart myocardium is formed by transversely striated muscle fibres, which are made up of cells – cardiomyocytes, which are connected to each other in muscle fibres by intercalated discs (Fig. 3.61).

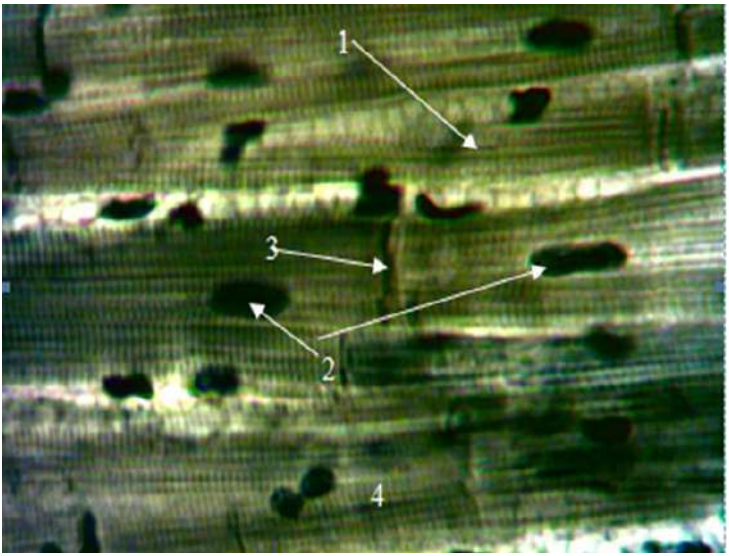

Fig. 3.61. Мікроскопічна будова міокарда лівого шлуночка серця статевозрілої великої рогатої худоби: 1 – кардіоміоцити; 2 – ядра кардіоміоцитів; 3 – вставні диски; 4 – поперечна посмугованість. Фарбування за методом Гейденгайна. х 600.

Under a light microscope, on histological preparations stained using the Heidenhain method, cardiomyocytes appear as intensely stained transversely striated structures with clearly defined contours. The cells show well-differentiated sarcolemma, sarcoplasm with numerous myofibrils, and centrally located oval or elongated nuclei (Fig. 3.61). Most cardiomyocytes have one nucleus, less often two, which is a characteristic feature of cardiac muscle tissue.

Myofibrils, oriented along the long axis of the cell, form characteristic transverse striations, which are caused by the orderly alternation of light and dark bands. This organisation reflects the regular arrangement of thin (actin) and thick (myosin) myofilaments in the sarcomeres, the structural and functional units of the contractile apparatus. Between the myofibrils is sarcoplasm with a large number of mitochondria, indicating a high level of energy supply to the cells.

Thanks to this structural organisation, cardiomyocytes are capable of rhythmic, powerful and synchronised contractions, which ensure the continuous pumping function of the heart and maintain effective haemodynamics.

Muscle fibres are connected to each other by anastomoses, thus forming a net-like structure. Between the muscle fibres are layers of intermuscular connective tissue, where blood and lymphatic vessels are located (Fig. 3.62; 3.63).

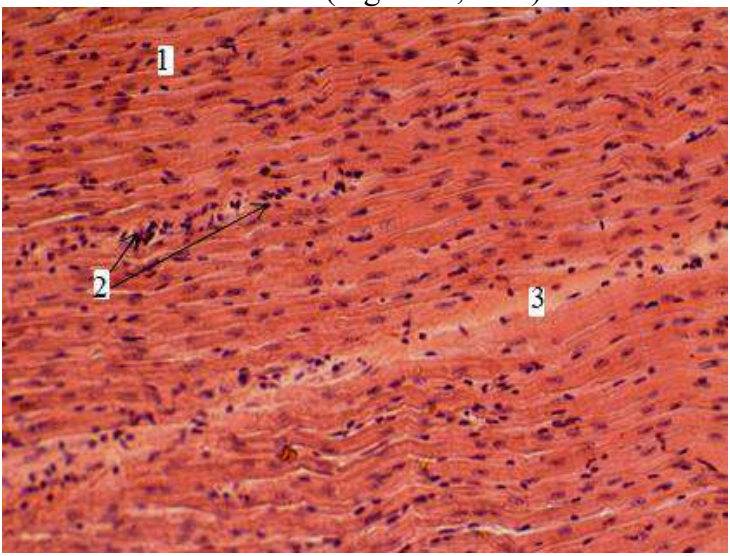

Fig. 3.62. Microscopic structure of the right ventricular myocardium of sexually mature cattle: 1 – muscle fibres; 2 – cardiomyocyte nuclei; 3 – intermuscular connective tissue. Haematoxylin and eosin. x 120.

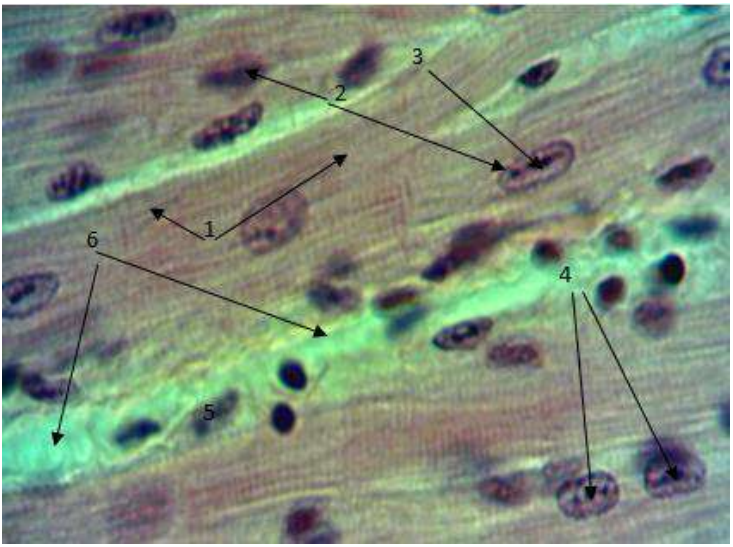

Fig. 3.63. Microscopic structure of the right ventricular myocardium of sexually mature cattle: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – nucleoli; 4 – nuclear chromatin; 5 – anastomoses; 6 – intermuscular connective tissue. Haematoxylin and eosin. x 600.

In muscle fibres, longitudinal (due to myofibrils) and transverse (due to actin and myosin proteins) striations are clearly differentiated (Fig. 3.61). At the same time, myofibrils, which are densely located next to each other, are located closer to the periphery of the fibres and pass from one fibre to another through anastomoses. With a relatively small number of myofibrils, the longitudinal striations of cardiomyocytes are clearly expressed, while the transverse striations are relatively weak. In addition, cardiomyocytes are significantly larger in width, poorly stained, their transverse striations are weakly expressed, and myofibrils in such cases acquire a refined shape.

Cardiomyocytes are narrow in width and oval in cross-section, with myofibrils arranged more densely. In the centre of cardiomyocytes there is one, rarely two nuclei, oval or elongated in shape, which are unevenly distributed. Nuclear chromatin in the

form of small or larger grains is found around the entire perimeter of the karyoplasm (Fig. 3.63).

According to the results of our cytometric studies, cardiomyocytes that form muscle fibres have ambiguous morphometric parameters depending on their morphotopography (left, right ventricles, atria).

Our detailed analysis of cytometric studies of myocardial microstructures shows that the quantitative indicators of cardiomyocytes in the left ventricle of the heart are higher than those in the right ventricle. Thus, in cattle, the length of cardiomyocytes in the left ventricle is 1.16 times greater than in the right ventricle and amounts to 72.02±1.08 μm, while the width of cardiomyocytes is 1.1 times greater and amounts to 14.06±0.41 μm. We found similar changes in a morphometric study of cardiomyocyte volumes and their nuclei. The largest cardiomyocyte volume is observed in the left ventricle – 11225.73±824.42 μm^3. In the right ventricle of the heart, this indicator is 1.4 times smaller and amounts to 7963.60±627.09 μm^3, respectively. Similar changes are observed when determining the volume of cardiomyocyte nuclei, which was larger in the nuclei of left ventricular cardiomyocytes – 124.55±7.99 μm^3 and slightly smaller in the right ventricle – 121.67±7.02 μm^3 (Table 3.15; Fig. 3.64). Therefore, ventricular cardiomyocytes had different nuclear-cytoplasmic ratios, which were lowest in left ventricular cardiomyocytes (0.0113±0.0068) and significantly higher in right ventricular cardiomyocytes (0.0156±0.0054), indicating their morphofunctional activity (Table 3.15; Fig. 3.64).

Cytometric analysis of cardiomyocytes from different parts of the heart revealed clear differences in their morphometric parameters, reflecting the degree of functional load and the level of cell specialisation.

The smallest morphometric parameters (length, width of cardiomyocytes, volume of cardiomyocytes, volume of their nuclei) were found in atrial cardiomyocytes, in which the YCV was the largest and amounted to 0.0234±0.0058, respectively (Table 3.15;

Fig. 3.65), which indicated a lower morphofunctional load of atrial cardiomyocytes compared to ventricular cardiomyocytes, since the most morphofunctionally active and mature somatic cells are those characterised by a low YCV index and, conversely, cells with a high YCV are less functionally active. This indicates that atrial cardiomyocytes have less load due to their role in more limited mechanical pumping function, while ventricular cardiomyocytes perform a more intensive and important function in the blood circulation process, which requires greater morphological and functional maturity.

The results obtained are consistent with the functional role of the atria in the cardiac cycle, which perform mainly reservoir and conduction functions, ensuring the accumulation and transfer of blood to the ventricles. While ventricular cardiomyocytes perform the main pumping load associated with the ejection of blood into the circulatory system, which causes greater morphological differentiation, cytoplasm volume and functional maturity of these cells.

Table 3.15

Histometric parameters of cardiomyocytes of sexually mature cattle (Bos Taurus taurus L., 1758), M ± m, n = 5

Parameter	Cardiomyocyte Length (μm)	Cardiomyocyte Width (μm)	Cardiomyocyte Volume (μm³)	Cardiomyocyte Nuclear Volume (μm³)	Nuclear-to-Cytoplasmic Ratio
Left ventricle	72,02±1,08	14,06±0,41	11225,73±824,42	124,55±7,99	0,0113±0,0068
Right ventricle	62,07±1,23	12,79±0,38	7963,60±627,09*	121,67±7,02	0,0156±0,0054*
Atria	56,08±1,37*	10,02±0,46*	5361,50±583,91**	101,05±6,04*	0,0234±0,0058**

Note: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$ in relation to the left ventricle.

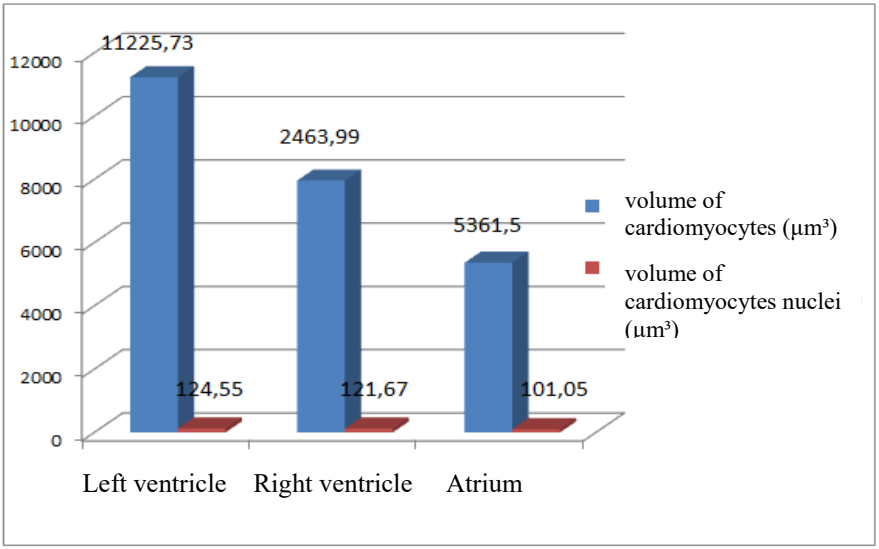

Fig. 3.64. Histometric parameters of cardiomyocytes in the heart myocardium of sexually mature cattle.

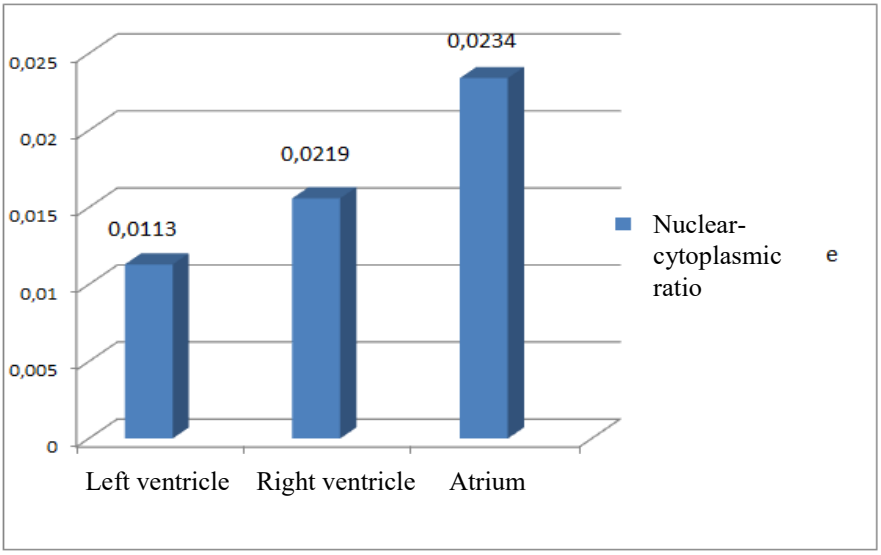

Fig. 3.65. Nuclear-cytoplasmic ratio of cardiomyocytes in the heart myocardium of sexually mature cattle.

3.1.6. Morphology of the Heart of the Domestic Horse (*Equus ferus Caballus L.,* 1758)

The domestic horse (*Equus ferus caballus L.,* 1758) is one of the most resilient and physiologically active members of the class Mammalia, possessing a highly organised cardiovascular system. Due to its large body mass, high mobility and rapid metabolic processes, the horse's heart is characterised by its considerable size, powerful myocardium and distinct chamber structure. The morphological structure of the heart ensures effective blood supply during prolonged physical exertion and is indicative of the adaptations of homeothermic animals to an active lifestyle.

The biological uniqueness of the horse as a species is largely linked to its evolutionary history and its development as a specialised cursorial (running) organism. During the course of phylogeny, members of the genus Equus underwent a series of morpho-functional changes aimed at improving the efficiency of prolonged movement across open landscapes, accompanied by a corresponding restructuring of their life-support systems, particularly the cardiovascular system.

From an ecological perspective, the horse belongs to a group of species with a high level of aerobic capacity, which results in increased demands on the transport of oxygen and nutrients. This specialisation reflects the general biological principles governing the functioning of organisms with an intense metabolic rate and a high level of physical activity. In this context, the heart acts not only as a circulatory organ, but also as the central link in the integration of physiological processes that ensure adaptation to physical exertion.

Furthermore, the domestic horse serves as an important model for studying the relationship between the structure and

function of organs in large mammals. Their use in veterinary practice, sport and human economic activities necessitates a thorough understanding of the biological foundations of cardiovascular system function, particularly in terms of individual variability, adaptive capacity and responses to extreme factors.

Particular attention should be paid to issues of breed, age and functional differences, which determine the specific characteristics of cardiac activity in different groups of animals. Taking these characteristics into account is important for assessing physiological status, predicting endurance and the timely detection of pre-disease changes.

In addition to its practical significance, research into the cardiovascular system of the horse is of fundamental biological interest, as it enables us to trace the general principles of the organism's morphofunctional integration, the mechanisms of adaptation to prolonged exertion, and the patterns underlying the development of functional reserves. This, in turn, broadens our understanding of the evolutionarily developed strategies for ensuring a high level of performance in large homeothermic animals.

In this context, the study of the horse's heart takes on not only a descriptive but also a systemic significance, as it allows us to view it as a component of the organism's unified functional system. A comprehensive approach to the analysis of the cardiovascular system facilitates a deeper understanding of the mechanisms of interaction between organs and systems that ensure adaptation to changes in the external and internal environment. Such an approach is a necessary prerequisite for forming a holistic understanding of the patterns of functioning of the organism of large mammals and provides a scientific basis for further morphological and physiological research.

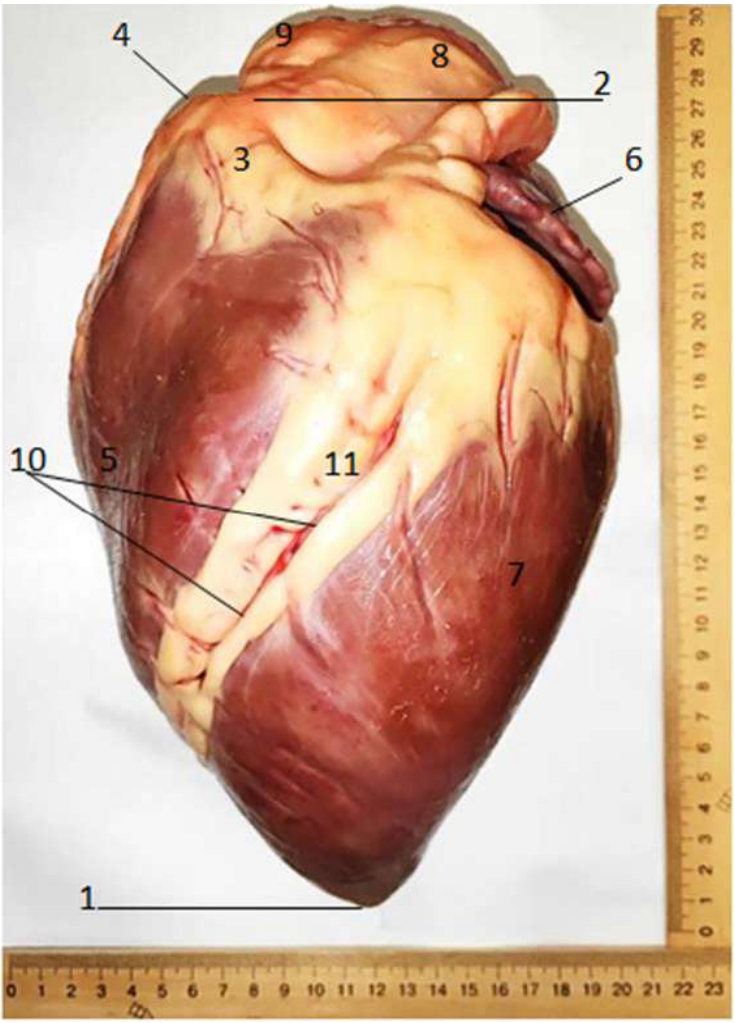

Fig. 3.66. Anatomical structure of the heart of a sexually mature horse (left lateral view of the heart): 1 – apex of the heart; 2 – base of the heart; 3 – subepicardial fat; 4 – right atrium; 5 – right ventricle; 6 – left atrium; 7 – left ventricle; 8 – aorta; 9 – brachiocephalic trunk; 10 – subconal interventricular sulcus; 11 – blood vessels. Macroscopic specimen.

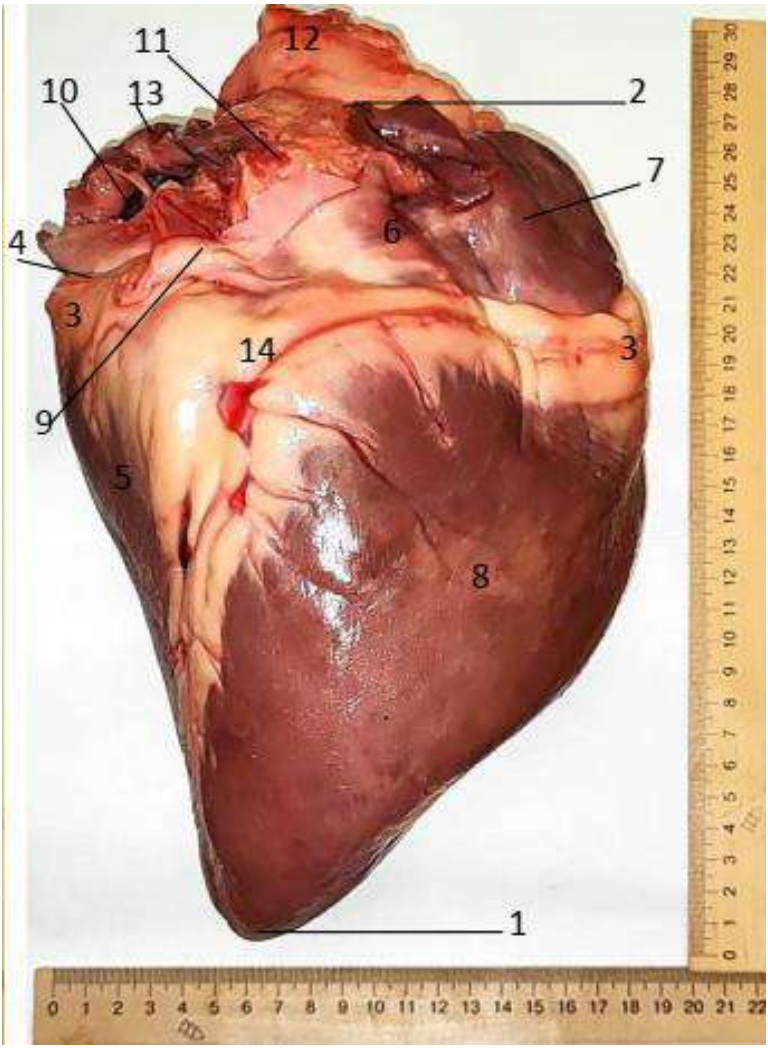

Fig. 3.67. Anatomical structure of the heart of a sexually mature horse (right-sided view of the heart): 1 – apex of the heart; 2 – base of the heart; 3 – subepicardial fat; 4 – left atrium; 5 – left ventricle; 6 – right atrium; 7 – right atrial appendage; 8 – right ventricle; 9 – fragment of the pericardium; 10 – caudal vena cava; 11 – cranial vena cava; 12 – aorta; 13 – pulmonary veins; 14 – subcostal interventricular groove. Macroscopic specimen.

The heart of an adult horse is cone-shaped (Fig. 3.66; 3.67). It is situated in the thoracic cavity between the right and left lungs. A significant portion of the heart lies to the left of the midline (sagittal) plane, beneath the lungs, in the region of the 3rd–4th intercostal spaces. Cranially, the heart is bounded by the third rib, and caudally by the costal cartilage of the fifth rib. The broad base of the heart lies at the level of the shoulder joint in the craniodorsal direction. The apex of the heart points caudoventrally and is situated extremely close to the sternum.

Externally, the horse's heart is enclosed within a distinctive sac (membrane) known as the pericardium, which consists of two layers separated by a space. The inner layer is firmly attached to the heart sac; it is called the visceral layer or epicardium. The outer layer consists of fairly inelastic connective tissue – the parietal layer. The space between the layers contains a small amount of fluid, which acts as a lubricant.

According to morphometric studies, the absolute heart weight is 2987.6±96.84 g, which accounts for 0.59±0.012% (relative weight) of the animals' total body weight. The net heart weight is 2807.32±92.79 g (Table 3.16).

On examination of the horse's heart, the left and right lateral (side) surfaces are clearly defined, as are the left and right ventricular margins (Fig. 3.66; 3.67).

The heart of a horse, like that of the other domestic mammals we have studied, is four-chambered and consists of two atria (the upper, dorsal, small chambers) and two ventricles (the lower, ventral, large chambers) (Fig. 3.66; 3.67). The atria serve as the main reservoirs for blood returning to the heart, ensuring the subsequent filling of the ventricles. The ventricles, in turn, perform the main work of pumping blood through the pulmonary artery to the lungs and through the aorta to the rest of the body's organs and systems. On the cranial plane of the right and left atria,

small projections are visible – the cardiac auricles, which are clearly defined and located on the left near the base of the aorta and the pulmonary trunk (Fig. 3.66; 3.67). On the outer surface of the heart, between the atria and ventricles, the coronary sulcus is visible.

Table 3.16

Linear parameters of the heart of a sexually mature horse (Equus ferus Caballus L., 1758), M ± m, n = 5

Parameter	Numerical Value
1. Heart height (cm)	30,26 ±0,38
2. Heart width (cm)	20,52±0,29
3. Heart thickness (cm)	12,8±0,21
4. Heart circumference (cm)	54,16±1,94
5. Cardiac development (shape) index (%)	147,52±7,36
6. Mean ventricular wall thickness (mm)	30,55± 0,76
7. Left ventricular wall thickness (mm)	40,14±0,88
8. Right ventricular wall thickness (mm)	20,92±0,54
9. Mean atrial wall thickness (mm)	10,53±0,32
10. Left atrial wall thickness (mm)	11,02±0,16
11. Right atrial wall thickness (mm)	10,05±0,14

The right ventricle of the horse's heart occupies a significant portion of the organ's cranial margin. In cross-section, it is crescent-shaped. The left ventricle is situated in the apical region of the heart and has a conical shape (Fig. 3.66; 3.67).

According to linear measurements of the heart and its components, the height of the organ in a horse is 30.26±0.38 cm, the width is 20.52±0.29 cm, the thickness is 12.8±0.21 cm, and the circumference is 54.16±1.94 cm. Moreover, the heart development (shape) index of the horse is 147.52±7.36 % (Table

3.16), therefore the heart of the domestic horse (Equus ferus Caballus L., 1758) is classified as of the dilated-shortened type.

The wall of the heart is composed of three layers: the epicardium (outer layer), the myocardium (middle layer) and the endocardium (inner layer). These layers work in close cooperation to ensure the heart functions normally, maintain its structural integrity and enable it to perform its primary function – pumping blood – effectively.

The outer layer of the heart is the thinnest; it is formed of delicate connective tissue. It contains nerves and large blood vessels.

The middle layer – the myocardium – is highly developed and consists of many layers of muscle tissue. It forms the main muscular layer of the heart wall. In the atria, the muscular layer comprises two layers: an outer layer and a deep layer. The outer layer of the myocardium is common to both atria, where the muscle fibres run transversely from one auricle to the other. The deep layer of the myocardium in the right and left atria runs longitudinally, and circular bundles of fibres are found in the region of the venous openings.

The myocardium of the heart's ventricles consists of five layers: the superficial outer and inner layers (whose muscle fibres are arranged in an obliquely longitudinal direction); the middle outer and inner layers (a deeper layer) and the deepest layer, in which the direction of the fibres resembles the shape of the number 'eight'.

The inner lining (endocardium) of the heart consists of a thin layer of endothelium, which is covered on the outside by a thin layer of loose connective tissue containing smooth muscle fibres. It forms a soft lining of the inner surface of the heart chambers and valves.

The left atrium, like the right atrium, is a thin-walled chamber located in the dorsal part of the heart. The right and left atria are separated by a relatively thin interatrial septum. The left and right ventricles of the heart are thick-walled chambers separated by the interventricular septum.

Measurements of the thickness of the walls of the horse's ventricles show that their total thickness is 30.55 ± 0.76 mm. The wall of the left ventricle (40.14 ± 0.88 mm) of the horse's heart is significantly ($p \leq 0.01$) 1.92 times thicker than that of the right ventricle (20.92 ± 0.54 mm). This increase in LV wall thickness compared to the right ventricle is associated with the significant development of the heart's musculature (myocardium), which in horses reaches up to 4 cm or even more, due to the fact that the contractile cardiomyocytes of the LV muscles perform an increased workload during operation, pumping blood (the systemic circulation) throughout the body under pressure. Thanks to this unique specific structure, the horse's heart functions, accordingly, as a blood circulation pump within the body, and the circulatory system maintains a constant unidirectional flow of blood within a closed vascular system. The reduced thickness of the right ventricle (RV) wall, compared to the left, is explained by the fact that the muscles of the right ventricle pump blood from the corresponding chamber into the small – pulmonary – circulatory system, thereby performing a lesser functional load than the LV muscles, as they pump blood throughout the entire body.

According to the results of morphometric analysis, the wall thickness of the left atrium of the horse's heart is 11.02 ± 0.16 mm, and that of the right atrium is 10.05 ± 0.14 mm; consequently, the atrial walls have a less developed muscular layer than the ventricles. The mean thickness of the atrial walls in horses is 10.53 ± 0.32 mm, which is significantly ($p \leq 0.001$) 2.9

times less than that of the ventricles (Table 3.16). This is explained by the fact that the main function of the atrial muscles is to pump blood in a ventral direction into the corresponding ventricles of the heart.

According to the results of morphometric analysis of the absolute mass of the ventricles and atria, the mean mass of the left atrium (LA) in the horse's heart is 338.67 ± 14.52 g, which represents 12.06 ± 0.47% of the net (epicardial fat-free) heart mass. The average mass of the right atrium is 212.91 ± 10.77 g (7.58 ± 0.11%), which is significantly ($P < 0.01$) 1.6 times lower than that of the left atrium. The average mass of both atria of the horse's heart is 551.57±42.34 g (19.64±0.51%) (Table 3.17).

Table 3.17

Morphometry of the heart, ventricles and atria of a sexually mature horse (Equus ferus Caballus L., 1758), M ± m, n = 5

Parameters	AM (g)	VM (%)
1. Left atrium	338,67±14,52	12,06±0,47
2. Right atrium	212,91±10,77	7,58±0,11
3. Right and left atria (together)	551,57±42,34	19,64±0,51
4. Left ventricle	1484,12±28,74	52,87±4,08
5. Right ventricle	771,63±19,27	27,49±0,82
6. Left and right ventricles (together)	2255,75±88,69	80,35±4,29
7. Heart weight (without epicardial fat)	2807,32±92,79	100
8. Ratio of ventricular mass to net heart mass	1:0,80	
9. Ratio of atrial mass to net heart mass	1:0,20	
10. Ratio of atrial myocardial mass to ventricular myocardial mass	1:0,24	

The absolute mass of the left ventricle is the highest, at 1484.12±28.74 g (52.87±4.08%), The mass of the right ventricle is, accordingly, significantly ($P < 0.01$) 1.9 times smaller than that of the LV and amounts to 771.63 ± 19.27 g (27.49 ± 0.82%). Overall, the mean AM of both ventricles is 2255.75 ± 88.69 g; accordingly, the relative mass to the total heart mass is 80.35 ± 4.29 % (Table 3.17).

The ratio of the absolute mass of the ventricles in a physiologically mature horse to the net (epicardial fat-free) heart mass is 1:0.8; the ratio of the absolute mass of the atria to the net heart mass is 1:0.20, and the ratio of the absolute mass of the atria to the ventricular AM is 1:0.24 (Table 3.17).

Microscopically, the structure of the myocardium consists of cardiac muscle tissue organised into muscle fibres, between which are layers of loose fibrous connective tissue known as endomysium. This tissue contains blood and lymphatic vessels, as well as nerve elements that provide trophism, drainage and neurogenic regulation of the heart muscle. The connective tissue component plays an important role in maintaining the structural integrity of the myocardium, ensuring the spatial organisation of cardiomyocytes and their functional interaction.

Muscle fibres are formed by cardiomyocytes (contractile myocytes), which have an elongated, branched shape and are arranged in chains (Fig. 3.68; 3.69). By interconnecting in different planes, cardiomyocytes form a three-dimensional reticular structure, which distinguishes cardiac muscle tissue from somatic striated muscle, despite their morphological similarity. The cytoplasm of cardiomyocytes contains a well-developed contractile apparatus, consisting of myofibrils with characteristic transverse striations, as well as a significant number of mitochondria, which accounts for the high level of oxidative processes.

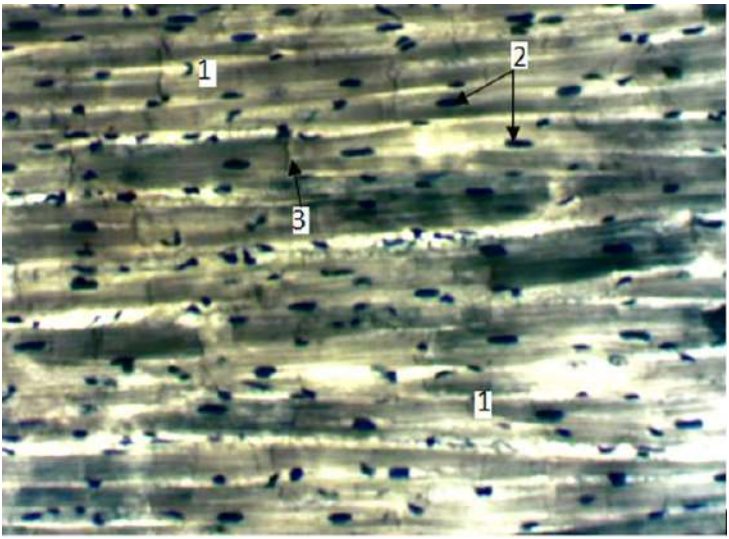

Fig. 3.68. Microscopic structure of the right ventricular myocardium of a sexually mature horse: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs. Stained using the Heidenhain method. ×400.

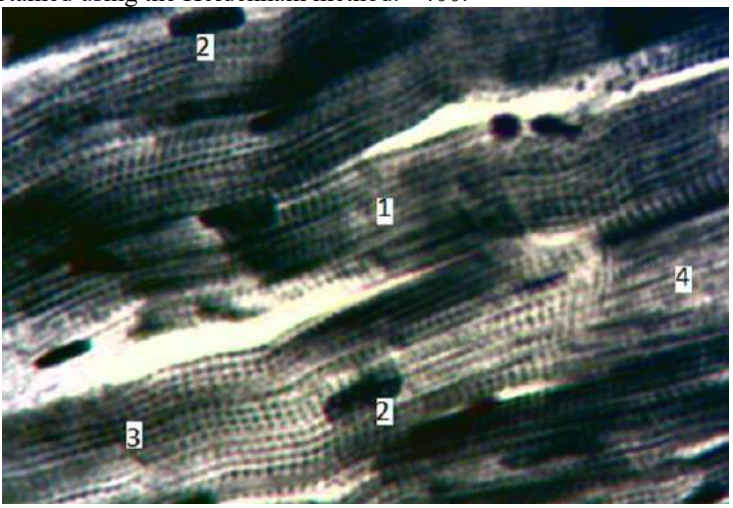

Fig. 3.69. Microscopic structure of the left ventricular myocardium of a sexually mature horse: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – transverse striations; 4 – longitudinal striations. Stained using the Heidenhain method. ×600.

Cardiomyocytes are connected to one another by means of intercalated discs (Fig. 3.70), which are complex, specialised structures of cell-cell contact. These consist of desmosomes and adhesion junctions, which provide mechanical strength and transmit contractile force, as well as gap junctions (nexuses), which facilitate the rapid propagation of electrical impulses between cells. This organisation achieves the electromechanical unity of the myocardium, manifested in the synchronous contraction of cardiomyocytes and the formation of a functional syncytium.

Contractile myocytes are cylindrical in shape; in their sarcoplasm, particularly when stained using the Heidenhain method, distinct transverse and longitudinal striations are clearly visible (Fig. 3.70).

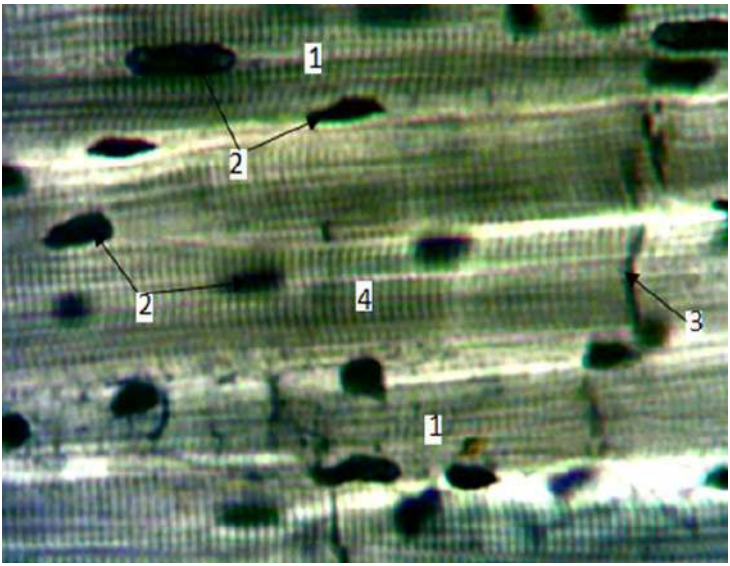

Fig. 3.70. Microscopic structure of the myocardium of the left ventricle of the heart of an adult horse: 1 – cardiomyocytes; 2 – cardiomyocyte nuclei; 3 – intercalated discs; 4 – cross striations. Stained using the Heidenhain method. ×600.

When examined under a light microscope, cardiomyocytes in a longitudinal section appear as elongated structures with characteristic transverse striations, caused by the alternation of light and dark bands within the sarcomeres. The sarcolemma, densely packed myofibrils and centrally located nuclei are clearly visible in the cells. The latter are usually oval or elongated in shape, corresponding to the spatial organisation of cardiomyocytes and their functional load.

Our own research has shown that the microscopic structure of the domestic horse's heart and its anatomical components share a histoarchitectonic pattern typical of domestic animals of the Mammalia class, yet differ in their cytometric parameters. Thus, cytometric results show that cardiomyocytes, which form the muscle fibres, have different quantitative cytometric values depending on their functional load (right and left ventricles, atria). In particular, the cardiomyocytes of the left ventricle, which are responsible for pumping blood into the aorta and the systemic circulation, are larger in size and contain a greater number of myofibrils compared to the cardiomyocytes of the right ventricle, which operate at a lower intensity and supply blood to the pulmonary circulation. This morphological and cytometric difference is due to the high functional load placed on the left ventricle, where muscle fibres must generate greater pressure to pump blood through large vessels. Compared to ventricular cardiomyocytes, atrial cardiomyocytes are smaller in size and have a different organisation of cytoskeletal elements, reflecting their lower functional load during the cardiac cycle. They act as reservoirs for blood entering the heart.

Thus, the volume of left ventricular cardiomyocytes in the myocardium of a domestic horse is significantly ($p \leq 0.05$) 1.49 times greater than that of the right ventricle (8400.67 ± 681.04 μm^3) and amounts to 12554.36 ± 877.52 μm^3. The volume of

atrial cardiomyocytes is the smallest and amounts to 5729.17 ± 513.37 μm³ (Table 3.18; Fig. 3.71). Calculations of the volume of ventricular and atrial nuclei yielded similar values: the volume of LV cardiomyocyte nuclei is 132.98 ± 9.12 μm³, and RA – 131.82 ± 7.92 μm³ and atria – 129.04 ± 7.76 μm³, (Fig. 3.71; Table 3.18).

Table 3.18

Histometric parameters of cardiomyocytes in a sexually mature horse (*Equus ferus Caballus L.*, 1758), M ± m, n = 5

Parameter	Cardiomyocyte Length (μm)	Cardiomyocyte Width (μm)	Cardiomyocyte Volume (μm³)	Cardiomyocyte Nuclear Volume (μm³)	Nuclear-to-Cytoplasmic Ratio
Left ventricle	77,99±1,62	14,32 ±0,72	12554,36± 877,52	132,98± 9,12	0,0107± 0,0074
Right ventricle	64,04±1,39	12,92±0,74	8400,67± 681,04*	131,82± 7,92	0,0159± 0,0098
Atria	60,98±1,40	10,94±0,73	5729,17± 513,37**	129,04± 7,76	0,0230± 0,0066

Note: * p≤0.05; ** p≤0.01; *** p≤0.001 in relation to the left ventricle.

Given these variable cytometric parameters for cardiomyocyte volumes and the almost uniform characteristics of their nuclear volumes, a distinct nuclear-cytoplasmic ratio has been established for each: the lowest NCR was observed in LV cardiomyocytes (0.0107±0.0074), significantly higher in right ventricular cardiomyocytes (0.0159 ± 0.0098), indicating enhanced functional activity of left ventricular cardiomyocytes, as the left ventricle functions primarily as a pump, whilst the right

ventricle functions as a reservoir. Therefore, the left ventricular cardiomyocytes of the heart bear a significantly greater load, facilitating blood flow through the vessels of the systemic circulation, whilst, correspondingly, the right ventricular cardiomyocytes bear a lesser load, facilitating blood flow through the vessels of the pulmonary circulation.

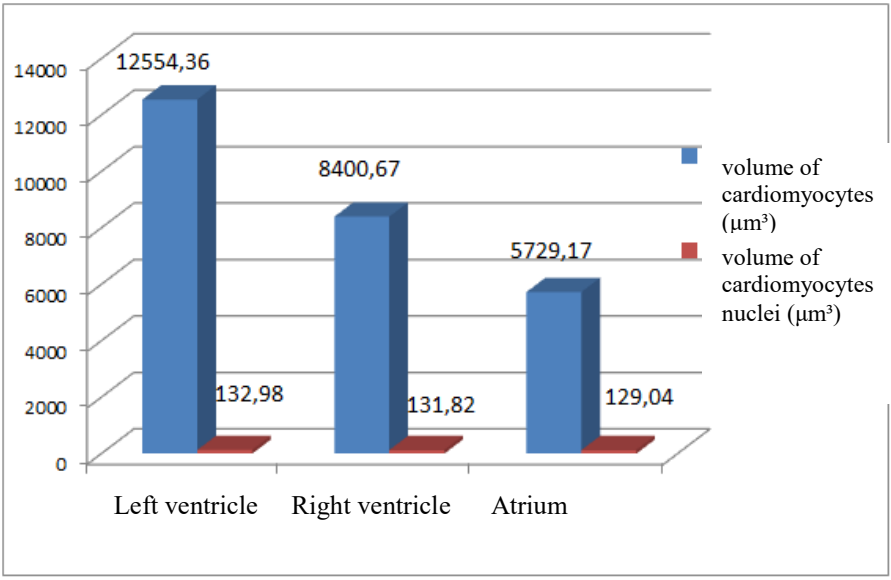

Fig. 3.71. Histometric parameters of cardiac myocytes in the myocardium of a sexually mature horse.

The highest YCV was observed in atrial cardiomyocytes – 0.023±0.0066 (Fig. 3.72; Table 3.18), which is associated with a significantly lower functional load on atrial cardiomyocytes compared with ventricular cardiomyocytes. After all, the more functionally active and mature cells are those characterised by a low YCV index, and, conversely, cells with a high YCV are less functionally active. And it is precisely for this reason that the

various cyto- and cardiometric parameters of the volumes of ventricular and atrial cardiomyocytes, and consequently the different YCV of contractile myocytes, are associated with the morphofunctional activity of the heart: the atria receive blood returning to the heart from the animal's body, whilst the ventricles pump blood from the heart to the body, bearing the greatest load.

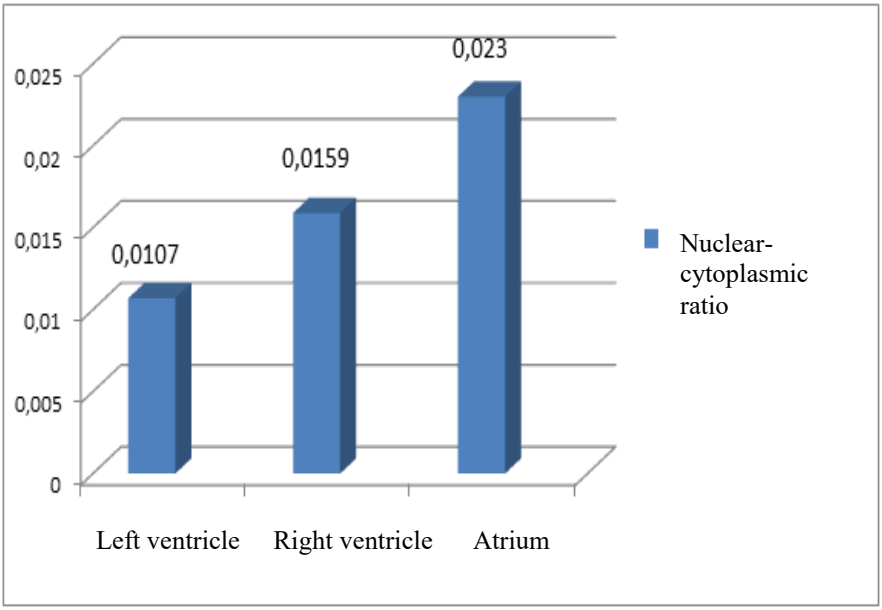

Fig. 3.72. The nuclear-cytoplasmic ratio of cardiac myocytes in the myocardium of a sexually mature horse.

Thus, the morphometric and cytometric differences observed in cardiomyocytes from different parts of the heart reflect their distinct functional specialisation, which forms the morphological basis for the heart's efficient and coordinated functioning as a single pumping organ.

3.2. Morphometry of the Heart in Domestic Mammals

3.2.1. Organometry of the Heart in Domestic Mammals

According to the results of organometric studies, the absolute and relative values of cardiac output and stroke volume in domestic mammals differ and are directly dependent on their body mass (Fig. 3.73; Table 3.19). It has been established that there is a clear correlation between body weight and cardiac parameters, reflecting the general biological patterns of allometric organ growth.

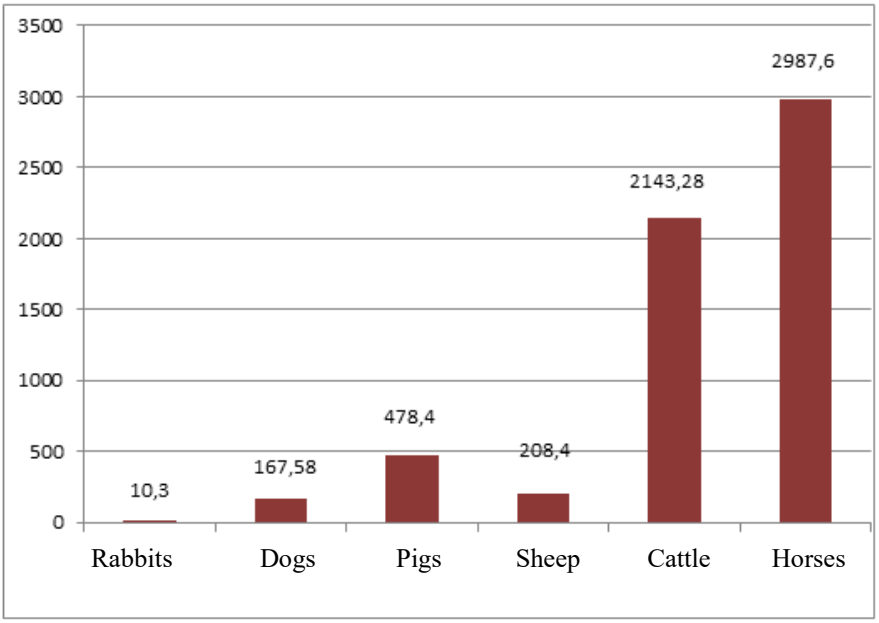

Fig. 3.73. Species-specific characteristics of the absolute heart mass in domestic mammals (g).

At the same time, the variability of organometric heart parameters may be influenced by functional load, the level of physical activity and the animal's physiological state. These features indicate the adaptive nature of changes in the heart, aimed at ensuring effective haemodynamics in accordance with the body's needs.

Thus, in rabbits, which are the smallest of the animals we studied, the absolute heart weight is the lowest, at 10.3±0.86 g. This figure is significantly higher in dogs, at 167.58±9.46 g. The largest absolute mass of the organ is found in large animals, namely cattle (2143.27 ± 38.76 g) and horses (2987.6 ± 96.84 g). In pigs and sheep, the absolute heart mass lies in between, amounting to 487.4 ±8.12 g and 208.4±9.82 g, respectively (Table 3.19).

Thus, according to the analysis of the results of morphometric studies, the absolute heart mass in domestic mammals varies and depends on the level of development of the animals in the phylogenetic series (the greater the body mass of the animals, the greater the absolute mass of the organ) (Fig. 3.73; Table 3.19).

The relative heart mass in domestic mammals varies depending on the species (their body weight) and the absolute mass of the organ. Thus, according to the results of our studies, the highest relative heart mass is found in dogs – 0.72±0.005%. The relative heart mass values in the other animals we studied are similar. However, in pigs, the relative heart mass is the lowest, at 0.29±0.004%, slightly higher in rabbits (0.31±0.008%), followed by cattle (0.43±0.006%), sheep (0.44±0.007%) and horses (0.59±0.012%) (Table 3.19; Fig. 3.74).

When analysing the organometric parameters of the heart and its components in domestic mammals, it should be noted that the linear parameters (height, width, thickness, circumference, the

heart's development or shape index) in experimental animals are directly dependent on the species, the structure and configuration of the thoracic cavity, the morphotopography of the heart, the absolute mass of the organ, and the ratio of heart mass to body mass. It is noted that the shape and size of the heart not only reflect species-specific characteristics but also determine its functional capabilities, in particular its ability to ensure effective haemodynamics and adaptation to various physiological loads.

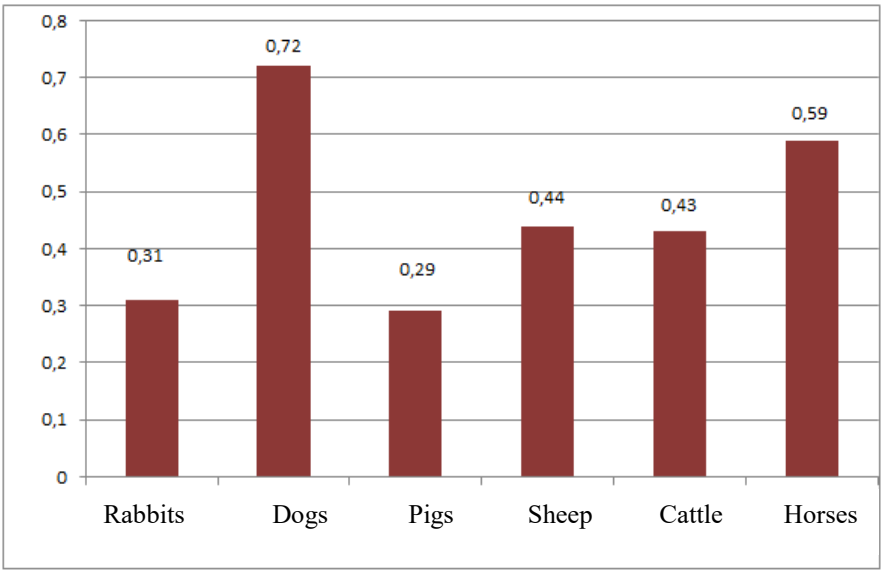

Fig. 3.74. Species-specific characteristics of the relative heart mass in domestic mammals (%).

Furthermore, the cardiac development index is an important morphometric parameter that enables the assessment of the organ's proportionality and adaptive potential, as well as the comparison of the morphofunctional characteristics of the heart across different groups of domestic mammals. This approach contributes to a deeper understanding of the relationship between

the structure, form and function of the cardiovascular system under conditions of varying physical activity and types of animal husbandry.

Thus, horses have the greatest total height, width, thickness and circumference of the heart, with measurements of 30.26 ± 0.38 cm, 20.52 ± 0.29 cm, 12.8 ± 0.21 cm and 54.16 ± 1.94 cm respectively. The heart development (shape) index in horses is 147.52 ± 7.36% (Table 3.20).

The large size of a horse's heart reflects the organ's high adaptability to intense physical activity and prolonged exertion. This ensures effective blood circulation and maintains an adequate supply of oxygen and nutrients to the tissues during running and muscular activity, which is particularly important for animals with large bodies and high levels of aerobic capacity. Furthermore, a high development index indicates a predominance of left ventricular mass, which corresponds to the increased haemodynamic demands of horses during physiological activity.

Table 3.19

Absolute and relative heart weights of domestic mammals, M ± m, n = 5

Animal Species	Parameters	
	Absolute Mass (g)	Relative Mass (%)
Rabbits	10,3±0,86	0,31±0,008
Dogs	167,58±9,46	0,72±0,005
Pigs	487,4 ±8,12	0,29±0,004
Sheep	208,4±9,82	0,44±0,007
Cattle	2143,27±38,76	0,43±0,006
Horses	2987,6±96,84	0,59±0,012

Примітка: * $p \leq 0,05$; ** $p \leq 0,01$; *** $p \leq 0,001$ по відношенню до попередньої дослідної групи.

The smallest measurements for total height, width, heart thickness and heart circumference were found in rabbits. Significantly larger measurements were found in dogs, followed by sheep, pigs and cattle, with the largest, as we have already noted, found in horses (Table 3.20).

Table 3.20

Linear parameters of the hearts of domestic mammals, M ± m, n = 5

Parameters	Animal Species					
	Rabbit	Dog	Pig	Sheep	Cattle	Horse
Heart Height (cm)	3,5 ± 0,04	11,09 ± 0,06	15,9± 0,07	13,1 ± 0,04	23,08 ± 0,11	30,26± 0,38
Heart Width (cm)	2,4± 0,03	7,6± 0,02	10,3± 0,06	9,0± 0,03	13,9± 0,18	20,52± 0,29
Heart Thickness (cm)	1,6± 0,02	4,8± 0,01	6,4± 0,05	5,6± 0,02	8,1± 0,12	12,8± 0,21
Heart Circumference (cm)	6,6± 0,06	17,7± 0,08	26,5± 0,12	22,2± 0,16	38,08± 0,9	54,16± 1,94
Heart Development (Shape) Index (%)	145,8± 4,16	145,9± 6,56	155,06± 6,32	145,5± 4,02	166,04± 5,14	147,52± 7,36
Mean Ventricular Wall Thickness (mm)	4,51± 0,08	13,24± 0,21	20,55± 0,24	12,42± 0,17	27,68± 0,36	30,55± 0,76
Left Ventricular Wall Thickness (mm)	5,91± 0,11	15,92± 0,34	26,7± 0,51	16,2± 0,22	36,54± 0,64	40,14± 0,88
Right Ventricular Wall Thickness (mm)	3,12± 0,09**	10,47± 0,11*	14,4± 0,32**	8,04± 0,11**	18,46± 0,52**	20,92± 0,54**
Mean Atrial Wall Thickness (mm)	3,21± 0,08	4,01± 0,02	6,93± 0,09	6,62± 0,43	7,69± 0,23	10,53± 0,32
Left Atrial Wall Thickness (mm)	3,82± 0,04	4,37± 0,08	7,81± 0,06	7,05± 0,09	8,24± 0,12	11,02± 0,16
Right Atrial Wall Thickness (mm)	2,61± 0,02*	3,32± 0,05*	6,02± 0,04*	5,06± 0,07*	7,22± 0,09*	10,05± 0,14*

Note: *$p \leq 0.05$; **$p \leq 0.01$; **$p \leq 0.001$ relative to the ratio of right-to-left ventricular wall thickness (RV/LV) and right-to-left atrial wall thickness (RA/LA).

Based on these linear parameters relating the total height of the heart to its width, we determined the following values for the heart development (shape) index: in rabbits – 145.8±4.16%, in dogs – 145.9±6.56%, in pigs – 155.06±6.32%, in sheep – 145.5±4.02%, in cattle – 166.04±5.14%, in horses – 147.52±7.36% (Table 3.20).

According to the analysis of the results of our studies of heart measurements in experimental animals, taking into account the IRS (Table 3.20), the heart in rabbits, dogs, sheep and horses is classified as of the dilated-shortened type, in pigs – of the dilated-elongated type, and in cattle – of the elongated-narrowed type. However, the heart in 66.7% (rabbits, dogs, sheep, horses) of the animals belongs to the first type – dilated-shortened, in 16.7% (pigs) of animals to the second type – the enlarged-elongated type – and in 16.7% (cattle) of animals to the third type – the elongated-narrowed type.

An analysis of the results of morphometric measurements of heart wall thickness in domestic mammals in general, and of their ventricles and atria in particular, has revealed certain characteristics of their wall thickness, depending on their functional load and, accordingly, on the species-specific characteristics of the experimental animals (Table 3.20).

Thus, according to the results of our studies, the walls of the left ventricle have the greatest thickness in all experimental animals: in rabbits – 5.91±0.11 mm, in dogs – 15.92±0.34 mm, in pigs – 26.7±0.51 mm, in sheep – 164.08±16.17 mm, in cattle – 36.54±0.64 mm, and in horses – 40.14±0.88 mm (Table 3.20).

The wall thickness of the right ventricles in domestic mammals was significantly lower compared to that of the left ventricles: in rabbits ($p \leq 0.01$) by 1.9 times, in dogs ($p \leq 0.05$) – by 1.52 times, in pigs ($p \leq 0.01$) – 1.85 times, in sheep ($p \leq 0.01$) –

1.98 times, in cattle ($p \leq 0.01$) – 1.98 times, and in horses ($p \leq 0.01$) – 1.98 times (Table 3.20).

The thinnest heart wall thicknesses were found in the left and right atria. Thus, in the left atrium, the wall thickness, depending on the species, had the following values: in rabbits – 3.82±0.04 mm, dogs – 4.37±0.08 mm, pigs – 7.81±0.06 mm, sheep – 7.05±0.09, cattle – 8.24±0.12 mm, horses – 11.02±0.16 mm (Table 3.20). However, the thickness of the heart walls in the right atrium, compared with that in the left atrium, was significantly ($p \leq 0.05$) lower in all experimental animals: in rabbits by 1.46 times, in dogs – 1.32 times, in pigs – 1.3 times, in sheep – 1.39 times, in cattle – 1.14 times, in horses – 1.1 times (Table 3.20).

Analysing the results of cardiac morphometry in domestic mammals as a whole and their chambers (ventricles, atria) in particular, and their absolute and relative characteristics, certain indicators of the absolute and relative mass of the ventricles and atria were established, depending on their functional load and, accordingly, the species-specific characteristics of the experimental animals (Table 3.21).

Thus, according to the results of our studies, the left ventricles of the heart have the highest AM in all experimental animals: in rabbits 4.6 ± 0.37 g, in dogs – 27.29 ± 3.21 g, in pigs – 250.9 ± 5.37 g, in sheep – 90.3 ± 5.21 g, in cattle – 984.91 ± 19.52 g, and in horses – 1484.12 ± 28.74 g (Table 3.21; Fig. 3.75).

The right ventricles of the heart had a significantly lower AM in all the domestic mammals we studied, compared with the LV AM: in rabbits ($p \leq 0.01$) by 1.84 times, in dogs ($p \leq 0.05$) – by 1.75 times, in pigs ($p \leq 0.001$) – 2.22-fold, in sheep ($p \leq 0.001$) – 1.98-fold, in cattle ($p \leq 0.05$) – 1.78-fold, and in horses ($p \leq 0.001$) – 1.92-fold (Table 3.21).

The lowest absolute mass values among the heart chambers of the domestic mammals studied were found in the left and right atria. In the left atrium, AM had the following quantitative values: in rabbits 1.5±0.14 g, in dogs – 24.2±2.88 g, in pigs – 59.6±2.16 g, in sheep – 27.9±3.31 g, in cattle – 255.02 ± 8.04 g, in horses – 338.67 ± 14.52 g (Table 3.21; Fig. 3.75).

Table 3.21

Morphometry of the heart, ventricles and atria of domestic mammals, M ± m, n = 5

Parameters	Animal Species					
	Rabbit	Dog	Pig	Sheep	Cattle	Horse
Absolute Heart Mass (g)	10,3± 0,86	167,58± 9,46	487,4 ± 8,12	208,4± 9,82	2143,27± 38,76	2987,6± 96,84
Relative Heart Mass (%)	0,31± 0,008	0,72± 0,005	0,29± 0,004	0,44± 0,007	0,43± 0,006	0,59± 0,012
Heart Mass without Apical Fat) (g)	9,7± 0,82	154,1± 8,04	461,4± 8,01	175,0± 8,17	1936,26± 41,12	2807,32± 92,79
Absolute Mass of the Left Atrium (g)	1,5± 0,14	24,2± 2,88	59,6± 2,16	27,9± 3,31	255,02± 8,04	338,67± 14,52
Relative Mass of the Left Atrium (%)	15,46± 0,88	15,7± 1,86	12,91± 0,09	15,94± 1,49	13,17± 0,21	12,06± 0,47
Absolute Mass of the Right Atrium (g)	1,1 ± 0,11*	9,6± 2,01***	38,1± 1,92**	11,2± 2,02***	142,16± 6,72**	212,91± 10,77**
Relative Mass of the Right Atrium %)	11,34± 0,62	6,23± 0,94	8,26± 0,11	6,4± 0,82	7,34± 0,09	7,58± 0,11
Absolute Mass of the Atria (Right + Left) (g)	2,6± 0,33	33,8± 0,48	97,7± 5,49	39,1± 4,64	397,18 ± 11,21	551,57± 42,34
Relative Mass of the Atria (Right + Left) (%)	26,8± 1,42	21,93± 2,14	21,17± 2,01	22,34± 2,02	20,51± 0,42	19,64± 0,51
Absolute Mass of the Left Ventricle g)	4,6 ± 0,37	76,2± 1,02	250,9± 5,37	90,3 ± 5,21	984,91 ± 19,52	1484,12± 28,74
Relative Mass of the Left Ventricle (%)	47,42± 2,76	49,45± 2,86	54,38± 3,18	51,6± 3,06	50,87± 1,32	52,87± 4,08
Absolute Mass of the Right Ventricle (g)	2,5± 0,19**	43,6± 0,62*	112,8± 4,03***	45,6± 3,04***	554,17 ± 14,21*	771,63± 19,27 ***

Relative Mass of the Right Ventricle (%)	25,77± 1,28	29,29± 1,79	24,45± 1,62	26,06± 1,32	28,62± 0,64	27,49± 0,82
Absolute Mass of the Ventricles (Left + Right) (g)	7,1± 0,52	120,3± 1,98	363,7± 11,14	135,9± 7,16	1539,08 ± 49,74	2255,75± 88,69
Relative Mass of the Ventricles (Left + Right) (%)	73,19± 3,92	78,07± 4,68	78,83± 5,92	77,66± 4,36	79,49± 2,18	80,35± 4,29
Ventricular-to-Heart Mass Ratio	1:0,73	1:0,78	1:0,79	1:0,78	1:0,79	1:0,8
Atrial-to-Heart Mass Ratio	1:0,27	1:0,21	1:0,21	1:0,22	1:0,21	1:0,20
Atria-to-Ventricles Mass Ratio	1:0,37	1:0,28	1:0,27	1:0,29	1:0,26	0:0,24

Note: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$ for the ratio of AM PS to AMLS and AMPP to AMLP.

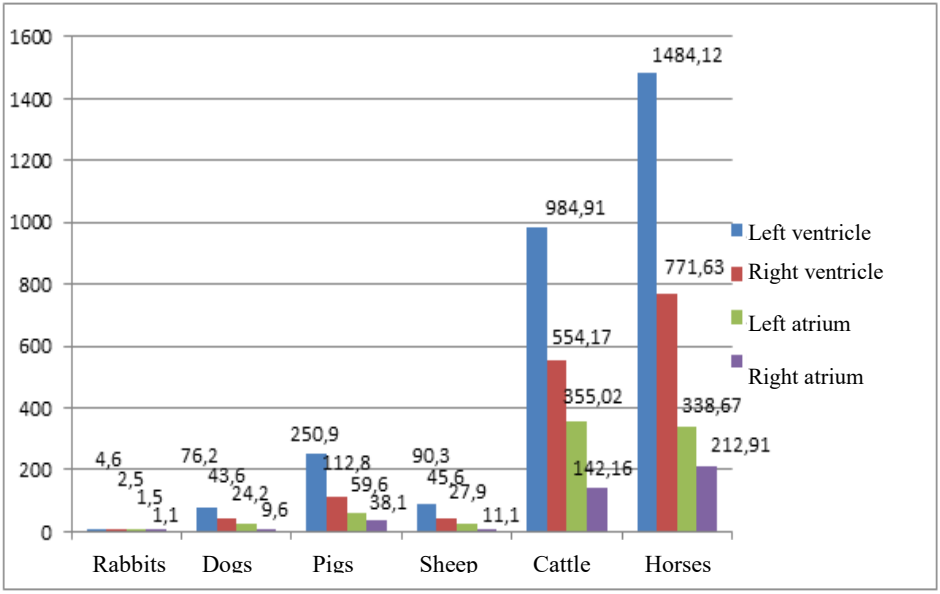

Fig. 3.75. The absolute mass of the ventricles and atria of domestic mammals (g).

When calculating the AM indices of the right ventricles, a statistically significant reduction was observed compared with the corresponding indices in the left atrium: in rabbits ($p \leq 0.05$) by a factor of 1.36, in dogs ($p \leq 0.001$) by a factor of 2.52, in pigs ($p \leq 0.01$) – 1.56-fold, in sheep ($p \leq 0.001$) – 2.49-fold, in cattle ($p \leq 0.01$) – 1.79-fold, in horses ($p \leq 0.01$) – 1.59-fold (Table 3.21).

The relative mass of the heart and its anatomical parts (left and right ventricles, left and right atria) (Table 3.21; Fig. 3.76) in a specific animal species was directly dependent on the absolute mass of the heart as a whole and its components (Table 3.21; Fig. 3.75), and, accordingly, on the functional load of the respective ventricles and atria as they perform their work.

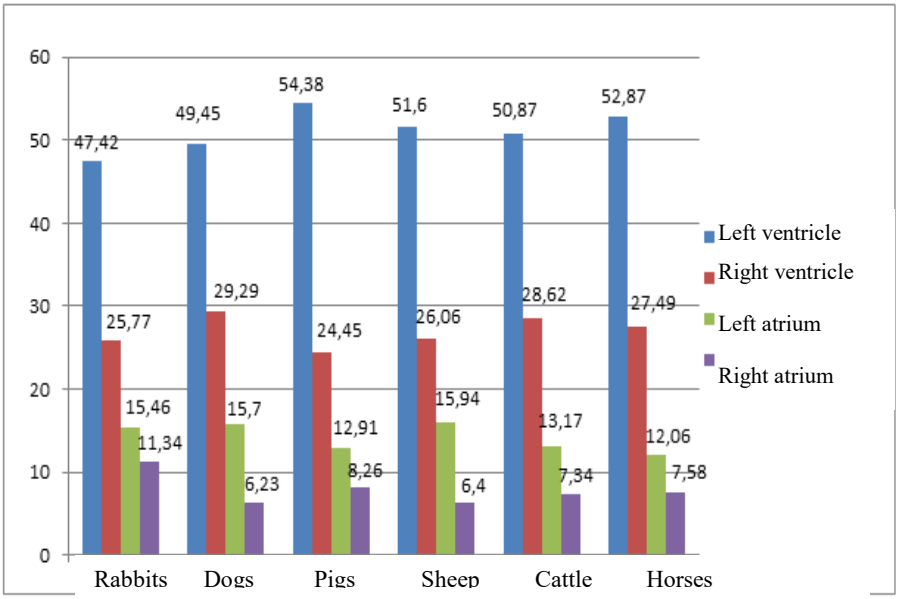

Fig. 3.76. Relative mass of the ventricles and atria in domestic mammals (%).

Thus, the left ventricle accounts for the largest percentage of the total heart mass in the experimental animals, amounting to: 47.42±2.76% in rabbits, in dogs – 49.45±2.86%, in pigs – 54.38±3.18%; these figures are similar across all animal species. This is due to the fact that in sheep it is 51.6±3.06%, in cattle 50.87±1.32%, and in horses 52.87±4.08%. However, in all experimental mammals, regardless of their position in the phylogenetic series, the contractile cardiomyocytes of the left ventricular muscles, whilst working, undergo an increased load, pumping blood under pressure through the closed system of vessels of the systemic circulation.

The right ventricle has a lower VM relative to the AM of the heart: in rabbits – 25.77±1.28%, in dogs – 29.29±1.79%, in pigs – 24.45±1.62%, in sheep – 26.06±1.32%, in cattle – 28.62 ± 0.64%, in horses – 27.49 ± 0.82% (Table 3.21; Fig. 3.76).

The relative mass of the right and left atria relative to the total absolute mass of the heart is lowest in all experimental animals (Fig. 3.76), which is associated with their morphofunctional load.

The relative mass of the heart and its anatomical components, from a species-specific perspective, showed a direct correlation with the body mass of the experimental animals and the organ's AM. This relationship reflects evolutionarily determined mechanisms that allow different species of domestic mammals to adapt to the specific functional needs of the organism. The dependence of relative heart mass on body mass is also closely linked to the functional characteristics of the organism, in particular, the level of physical activity, diet, and the environmental conditions in which the animals live. Whilst the absolute mass of the heart and its anatomical structures increased depending on the species (the more advanced the animal in phylogenetic development, the greater the absolute mass of its

organs) (Fig. 3.75), the relative mass of the organ was directly proportional to the body mass of the animals and had similar values (Fig. 3.68). However, the largest percentage of the net heart mass in all experimental animals was accounted for by the left ventricle, followed by the right ventricle, and then the left and right atria (Fig. 3.76).

Given these absolute measurements of the ventricles and atria in domestic animals, the ventricular-to-total-heart-weight ratio (ventricular-to-total-heart-weight index (VTI)) yields the highest values, which are similar across all the mammals studied: in rabbits – 1:0.73, in dogs – 1:0.78, in pigs – 1:0.79, in sheep – 1:0.78, in cattle – 1:0.79, in horses – 1:0.79. Accordingly, the ratio of atrial mass to net heart mass (atrial-cardiac index (ACI)) in all experimental animals is lower and amounts to: in rabbits – 1:0.27, in dogs – 1:0.21, in pigs – 1:0.21, in sheep – 1:0.22, in cattle – 1:0.21, and in horses – 1:0.20. The ratio of atrial mass to ventricular mass (atrial-ventricular index (AVI)) of the heart in domestic mammals is characterised by the following values: in rabbits – 1:0.37, in dogs – 1:0.28, in pigs – 1:0.27, in sheep – 1:0.29, in cattle – 1:0.26, in horses – 1:0.24 (Table 3.21).

The organometric measurements of the heart's components that we have identified (wall thickness, absolute and relative chamber masses, the ventricular-to-total-heart-mass ratio, the atrial-to-total-heart-mass ratio, ratio of atrial mass to ventricular mass) in domestic mammals unequivocally indicate the intensive development of the left ventricle, followed by the right ventricle, and the left and right atria, as a result of their respective functional loads within the cardiovascular system.

Thus, the more pronounced development of wall thickness and the absolute and relative mass of the left ventricle, compared with the right, is explained by the significant development of the left ventricular myocardium, where the contractile

cardiomyocytes of the muscle are subjected to an increased workload during contraction (blood under pressure is supplied to the entire body via the closed system of vessels of the systemic (somatic) circulatory system). The reduction in the wall thickness of the right ventricle of the heart, and its absolute and relative mass in domestic mammals, compared to the left, is explained by the fact that the cardiomyocytes of the right ventricle pump blood into the small (pulmonary) circulation, thereby performing a lesser functional load. We attribute the reduction in these parameters in the left and right atria, relative to the ventricles, to the lower functional load on the atrial cardiomyocytes: the atria receive blood returning to the heart from the animal's body, performing a lesser load, whilst the ventricles pump blood from the heart to the body, thereby performing a greater workload.

3.2.2. Cytometry of cardiac myocytes in domestic mammals

Our cytometric studies have shown that the average volume of cardiomyocytes, their nuclei, and consequently the nuclear-cytoplasmic ratio (NCR) in domestic mammals vary and depend both on the species-specific characteristics of the animals studied and on the morphofunctional state of the ventricular and atrial myocardium (Table 3.22). The differences identified reflect the degree of functional load on individual sections of the heart and the characteristics of their structural organisation.

Changes in the volume of cardiomyocytes and their nuclei can be regarded as manifestations of the morphofunctional plasticity of cardiac muscle tissue, which ensures adaptation to variations in haemodynamic conditions. In particular, the variability of the nuclear-cytoplasmic ratio indicates the intensity of metabolic processes in the cells and the level of their functional activity.

The data obtained confirm that the hearts of domestic animals are capable of adapting to changes in workload resulting from physiological processes, particularly under conditions of varying levels of physical activity, stress or the development of pathological conditions. Such adaptive changes occur at the cellular level and are aimed at maintaining effective myocardial contractile function.

Furthermore, it has been established that the parameters of the cytometric characteristics of cardiomyocytes differ significantly among different mammalian species, indicating species-specific features of cardiac tissue organisation and the specificity of their adaptive mechanisms. This allows cytometric parameters to be considered as informative criteria for assessing the morphofunctional state of the myocardium and its adaptive potential.

With regard to the cytometric characteristics of cardiac cardiomyocytes, the largest parameters (length, width, volume of cardiomyocytes and their nuclei) were found in the left ventricle of the heart in all experimental animals. The volume of cardiomyocytes in the LV of the rabbit was 2834.59±319.99 μm³, in the dog – 2941.76±127.44 μm³, in the pig – 6130.98±922.18 μm³, in sheep – 3982.99±423.96 μm³, in cattle – 11225.73±824.42 μm³, and in horses – 12554.36±877.52 μm³ (Table 3.22; Fig. 3.77).

The results obtained indicate a clear correlation between cardiomyocyte size and the level of functional load on the heart chambers, as the left ventricle maintains systemic circulation and functions under conditions of elevated haemodynamic pressure; at the same time, the interspecies variability observed is consistent with general allometric patterns and reflects the close relationship between an animal's body size, heart mass and the level of its functional activity.

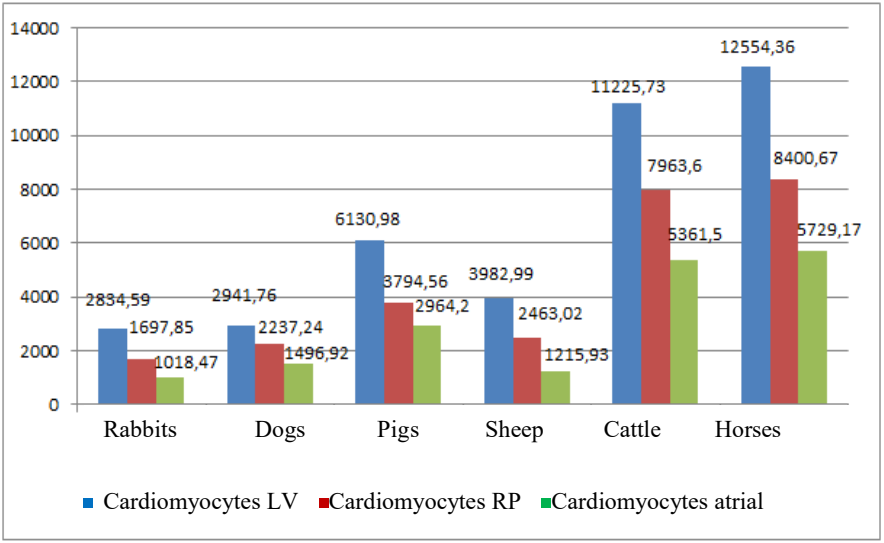

Fig. 3.77. The volume of contractile (typical) cardiomyocytes in the hearts of domestic mammals.

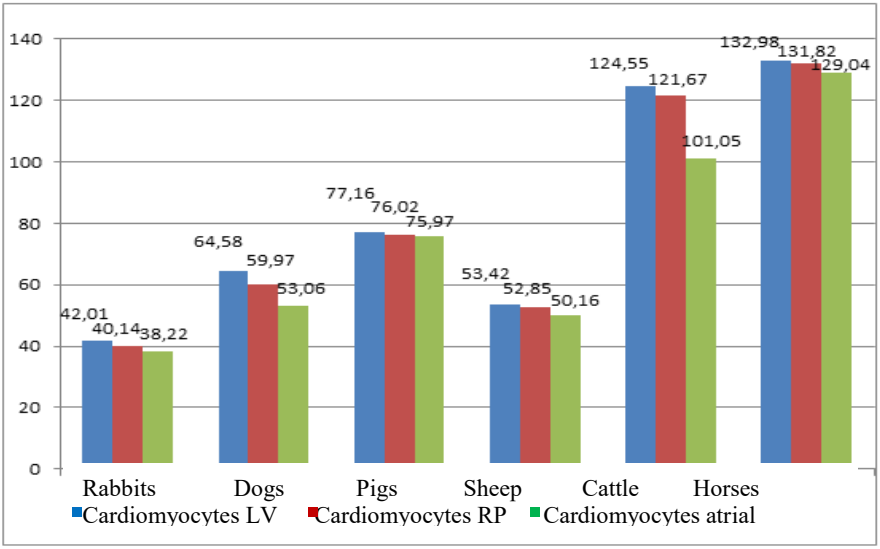

Fig. 3.78. The volume of the nuclei of contractile (typical) cardiomyocytes in the ventricles and atria of domestic mammals.

Table 3.22.

Cytometry of myocardial cardiomyocytes in domestic mammals, M ± m, n = 5

Animal Species	Parameters	Cardiomyocyte Length (μm)	Cardiomyocyte Width (μm)	Cardiomyocyte Volume (μm³)	Cardiomyocyte Nuclear Volume (μm³)	Nuclear-to-Cytoplasmic Ratio
Rabbit	Left ventricle	56,14± 1,81	8,02± 0,112	2834,59± 319,99	42,01± 3,12	0,0161± 0,0054
	Right ventricle	43,64± 1,38*	7,04± 0,42*	1697,85± 239,06*	40,14± 3,93	0,0242± 0,0048*
	Right and left atria	37,02± 1,26*	5,92± 0,29*	1018,47± 119,66**	38,22± 3,98	0,0389± 0,0062
Dog	Left ventricle	46,06± 1,12	9,02± 0,39	2941,76± 127,44	64,58 ± 5,09	0,0224± 0,0076
	Right ventricle	41,47± 1,24	8,29± 0,42	2237,24± 103,02*	59,97± 5,83	0,0275± 0,0081*
	Right and left atria	39,06±1 ,35*	7,19±0, 49*	1496,92± 98,02**	53,06 ± 6,02*	0,0367± 0,0105**
Pig	Left ventricle	64,08± 2,02	11,04± 0,132	6130,98± 922,18	77,16± 2,01	0,0127± 0,0056
	Right ventricle	59,15± 2,12	9,04± 0,143	3794,56± 489,87*	76,02± 2,43	0,0204± 0,0068*
	Right and left atria	55,49± 1,98*	8,25± 0,182*	2964,20± 412,02**	75,97± 3,24	0,0263± 0,0097**
Sheep	Left ventricle	62,92± 1,84	8,98 ± 0,64	3982,99± 423,96	53,42 ± 5,18	0,0136± 0,0062
	Right ventricle	49,52± 1,62*	7,96 ± 0,56*	2463,02± 318,04*	52,85 ± 4,33	0,0219± 0,0079**
	Right and left atria	42,04± 1,27**	6, 07± 0,38*	1215,93± 176,94**	50,16 ± 4,57	0,0430± 0,0096***
Cattle	Left ventricle	72,02± 1,08	14,06± 0,41	11225,73 ±824,42	124,55± 7,99	0,0113± 0,0068
	Right ventricle	62,07± 1,23	12,79± 0,38	7963,60± 627,09*	121,67± 7,02	0,0156± 0,0054*
	Right and left atria	56,08± 1,37*	10,02± 0,46*	5361,50± 583,91**	101,05± 6,04*	0,0234± 0,0058**
Horse	Left ventricle	77,99± 1,62	14,32 ± 0,72	12554,36± 877,52	132,98 ± 9,12	0,0107± 0,0074
	Right ventricle	64,04± 1,39*	12,92± 0,74	8400,67± 681,04*	131,82± 7,92	0,0159± 0,0098*
	Right and left atria	60,98± 1,40*	10,94± 0,73*	5729,17± 513,37**	129,04± 7,76	0,0230± 0,0066**

Note: * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$ compared with the left ventricle.

With regard to species-specific characteristics concerning the volume of cardiomyocytes in the left ventricle of the experimental animals, the results we obtained were consistent with the generally accepted fact that cell size depends on the level of mammalian evolution (the higher the species in the systematic classification, the greater the cell volume), as well as on the size (mass) of the animal's body. Thus, according to our cytometric studies in this area, the largest volume of cardiomyocytes in the LV was found in the contractile heart cells of the horse (12,554.36 ± 877.52 μm) and, accordingly, the smallest volume was characteristic of rabbit cardiomyocytes – 2834.59 ± 319.99 μm³ (Table 3.22; Fig. 3.77).

The volume of the nuclei of left ventricular cardiomyocytes in the experimental animals was directly proportional to the volume of the cardiomyocyte sarcoplasm: the smallest volume of cardiomyocyte nuclei was observed in rabbits – 42.01 ± 3.12 μm³ and the largest in horses – 132.98 ± 9.12 μm³ (Table 3.22; Fig. 3.78).

Given these values for the volume of cardiomyocytes and their nuclei in the left ventricle of the mammals we studied, the YACV of contractile cardiac cells varied. According to our findings, the highest YCV value was observed in the cardiomyocytes of the dog's left ventricle (0.0224±0.0076), and 1.4 times lower in the rabbit (0.0161±0.0054). This parameter was found to be lowest in large animals – cattle (0.0113±0.0068) and horses (0.0107±0.0074), which indicates a higher level of morphofunctional maturity of cardiomyocytes in representatives of these domestic animal species of the class Mammalia (Table 3.22; Fig. 3.79).

The volume of cardiomyocytes in the right ventricle of all domestic mammals studied was significantly lower than the corresponding values in the left ventricle: in rabbits ($p \leq 0.05$) –

1.76 times, in dogs ($p \leq 0.05$) – 1.32 times, pigs and sheep ($p \leq 0.05$) – 1.62-fold, cattle ($p \leq 0.05$) – 1.41-fold, and horses ($p \leq 0.05$) – 1.49-fold (Table 3.22; Fig. 3.77). This difference is due to the lower functional load on the right ventricle, which supplies blood to the pulmonary circulation and operates under lower pressure.

In terms of species-specific characteristics, the smallest cardiomyocyte volume was found in rabbits, whilst the largest was in horses (Table 3.22; Fig. 3.77), reflecting general allometric patterns and correlating with body mass and the level of functional cardiac activity in different animal species.

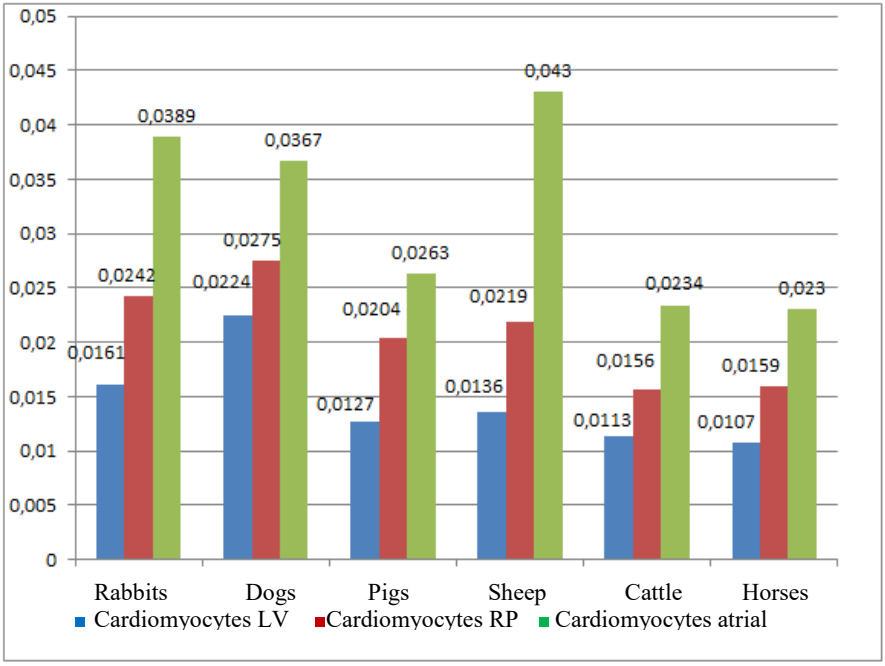

Fig. 3.79. The nuclear-cytoplasmic ratio of contractile (typical) cardiomyocytes in the hearts of domestic mammals.

Overall, the results obtained indicate a clear morphofunctional differentiation of cardiomyocytes in different regions of the heart in domestic mammals. The observed differences in their sizes reflect the myocardium's adaptive characteristics to specific haemodynamic conditions and functional load. Such patterns confirm the existence of a close relationship between the structural organisation of cardiac muscle tissue and its functional role, which is important for understanding the mechanisms ensuring the effective functioning of the heart in animals of different species.

According to the results of karyometric studies, the volume of the nuclei of right ventricular cardiac cardiomyocytes in all experimental animals differed almost not at all from that in the left ventricle; only a slight tendency towards a decrease was observed (Table 3.22; Fig. 3.78). Consequently, the nuclear-cytoplasmic ratio of right ventricular cardiomyocytes in all experimental animals, compared with that in the left ventricles, was significantly ($p \leq 0.05$) higher and amounted to: in rabbits – 0.0242±0.0048, in dogs – 0.0275±0.0081, in pigs – 0.0204±0.0068, in sheep – 0.0219±0.0079, in cattle – 0.0156±0.0054, in horses – 0.0159±0.0098 (Table 3.22; Fig. 3.79).

The smallest cardiomyocyte volumes were characteristic of the atria, which were significantly smaller in all the animals we studied compared with ventricular volumes. The mean values for the volume of cardiomyocytes in the right and left atria of domestic mammals were as follows: in rabbits – 0.0389±0.0062 μm³, in dogs – 0.0367±0.0105 μm³, in pigs – 2964.20 ± 412.02 μm³, in sheep – 1215.93 ± 176.94 μm³, in cattle – 5361.50 ± 583.91 μm³, in horses – 1215.93 ± 176.94 μm³. With regard to species-specific characteristics, the largest volume of

cardiomyocytes was characteristic of the horse's atria, and the smallest of the rabbit's atria (Table 3.22; Fig. 3.77).

The mean values for the volume of cardiomyocyte nuclei in the right and left atria of the experimental animals were similar to those for the left and right ventricles in the same animals. At the same time, a trend towards a decrease was observed (Table 3.22; Fig. 3.78).

Given these ambiguous quantitative indicators regarding the volume of cardiomyocytes and their nuclei in the atria of domestic mammals, the highest YCV coefficient was found in their cardiomyocytes compared to the right and, particularly, the left ventricles of the heart, the values of which were as follows: the highest in sheep (0.0430±0.0096), an intermediate value in rabbits (0.0389±0.0062) and dogs (0.0367±0.0105), the lowest values (close to one another) were found in the pig (0.0263±0.009), cattle (0.0234±0.0058) and the horse (0.0230±0.0066) (Table 3.22; Fig. 3.79). Such mixed results of the YACV characterise the level of morphofunctional activity of atrial cardiomyocytes during their spontaneous rhythmic contractions.

Thus, the increase in the cytometric parameters of cardiomyocytes (length, width, volume) and the decrease in their mean cell volume in the left ventricular myocardium of all the mammals we studied, compared with the right ventricle, are associated with the functional characteristics of the myocardial muscle tissue, which is capable of spontaneous rhythmic contractions, facilitating blood flow through the vessels: the contractile myocytes of the left ventricle (LV) bear a significantly greater load, facilitating blood flow through the vessels of the systemic circulation, whilst the cardiomyocytes of the right ventricle bear a lesser load, facilitating blood flow through the vessels of the pulmonary circulation.

At the same time, the statistically significant (Table 3.22) reduction in the cytometric parameters of cardiomyocytes (length, width, volume) and the increase in their mean cell volume in the myocardium of the right and left atria, compared with the ventricles, in all the animals we studied is associated with the functional characteristics of the atrial muscle tissue: the left atrium closes the pulmonary circulation, which begins in the right ventricle; accordingly, the right atrium closes the systemic circulation, which begins in the left ventricle, whilst performing a significantly lower workload, therefore their cardiomyocytes have smaller volumes and, consequently, a high YACV index.

CHAPTER IV

ANALYSIS AND GENERALIZATION OF RESEARCH FINDINGS

The main focus today is on the effective development of the livestock sector and, consequently, a significant increase in the production volumes of all types of livestock products [511, 510, 645]. Modern approaches to intensifying production are based not only on improving animal husbandry and feeding technologies, but also on an in-depth study of the biological characteristics of their organisms. Of particular relevance is the integration of morphological, physiological and biochemical studies, which allows for a comprehensive assessment of the state of the animal organism under normal conditions and under the influence of various environmental factors. In this regard, there is a need for in-depth and comprehensive research into the morphology of all body systems in clinically healthy animals [467, 647–649], which provides the basis for a scientifically sound approach to improving their productivity and maintaining their health.

This approach makes it possible not only to identify the structural characteristics of an animal organism at various stages of its structural organisation and ontogenetic development, but also to reveal the patterns governing the formation and functioning of the morphofunctional units of organs at the organ, tissue and cellular levels. At the same time, a comprehensive study of these levels helps to establish the interrelationships between the structural components of organs and their functional activity, which is key to understanding the mechanisms by which the organism adapts to changes in its environment. It is at these levels that intense biochemical reactions of intracellular metabolism take place, the products of which directly influence the vital functions not only of individual cells but also of the

entire animal organism. A deeper understanding of these processes provides the theoretical basis for the development of effective measures for the prevention and correction of disorders in the functions of organs and systems.

Therefore, determining the morphophysiological norm of the state of animals remains one of the most important tasks of morphological research in biological, veterinary, medical, and related studies [165, 360, 422, 441, 128]. The study of normal anatomical and histological parameters of different animal species is not only of academic but also of practical importance, since the data obtained can be used as a reference in the diagnosis of diseases of various origins, in assessing the impact of housing conditions, feeding levels, and technological factors, as well as in the development of veterinary drugs and productivity stimulants.

In this regard, morphological studies of domesticated agricultural mammals are conducted on a large scale. They are an indispensable source of information for veterinary medicine and animal husbandry, as they allow determining the species and age characteristics of organ structure, establishing the range of physiological fluctuations, and assessing the adaptive capabilities of animals to changes in the external environment.

Of the animals we studied, rabbits, dogs, sheep, pigs, cattle, and horses were used to assess their morphofunctional status in a comparative species aspect. This species spectrum of objects allowed us to trace both the general patterns of the structure and functioning of organs in mammals and the specific features inherent in individual species, which is important for veterinary diagnostics and scientific generalizations.

Of particular importance here is a comprehensive study of the morphology of the cardiovascular system, which is one of the most vital systems in the human body. It comprises the heart, blood vessels and lymphatic vessels, which are closely integrated

with one another and ensure the continuous transport of oxygen, nutrients, hormones and immune components to all tissues of the body [643, 592, 198, 245, 259, 260, 427, 434]. Such research allows us not only to assess the anatomical and histological features of organs, but also to understand the patterns of their functional interaction, the spatial organisation of the vascular network, and the mechanisms of adaptation to physiological and pathological stresses. Of particular value is the study of morphofunctional characteristics at various levels of organisation – from macroanatomical structures to cellular and subcellular components – which provides a comprehensive picture of the cardiovascular system's functioning under normal conditions and in altered environmental conditions.

The central organ of the cardiovascular system is the heart, which, thanks to the constant contraction of the cardiomyocytes of the heart muscle, ensures blood flow through a closed system of blood vessels. The cardiovascular system in humans and animals ensures extremely vital functions: metabolism, respiration, trophic, excretory functions, etc. [25, 108, 467, 575, 179, 414, 455, 516]. Together with the nervous system, the cardiovascular system connects all organs and systems of the body into a single whole [107]. The organs of the cardiovascular system help regulate blood pressure, supply blood to organs, drain lymph from organs and transport it to veins, play a role in maintaining homeostasis, and ensure the functioning and regulation of the nervous and endocrine systems, immune organs, etc. [709, 465, 335].

In the cardiovascular system, as in all organic nature as a whole, the morphofunctional regularity of the continuous unity and interdependence of anatomical structure and function is clearly manifested [75, 398, 282, 396, 442]. This is no coincidence, because there is a clear connection between the

morphological structure of the cardiovascular system and other systems of the body. Thus, thanks to the cardiovascular system and respiratory organs, through the large (systemic) and small (pulmonary) circulatory systems, oxygen from the air enters the venous blood in humans and animals, and carbon dioxide moves in the opposite direction [187, 464]. In addition, the cardiovascular system in general, and the heart in particular, especially in an era of development and introduction of progressive, innovative technologies in agriculture for breeding, feeding, and keeping domestic animals, is associated with the emergence and spread of various infectious, invasive, and non-infectious diseases.

Therefore, studying the characteristics of the internal structures of the heart is considered a relevant and essential link in the development of domestic morphology. This explains why veterinary cardiology, which studies heart and vascular diseases in animals, as well as cardiovascular surgery, are currently among the priority areas that are actively developing in veterinary medicine. In addition, knowledge of morphoarchitectonics and functional status in normal and pathological conditions of the cardiovascular system as a whole is fundamental to understanding not only how the body is organized, but also how it works and how it is affected by various pathological processes. At the same time, the priority direction today for the timely and reliable diagnosis of diseases of various origins is morphometric studies of organs and systems in clinically healthy animals, which are diagnostic criteria as indicators of the norm for the diagnosis of infectious and non-infectious pathologies [4, 268, 266, 273, 234, 474, 622, 629].

That is why knowledge of the features of the macro- and microscopic structure of the cardiovascular system organs, including the heart, their organ- and cytometric characteristics,

will make it possible to develop and introduce criteria for assessing the morphofunctional structure of the heart as indicators of normality for the diagnosis of diseases of various origins in veterinary medicine. Such studies are also important and relevant in the study and elucidation of the pathogenesis of diseases associated with the organs of the cardiovascular system and the impact of various adverse environmental factors on the body of animals [278, 280].

Therefore, based on the objectives of our research, the morphological studies in our work included the following stages: preparation of the heart, description of its shape, structure, and topography; determination of the absolute and relative mass of the heart and its components; assessment of the microscopic structure of the heart at the tissue and cellular levels – determination of the volume of cardiomyocytes, their nuclei, and the nuclear-cytoplasmic ratio.

Over the past decades, many fundamental works have been published that summarize modern concepts and achievements in the field of morphofunctional patterns of the structure and development of the heart in domestic mammals and birds, the structural components of its wall, etc. [62, 227, 241, 136, 2, 23, 298, 329, 389, 394, 395], which is important for clinical cardiology in establishing diagnoses in domestic animals of certain species, including humans.

Research on the structure of the heart and its components in vertebrate animals of the Mammalia class is covered in the scientific works of V.L. Abdul-Ogly (2003), M.S. Gnatyuk (2015–2017), O.B. Slaboy (2016–2017), V.Z. Sikora (2006; 2013), Yu.V. Silkin (2004–2011), and others. Their research has revealed new, previously unknown facts about the mechanisms of morphogenesis, etc. At the same time, the literature sources provided mainly refer to the structure of the heart and its

structures, predominantly in laboratory and small domestic animals, and to a lesser extent in farm animals.

That is why our research on the morphotopography, macroscopic and microscopic structure of the heart in comparative anatomical, species, breed, and age aspects in domestic mammals is a relevant task in biology and veterinary medicine.

The heart in the studied domestic animals is located in the chest cavity and is slightly shifted to the left. At the same time, its macroscopic structure, shape, and morphotopography in these animals are similar to each other but have certain features.

In rabbits, the heart is located in the chest cavity, in the mediastinal space, and is shifted to the left. The mediastinal space is bounded by the pleural layers of the middle mediastinum. The heart is poorly developed, oval in shape, elongated and narrowed, slightly flattened, with a blunt apex. In dogs, the heart occupies the space from the 3rd to the 7th rib and is slightly shifted to the left. Its base is located at the level of the middle of the first rib, and the apex is in the area of the 6th–7th ribs. The heart of a dog has an enlarged base that is directed dorsocranially and a narrowed apex that is directed ventrocaually. In pigs, the heart is relatively large and has an ellipsoidal-conical shape due to its broad base and pointed (narrowed) apex. The broad base of the heart is located at the level of the shoulder joint (at the level of the middle of the first rib) and is directed dorsocranially and to the right. The pointed apex of the heart is located in the 5th–6th intercostal space, near the sternum at the junction of the 7th rib and its cartilage. It is directed ventrocaudally and to the left, without reaching the diaphragm and sternum. The cranial edge of the heart is located at the level of the third rib, and the caudal edge at the level of the sixth rib. The heart of sheep is cone-shaped, with a broad base and a narrow apex. Topographically, the heart is

located in the mediastinum of the chest cavity between the right and left lungs, in the area from the third to the sixth rib cranially to the diaphragm (cranially reaching the third rib, caudally reaching the sixth rib). According to the median sagittal plane, the heart of sheep is shifted to the left by 5/7, adjacent between the third and fourth ribs to the left chest wall. The base of the heart has a craniocaudal direction, it is located at the height of the middle of the first-second rib. The apex of the heart has a caudoventral direction and is located opposite the fifth costal cartilage, or caudally from it, not reaching the sternum by two cm, and cranially from the diaphragm – from two to five cm. The heart of cattle has a conical shape. Topographically, the organ in the area of the 3rd-4th ribs is adjacent to the left chest wall. The apex of the heart is located in the area of the 5th costal cartilage. Its base has a dorsal direction, and its apex has a ventral direction. The horse's heart is located in the chest cavity between the right and left lungs. A significant part of the heart is located to the left of the median (sagittal) plane, under the lungs, in the area of the 3rd–4th intercostal space. Cranially, the heart is limited by the third rib, and caudally by the costal cartilage of the fifth rib. The broad base of the heart is located at the level of the shoulder joint in the craniocaudal direction. The apex of the heart has a caudoventral direction and is located close to the sternum [293, 229, 230, 462, 460, 188, 560–563, 28, 470, 471, 522, 527].

A similar morphophotography of the heart in domestic mammals has also been described by other scientists, who believe that the cone-shaped or oval shape of the heart is associated with the peculiarities of the structure of the chest in domestic mammals, which gives the organ as a whole such a shape. The chest cavity, where the heart is located, has a pyramid shape with a truncated top, characteristic of a certain species of animals, with a wide base (outlet) directed caudally and a narrow top (outlet)

located cranially. That is why the shape of the heart in its natural state, together with the lungs and other organs of the chest cavity (aorta, esophagus, thymus, etc.), generally reproduces the shape of the chest cavity [210, 254, 583, 694, 714].

The descriptive and overview nature of morphological studies is not always sufficient for an in-depth analysis of general morphofunctional processes related to age, species, and pathomorphological changes in the animal organism, since an objective assessment of their interrelationships is necessary. Therefore, traditional methods of studying morphological changes at the organ, tissue, and cellular levels are currently basic but need to be supplemented with systematic quantitative (morphometric) studies [226, 558, 314].

Organometric studies are an important morphological criterion for the development and morphofunctional state of organs and tissues in animals. Such studies make it possible to determine and establish the quantitative characteristics of the animal organism at the organ and tissue levels in the process of ontogenetic and phylogenetic development of animals and under the influence of various environmental factors on the animal organism, etc. [226, 236, 234].

An important criterion for organ development, which directly indicates its morphofunctional maturity, is its absolute and relative mass, linear parameters, etc. [360]. Morphometric parameters not only indicate the development and morphofunctional maturity of an organ, but also have cognitive significance and form the basis for determining the shape, establishing the development index, and comparative anatomical types of various organs [390], which is important in clinical and preventive medicine, etc. The results of organometry are also of cognitive importance and form the basis for determining the

shape, establishing the development index, and comparative anatomical types of various organs [272, 27, 126, 33].

The results of numerous studies indicate that the AM and BM indicators of the heart directly depend on the age of the animal, species, breed, and functional load. Thus, in pigs, these indicators are 307.2–334.3 g and 0.28–0.3%, respectively; in horses, 2150–4300 g and 0.58–0.60%; and in cattle, 1300–2400 g and 0.35–0.4%. The heart weight of a newborn animal is 0.76% of its body weight [136, 467, 465, 575].

The size of animals also affects the weight of the heart, which is especially characteristic of dogs: absolute weight ranges from 48.0 g in small breeds to 301.0 g in large breeds, while the relative weight remains almost unchanged and equals 0.64–0.78% regardless of the size of the animals [465].

The heart weight is greater in males than in females (in bulls – 0.50%, in cows – 0.42%). With increased physical exertion, the heart weight increases [575].

Our analysis of organometric studies in this area confirms the views of the above-mentioned scientists and confirms the data that the absolute mass of the heart in domestic mammals correlates with the species characteristics of animals in terms of their size and live weight: animals with a large live weight are characterized by the largest AM of their organ. This is not accidental, since the development of the animal organism as a whole, its organs and systems in particular, is subject to well-known and recognized facts of development, depending on the phylogenetic level of animal development: the higher the species of animals in systematic terms, their size, and live body weight, the greater the organometric indicators of the organ. Therefore, our organometric quantitative studies in this area have made it possible to confirm the point of view from the position of the relative dependence between the absolute and relative mass of the

heart in relation to the species characteristics of domestic mammals [460, 188, 562, 463, 464, 470, 471, 522].

According to morphometric studies, cattle and horses had the highest body weight among the animals studied, and their heart AM was the highest, respectively, 2143.27±38.76 g in cattle and 2987.6±96.84 g in horses. Pigs had a significantly lower heart AM (487.4 ±8.12 g), followed by sheep (208.4±9.82 g) and dogs (167.58±9.46 g). Rabbits had the smallest absolute heart mass (10.3±0.86 g) and also had the smallest body mass (Fig. 4.80).

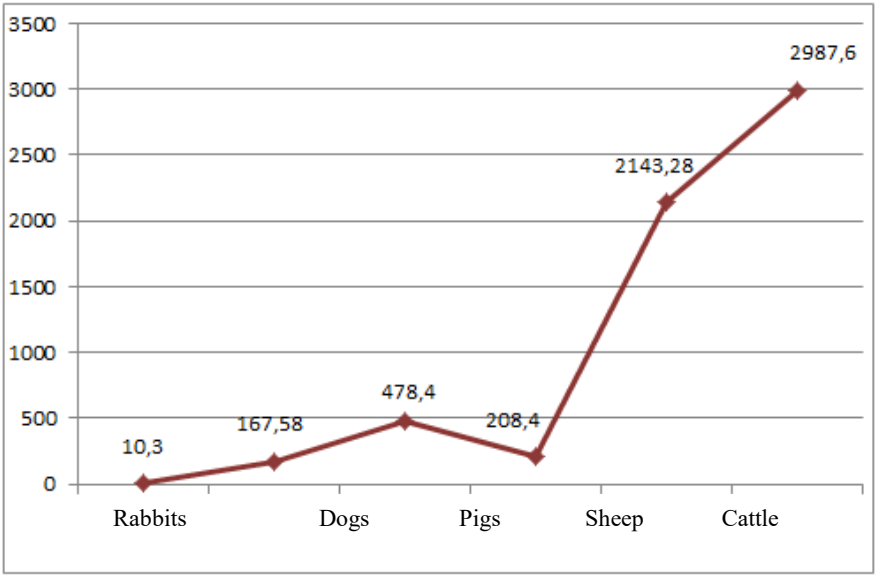

Fig. 4.80. Species-specific characteristics of the absolute heart mass in domestic mammals (g).

The relative weight of the heart in the animals we studied is proportional to the body weight of the animals and the AM of the organ. It is an important morphometric indicator that reflects the degree and morphofunctional structure of the organ, indicates disturbances in the morphological structure of the organ, in

particular, and the organism of animals as a whole in diseases of infectious and non-infectious etiology, is an important indicator that changes depending on environmental conditions, the impact of various environmental factors on the organism, etc. Therefore, the indicators of the organ's BM are a marker and criterion for determining the morphofunctional state of animals in normal conditions and in diseases of various etiologies, etc.

According to our research, the relative mass of the heart in domestic mammals varies [460, 188, 562, 563, 464, 470, 471, 522].

According to our data, the highest cardiac VM in dogs is 0.72±0.005%. We explain this feature by the interrelated functioning of the heart and lungs in dogs as a single system of large and small blood circulation, which ensures gas exchange in the body, the regulatory activity of which occurs with the participation of the nervous system, which coordinates and regulates their work, uniting the body into a single whole. The respiratory organs and the cardiovascular system are interconnected and perform extremely important functions for the body's vital activity, the main one being to ensure gas exchange by inhaling air from the environment and exhaling carbon dioxide already formed in the body into the external environment. Gas exchange occurs directly in the lungs, between air and blood, through the diffusion of oxygen and carbon dioxide through the walls of the pulmonary alveoli into the blood capillaries. Therefore, in our opinion, the highest heart rate in dogs compared to other domestic mammals is associated with the peculiarities of the physiology of the respiratory organs: in this species, breathing is rapid and vigorous, and residual air is used up quite quickly. On average, depending on the age and size of the animal, a dog makes 14–30 respiratory movements per minute at rest, and

during movement and under other circumstances, the intensity of breathing can increase by 2–2.5 times [24].

Horses ranked second in terms of heart VM (0.59±0.012%). We attribute this peculiarity of heart VM growth in horses, compared to that in rabbits, pigs, sheep, and cattle, to the adaptive features of the organism to the conditions of existence. It is known that the lungs and heart are most developed in animals that are subject to significant physical and physiological stress on the corresponding organs and systems [228].

In most other domestic animals studied by us, the heart VM was similar: in rabbits – 0.31±0.008%, in pigs – 0.29±0.004%. Slightly higher values (similar to each other) were found in ruminants: in sheep – 0.44±0.007% and in cattle – 0.43±0.006% (Fig. 4.81).

Thus, the relative heart weight (Fig. 4.81) in the domestic mammals we studied-rabbits, dogs, pigs, sheep, cattle, and horses-changes asynchronously and directly depends on their body weight and the absolute weight (Fig. 4.80) of the heart (the percentage of organ mass relative to the body mass of animals), which changes (increases) in direct proportion to the body mass of animals depending on the characteristic structure of the heart for a given species of animals.

The functional state of organs and their systems is evaluated using linear dimensions (length, width, thickness, circumference), which allow for the assessment of organ shape, development index, and the proportionality of structural elements. The shape of the heart is individual and determined by a range of factors, including age, sex, body conformation, physiological condition, and the animal's health status, as well as specific functional loads. Analysis of linear parameters enables not only a quantitative assessment of organ size but also the determination of its anatomical proportionality and morphofunctional adequacy. The

elongation factor of heart shape is defined as the ratio of its greatest longitudinal (height) to transverse (basal width) dimensions [595, 390] and serves as an important indicator for comparing the morphological characteristics of the heart among different animal species, as well as for evaluating its adaptive potential in response to physiological and pathological loads. This approach allows for the identification of patterns in the relationship between heart shape and function, which is crucial for assessing its efficiency in maintaining systemic circulation.

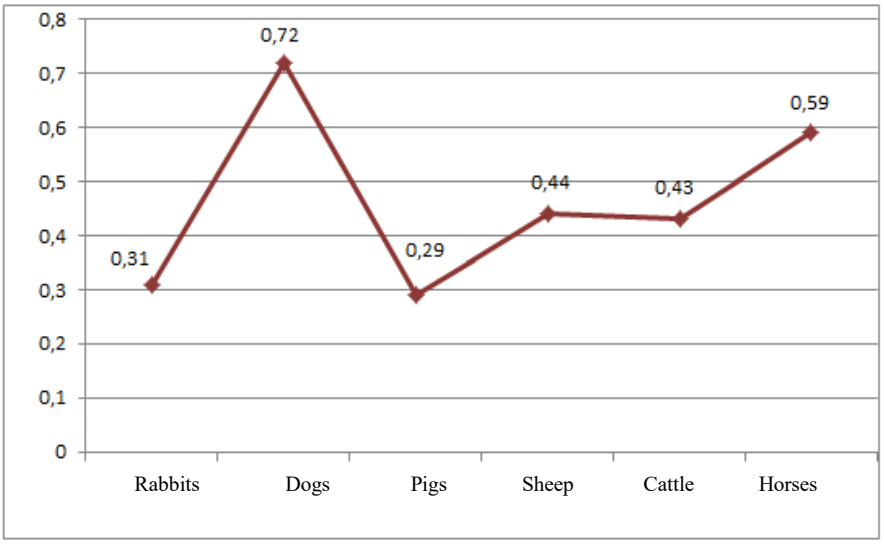

Fig. 4.81. Species-specific features of the relative mass of the heart of domestic mammals (%).

According to the results of our research on the analysis of linear measurements (height, width, thickness, circumference, development index (shape) of the heart) in domestic mammals, their values vary and are directly dependent on the structure and shape of the chest, the morphotopography of the heart, and the

absolute mass of the heart in the experimental animals [460, 188, 562, 563, 464, 470, 471, 522].

Thus, the highest indicators – total height, width, thickness, and circumference of the heart – are characteristic of horses, which are 30.26±0.38 cm, 20.52±0.29 cm, 12.8±0.21 cm, and 54.16±1.94 cm, respectively. The heart development index in horses is 147.52±7.36%.

The smallest parameters of these indicators are characteristic of rabbits, while dogs have significantly larger parameters, followed by sheep, pigs, and cattle (Table 3.20).

With such linear parameters (the ratio of the total height of the heart to its width), the values of the heart development index are as follows: in rabbits – 145.8±4.16%, in dogs – 145.9±6.56%, in pigs –155.06±6.32%, in sheep – 145.5±4.02%, in cattle – 166.04±5.14%, in horses – 147.52±7.36 (Fig. 4.82).

Depending on species, breed characteristics, and age, domestic mammals have different morphological structures of the heart: narrowed-elongated (cattle), narrowed-shortened (rabbits), widened-shortened (horses), round-oval (dogs). In dogs, the shape of the heart (depending on their breed characteristics) can be elliptical in 43% of cases, cone-elliptical in 24%, elliptical-spherical in 26%, and spherical in 7% of cases. In cattle, the heart shape is conical, elongated-narrowed, and enlarged-shortened. Analyzing the literature, it can be noted that pigs have three main types of heart: elongated and narrowed (conical); shortened (relatively narrowed); widened and shortened (triangular) [136, 575, 464].

Based on the analysis of heart development index indicators in domestic animals and taking into account the macroscopic structure, we developed a morphological scale (marker features) according to which we classified the heart into three types based on its development index: the first is the enlarged-shortened type

(IRL = 140–150%), the second is the enlarged-elongated type (IRL = 151–160%), and the third is the elongated-narrowed type (IRL = 161–170%). According to the IRS indicators (Fig. 4.82), the heart of a rabbit, dog, sheep, and horse is classified as enlarged-shortened type, in pigs – enlarged-elongated type, in cattle – elongated-narrowed type. Based on these results, the hearts of 66.7% of animals (rabbits, dogs, sheep, horses) belong to the first type (enlarged-shortened), 16.7% of animals (pigs) to the second type (widened-elongated), and 16.7% of animals (cattle) to the third type (elongated-narrowed).

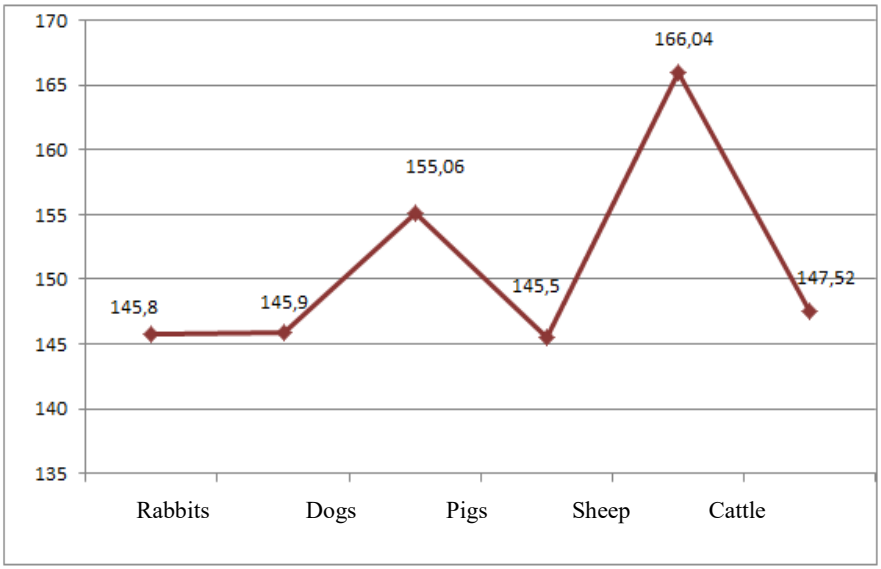

Fig. 4.82. Heart development index indicators in domestic mammals (%).

In modern morphology, morphometric (quantitative morphology) research methods allow not only to determine the quantitative characteristics of an organ as a whole, but also to establish the interrelationships and interdependence of quantitative changes in individual structures of a particular organ,

quantitative and relative characteristics of certain morphological components (individual structures, individual areas, etc.) at different stages of individual and phylogenetic development and in different functional states of a particular system of the animal organism, depending on their species characteristics. That is why, in recent years, morphologists have been increasingly using morphometric methods to study intact and damaged heart muscle. Many researchers are interested in the adequate determination of the size of the heart and its components in terms of measurements of the thickness of the walls of the left and right ventricles, atria, etc. [62, 242, 748, 642, 601, 602, 244, 299, 526, 586].

According to the analysis of the results of morphometry of the heart wall thickness in domestic mammals in general and its ventricles and atria, certain features of their wall thickness were established, depending on their functional load and species characteristics of the experimental animals.

The thickest walls in all experimental animals are those of the left ventricle: in rabbits – 5.91±0.11 mm, dogs – 15.92±0.34 mm, pigs – 26.7±0.51 mm, sheep – 164.08±16.17 mm, cattle – 36.54±0.64 mm, horses – 40.14±0.88 mm. This is explained by the fact that the left ventricle of the heart participates in the large circle of blood circulation, where blood in animals, which enters the aorta from the left side of the heart, is under significantly high systolic "upper" pressure – 120–130 mm Hg, depending on the type of animal [460, 188, 562, 563, 462, 470, 471, 522].

The wall thickness indices of the right ventricle in all domestic mammals had intermediate values compared to those in the left ventricle and right and left atria. However, their values were significantly lower compared to the wall thickness of the left ventricle: in rabbits ($p \leq 0.01$) by 1.9 times, in dogs ($p \leq 0.05$) by 1.52 times, in pigs ($p \leq 0.01$) by 1.85 times, in sheep ($p \leq 0.01$) – 1.98 times, in cattle – ($p \leq 0.01$) – 1.98 times, in horses ($p \leq 0.01$) –

1.98 times. This significant difference is explained by the fact that the right ventricle of the heart participates in the pulmonary circulation, performing a significantly lower load [460, 188, 562, 563, 462, 470, 471, 522].

The atria perform significantly less work: the left atrium closes the pulmonary circulation, and the right atrium closes the systemic circulation [25, 465, 575]. That is why the wall thickness in the left and right atria of the heart in all animal species was significantly lower: in the LA in rabbits – 3.82±0.04 mm, in dogs – 4.37±0.08 mm, in pigs – 7.81±0.06 mm, in sheep – 7.05±0.09 mm, in cattle – 8.24±0.12 mm, in horses – 11.02±0.16 mm; in PP – 2.61±0.02 mm in rabbits, 3.32±0.05 mm in dogs, 6.02±0.04 mm in pigs, 5.06±0.07 mm in sheep, 7.22±0.09 mm in cattle, 10.05±0.14 mm in horses. Compared with LP, in all experimental animals, the thickness of the PP wall was significantly ($p \leq 0.05$) lower: in rabbits by 1.46 times, in dogs by 1.32 times, in pigs by 1.3 times, in sheep – 1.39 times, in cattle – 1.14 times, in horses – 1.1 times [460, 188, 562, 563, 462, 470, 471, 522].

The ambiguous morphometric parameters of ventricular and atrial wall thickness that we identified, where the largest morphometric parameters were characteristic of the LV, followed by the RV, left and right atria, indicate their morphofunctional activity during their functioning in the large and small circles of blood circulation. This is not a coincidence, but a real and objective characteristic of the difference in the activity of the heart ventricles, since the left ventricle functions mainly as a pump, and the right ventricle as a volume [694]. Therefore, the increase in the cytometric parameters of the left ventricle, compared to the right, is associated with the functional characteristics of the myocardial muscle tissue, which is capable of spontaneous rhythmic contractions, promoting blood flow

through the vessels. The contractile myocytes of the left ventricle of the heart perform a significantly greater load, promoting blood flow through the vessels of the systemic circulation, while the cardiomyocytes of the right ventricle perform a lesser load, promoting blood flow through the vessels of the pulmonary circulation.

We associate significantly smaller parameters of atrial wall thickness with the morphofunctional activity of the heart: the atria receive blood returning to the heart from the body of animals, while performing a significantly lower load.

At the same time, the diversity and variability of the parameters obtained in these macrometric measurements do not satisfy researchers, so the search for adequate and optimal morphometric research methods continues to this day [62, 235, 421, 474]. A more accurate macrometric method that allows the degree of hypertrophy of parts of the heart muscle to be diagnosed is the separate weighing of parts of the heart, which morphologists have been using for a long time and are constantly improving [667, 705]. Using this method, the free walls of the left and right ventricles, the interventricular septum, and the atria are weighed separately. The interventricular septum is divided proportionally to the masses of the left and right ventricles, determining their absolute masses. These indicators are used to determine the ventricular index – the ratio of the absolute mass of the right ventricle to the left. In an intact heart, the ventricular index ranges from 0.4 to 0.6 and reflects the physiological limits of the heart muscle [62, 269, 158, 666, 667].

Cardiac morphology also often uses modifications of the method of separate weighing of parts of the heart muscle, aimed at simplifying and expanding this method, which also takes into account the mass characteristics of the left and right atria [62, 660].

According to the results of our studies, the linear parameters of the ventricular and atrial walls of the heart correlate with their absolute and relative mass indicators. Moreover, there is a certain relationship between the thickness of the ventricular and atrial walls and their absolute and relative mass, which emphasizes the connection between the linear dimensions of the heart and its AM [460, 188, 562, 563, 462, 470, 471, 522].

According to the results of our morphometry of the anatomical structures of the heart in all studied animals, the most developed anatomical structures of the heart and the most voluminous in terms of AM indicators, relative to the pure mass of the heart (without epicardial fat), are the left and right ventricles. The left and right atria have the lowest AM values. Thus, according to the results of our studies, the AM of the left ventricles of the heart is the largest and amounts to: in rabbits (4.6±0.37 g), dogs (76.2±1.02 g), pigs (250.9±5.37 g), sheep (90.3±5.21 g), cattle (984.91±19.52 g), horses (1484.12±28.74 g) [460, 188, 562, 563, 462, 470, 471, 522].

We attribute such high values of left ventricular AM in domestic mammals to their development under functional load, since the left ventricle functions primarily as a pump that initiates the somatic circulation, pumping blood throughout the body [465, 575].

Lower morphometric values of AM were characteristic of the right ventricles of the heart: in rabbits – 2.5±0.19 g, in dogs – 43.6±0.62 g, in pigs –112.8±4.03 g, in sheep – 45.6±3.04 g, in cattle – 554.17±14.21 g, in horses – 771.63±19.27 g. Accordingly, in all studied domestic mammals, AM PS was significantly lower than AM LS: in rabbits ($p \leq 0.01$) by 1.84 times, in dogs ($p \leq 0.05$) by 1.75 times, in pigs ($p \leq 0.001$) by 2.22 times, in sheep ($p \leq 0.001$) – 1.98 times, in cattle – ($p \leq 0.05$) – 1.78 times, in horses ($p \leq 0.001$) – 1.92 times. This is due to the fact that cardiomyocytes

of the right ventricular muscle membrane perform significantly less work than LV cardiomyocytes, facilitating blood flow through the vessels of the pulmonary circulation [465, 575].

The AM of the left and right atria was significantly smaller among the heart chambers of domestic mammals: in the left atrium of rabbits it was 1.5±0.14 g, in dogs – 24.2±2.88 g, in pigs – 59.6±2.16 g, in sheep – 27.9±3.31 g, in cattle – 255.02±8.04 g, in horses – 338.67±14.52 g. The absolute mass of the right atrium, compared to the left, was significantly smaller: in rabbits ($p \leq 0.05$) by 1.36 times, in dogs ($p \leq 0.001$) by 2.52 times, in pigs ($p \leq 0.01$) by 1.56 times, in sheep ($p \leq 0.001$) – 2.49 times, in cattle ($p \leq 0.01$) – 1.79 times, in horses ($p \leq 0.01$) – 1.59 times. Significantly lower AM values in the atria compared to the ventricles of the heart are explained by the fact that the atria receive blood returning to the heart from the body of the animals, performing a smaller load, while the ventricles of the heart, pumping blood from the heart to the body of the animals, perform the greatest load [465, 575].

The absolute mass of heart components in domestic mammals varies depending on the species and is subject to biological criteria regarding the level of development of animals in the phylogenetic series-the greater the body mass of animals, the greater the AM of the organ. The analysis of organometric studies confirmed the data on the indicators of the anatomical structures of the AM of the heart in domestic mammals in this direction: animals with a large live weight are characterized by the largest AM of their heart and, accordingly, its components (Fig. 4.83).

The relative mass of the heart and its anatomical components in terms of species is directly dependent on the body mass of the animals studied and the AM of the organ. At the same time, the absolute mass of the organ and its anatomical structures

increases depending on the species of animal (the larger the animal in phylogenetic development, the greater the AM of its organs), while the relative mass of a particular anatomical structure in domestic animals is directly proportional to their body mass [360]. The increase in the absolute mass of the heart in large animals (cattle, horses, etc.) can be explained by the increased need for blood supply to ensure the vital processes of their organism. At the same time, the relative mass of the heart in these animals may be smaller, since the organism's need for blood circulation does not increase proportionally to the increase in body mass. This indicates evolutionary adaptations that allow organisms, depending on their size, to maintain optimal functional proportions between body weight and heart weight, taking into account the specifics of physiology and environmental conditions.

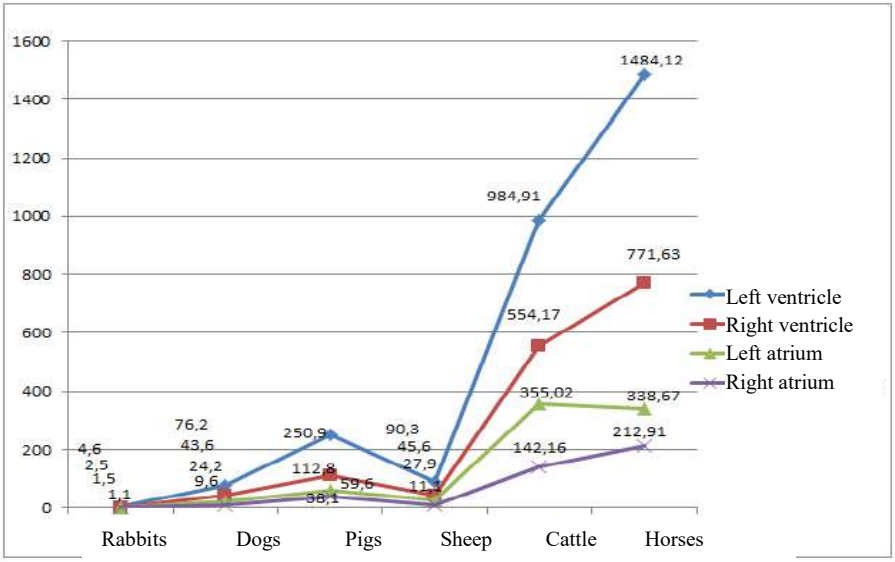

Fig. 4.83. Absolute mass of ventricles and atria of domestic mammals (g).

According to the results of our studies, the relative mass of the anatomical structures of the heart (left and right ventricles, left and right atria) in experimental domestic mammals, relative to the average AM of the heart, is directly proportional to the body mass of animals and the AM of the organ and varies depending on the AM indicators of the corresponding heart chambers and the absolute mass of the heart [229, 230, 460, 475, 473, 188, 561]. The relative mass of the anatomical parts of the heart-the left and right ventricles, left and right atria-according to their functional load was ambiguous (Fig. 4.84).

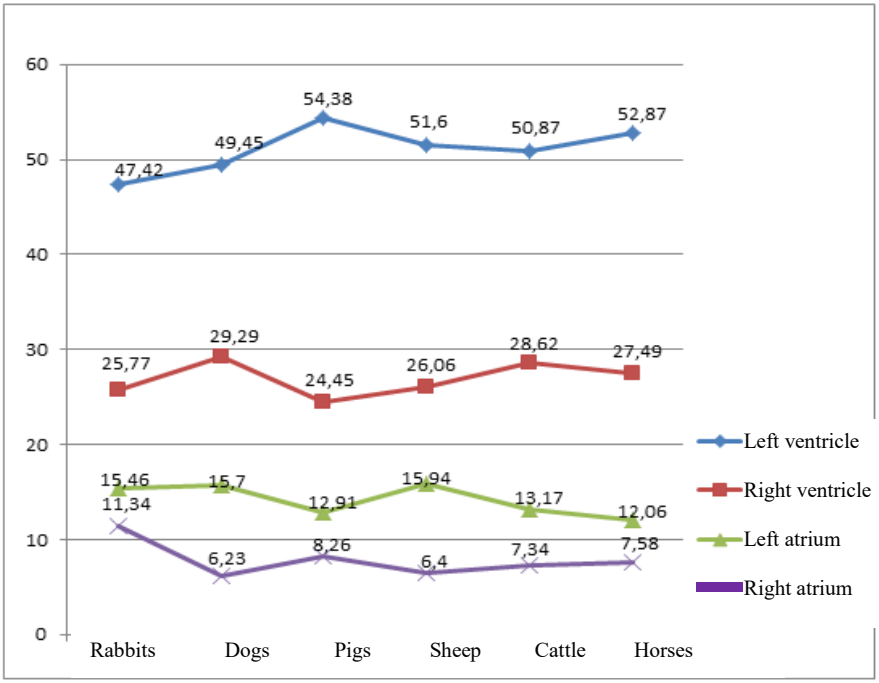

Fig. 4.84. Relative mass of ventricles and atria of domestic mammals (%).

According to our morphometric studies, the left ventricles account for the largest percentage of the total net heart mass (without epicardial fat), with similar values in all animal species: in rabbits – 47.42±2.76%, in dogs – 49.45±2.86%, in pigs – 54.38±3.18%, in sheep – 51.6±3.06%, in cattle – 50.87±1.32%, in horses – 52.87±4.08% [460, 188, 562, 563, 462, 470, 471, 522].

This depends on the fact that in all studied mammals, regardless of their position in the phylogenetic series, the cardiomyocytes of the muscular membrane of the left ventricle of the heart, while performing their work, carry out an increased load, pumping blood under pressure, through the closed system of vessels of the large (somatic) circle of blood circulation.

The right ventricles have a lower VM relative to the pure AM of the heart: in rabbits – 25.77±1.28%, in dogs – 29.29±1.79%, in pigs –24.45±1.62, in sheep – 26.06±1.32%, in cattle – 28.62± 0.64%, in horses – 27.49± 0.82% (Fig. 4.84).

The relative mass of the right and left atria relative to the pure absolute mass of the heart in all experimental animals was the smallest, which is associated with the functional load of cardiomyocytes of the myocardial muscle tissue of the heart when they perform certain work during spontaneous rhythmic contractions: the atria perform less work, receiving blood that returns to the heart from the body of animals [465, 575, 30].

Thus, the largest absolute and relative mass in all experimental animals was characteristic of the left ventricle, then the right ventricle, and the smallest for the left and right atria. With such numerical absolute indicators of the ventricles and atria in domestic animals, the ventricles of the heart are more functionally developed, as evidenced by the ratio of the mass of the ventricles to the net mass of the heart, which is similar in all experimental mammals: in rabbits – 1:0.73, in dogs – 1:0.78, in pigs – 1:0.79, in sheep – 1:0.78, in cattle – 1:0.79, in horses –

1:0.79. The ratio of atrial mass to pure heart mass is less significant in all experimental animals and is as follows: in rabbits – 1:0.27, in dogs – 1:0.21, in pigs – 1:0.21, in sheep – 1:0.22, in cattle – 1:0.21, in horses – 1:0.20. The ratio of atrial mass to ventricular mass in domestic mammals is characterized by the following values: in rabbits – 1:0.37, in dogs – 1:0.28, in pigs – 1:0.27, in sheep – 1:0.29, in cattle – 1:0.26, in horses – 1:0.24 [460, 188, 562, 563, 462, 470, 471, 522].

Thus, the organometric digital values of the heart components (absolute and relative masses of the heart chambers, the ratio of ventricular mass to total heart mass, the ratio of atrial mass to total heart mass, ratio of atrial mass to ventricular mass) in domestic mammals are convincing evidence of the intensive development of the LV, followed by the right ventricle, left and right atria due to their functional load: contractile cardiomyocytes of the LV muscles perform an increased load, pumping blood under pressure through a closed system of vessels of the large circle of blood circulation throughout the body; The cardiomyocytes of the right ventricle pump blood into the small (pulmonary) circle of blood circulation, performing a significantly lower functional load. The atria receive blood returning to the heart from the body of animals, performing a lower load [465, 575].

It should be noted that in recent years, histological and stereological research methods have been increasingly used at these levels of structural organization of the heart [666, 667].

According to literary sources [619, 624, 381, 457] and our own histological studies [261, 230, 436, 437, 460, 187, 559], the microscopic structure of the heart and its components (atria, ventricles) in domestic animals of the class Mammalia has a similar structure. Histologically, the wall of the heart of animals of the class Mammalia is formed by three layers: the inner layer –

the endocardium, the middle layer – the myocardium, and the outer layer – the epicardium. The inner membrane (endocardium) lines the inside of the heart chambers, tendon cords, papillary muscles, and heart valves; the outer membrane (epicardium) covers the myocardium from the outside; the middle membrane (myocardium) is the most developed membrane of the heart. The myocardium is formed by muscle cells – cardiomyocytes, which form a single array of muscle fibers. There are typical cardiomyocytes, which provide the working effect (increase pressure in the heart cavity and move blood), and atypical cardiomyocytes, whose activity is associated with the excitation of the heart and conduction through the tissue [294, 459, 529, 726].

When staining histological preparations using the Hodenheim method, the cardiomyocytes of the heart in a longitudinal section in all domestic mammals are rectangular in shape. They are clearly defined by the sarcolemma and contain sarcoplasm and nuclei. The sarcoplasm has clearly defined transverse and longitudinal striations. Between the cardiomyocytes, there are layers of loose connective tissue containing blood vessels and nerves. The nuclei (one, rarely two) are oval, round, or elongated (rod-shaped) and located in the central part of the sarcoplasm [261, 230, 436, 437, 460, 187, 559].

In modern cardiomorphology, histological and cytometric methods of research are widely used to identify quantitative and relative characteristics of the microscopic structure of the cardiovascular system organs. Such methods allow establishing the interrelationships and interdependence of the morphological components of the body's structures depending on the functional load, respectively at different stages of ontogenetic and phylogenetic development of animals, in normal and pathological conditions, etc. [271, 234].

Mathematical analysis of morphological structures has gained recognition as a modern method distinguished by its objectivity and reliability, which allows for a deeper understanding of the development of pathological processes and logical interpretation of scientific research results. This approach, which is widely used in modern veterinary cardiology, provides objective information about the course of various physiological and pathological processes that occur in the organs and systems of the body when the cardiovascular system is affected [745, 472].

Some scientists point out that volumetric and surface-volumetric ratios are better for determining the characteristics of structural changes in the heart muscle. Morphometric analysis at the cellular level includes the determination of parameters such as cell size, number, and shape. Based on the results obtained, it is possible to draw conclusions about the morphofunctional state of the myocardium during its ontogenetic development and in terms of species in domestic animals, to identify myocardial hypertrophy and atrophy, and to determine the elements for predicting complications that may arise in damaged myocardium, etc. [62, 627, 574].

There are different opinions in the literature regarding the diameter of these cells. Most researchers believe that the diameter of cardiomyocytes in the myocardium of humans, dogs, rabbits, and rats is the same and ranges from 10.0 to 12.0 μm [585, 701]. According to the results of L.M. Dugadko et al. (1990), the thickness of cardiomyocytes in the intact heart of domestic animals is 15.0–20.0 μm [252], the thickness of cardiomyocytes in the myocardium of sheep and horses is 9.19±0.71 μm and 9.87±1.1 μm, in cattle – 13.2±0.36 μm [228], and in pigs – 12.23±0.12 μm [297]. According to T. Hoshino et al. (1983), the length of cardiomyocytes ranges from 50 to 120 μm: in the left

and right ventricles – 60–120 μm (modal class 90 μm), in the right and left atria – 70–90 μm (modal class – 100 μm) [481].

The reasons for such variability in the size of cardiomyocytes in an intact heart may be the methods of fixation, the methods of passing the study material through alcohols of increasing strength, and even the peculiarities of staining. Some researchers explain the variability in the spatial characteristics of cardiomyocytes in an intact heart by the different cross-sectional shapes of cardiomyocytes, which in transverse histological sections are far from the shape of classical geometric figures, etc. [666, 667].

According to the results of our cytometric analysis, the parameters of cardiomyocytes forming the muscle fibers exhibit certain variability and depend both on the animal species and on the morphotopography of the cells within the respective heart chambers (myocardium of the left and right ventricles, atria). This, in turn, reflects the level of functional load on the contractile cells in different regions of the heart in domestic animals [261, 230, 437, 441, 187, 559]. It was found that cardiomyocytes of the left ventricle have significantly greater quantitative characteristics (volume, length, width) compared to those of the right ventricle, which is associated with the higher hemodynamic and contractile demands of the left ventricle responsible for systemic circulation.

These patterns indicate the morphofunctional adaptability of the myocardium, where the size and shape of cardiomyocytes are shaped by specific functional loads, ensuring the effective performance of the heart under various physiological conditions. Furthermore, the interspecies variability of cytometric parameters highlights species-specific features of cardiac muscle morphology and the adaptive strategies implemented at the cellular level to maintain optimal contractile activity of the heart.

According to the results of our cytometric studies, the volume of LV cardiomyocytes in rabbits was the smallest (2834.59±319.99 μm^3), then, in relation to the species characteristics of animals, and therefore their stage of phylogenetic development, the volume of cardiomyocytes increased and amounted to: in dogs – 2941.76±127.44 μm^3, in pigs – 6130.98±922.18 μm^3, in sheep – 3982.99±423.96 μm^3, in cattle – 11225.73±824.42 μm3, in horses – 12554.36±877.52 μm^3 (Fig. 4.85).

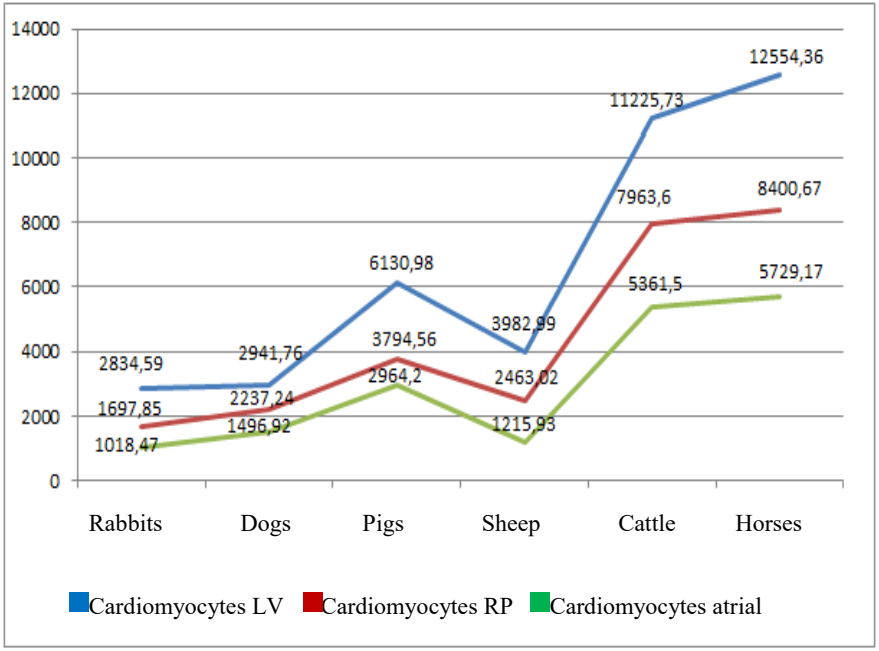

Fig. 4.85. The volume of contractile (typical) cardiomyocytes of the ventricles and atria of the heart of domestic mammals.

Thus, according to the species characteristics of animals, the smallest volume of cardiomyocytes in the left ventricle of the

heart, among all domestic mammals studied by us, was found in rabbits, and the largest – in horses (Fig. 4.81). Thus, our research results were consistent with the generally accepted fact that cell size is directly dependent on the level of mammalian development (the higher the species in systematic terms, the larger the cell body volume) and on the size (mass) of the animal's body.

Our detailed analysis of morphometric studies of myocardial microstructures shows that the volume of cardiomyocytes in the right ventricle of the heart of experimental animals also increases in terms of species [261, 230, 436, 437, 187, 559], following the generally accepted rules of phylogeny – the higher the species in phylogenetic development, the greater the cell volume. Therefore, the volume of cardiomyocytes in the right ventricle of the heart, as well as in the left ventricle, was smallest in rabbits and largest in horses (Fig. 4.85).

With regard to individual characteristics of animals, the volume of cardiomyocytes in the right ventricle of the heart was significantly ($p \leq 0.05$) smaller in all experimental animals compared to that in the left ventricle of the heart: in rabbits (1697.85±239.06 μm^3) by 1.76 times, in dogs (2237.24±103.02 μm^3) by 1.32 times, in pigs (3794.56±489.87 μm^3) and sheep (2463.02±318.04 μm^3) by 1.62 times, in cattle (7963.60± 627.09 μm^3) by 1.41 times, in horses (8400.67±681.04 μm^3) by 1.49 times. This is not a coincidence, but a real and objective characteristic of the difference in ventricular activity, since the left ventricle functions mainly as a pump, and the right ventricle as a volume [465, 575]. Therefore, the larger volume of the left ventricle of the heart in all experimental animals, compared to the right ventricle, is associated with the functional characteristics of the myocardial muscle tissue, which is capable of spontaneous rhythmic contractions, promoting blood flow through the vessels: the cardiomyocytes of the left ventricle perform more work,

promoting blood flow through the vessels of the systemic circulation, while the cardiomyocytes of the right ventricle perform less work, promoting blood flow through the vessels of the pulmonary circulation [465, 575].

According to the results of cytometric studies of atrial cardiomyocytes, their volume in all experimental animals was significantly smaller compared to that in the right and left ventricles of the heart (Fig. 4.85). This is explained by the fact that the atria, compared to the ventricles of the heart, perform significantly less work, ensuring blood flow through a closed system of blood vessels – the left atrium closes the pulmonary (small) circle of blood circulation, and the right atrium closes the large (somatic) circle of blood circulation [25, 467, 575].

According to our calculations, the average volume of atrial cardiomyocytes (right and left together) in the domestic animals we studied was as follows: in rabbits – 0.0389±0.0062 μm_3, in dogs – 0.0367±0.0105 μm^3, in pigs – 2964.20±412.02 μm^3, in sheep – 1215.93±176.94 μm^3, in cattle – 5361.50±583.91 μm^3, in horses – 1215.93±176.94 μm^3. Compared to these indicators in LSH, their volumes were significantly lower: in rabbits ($p \leq 0.01$) by 2.78 times, in dogs ($p \leq 0.01$) by 1.96 times, in pigs ($p \leq 0.01$) by 2.07 times, in sheep ($p \leq 0.001$) – 3.27 times, in cattle ($p \leq 0.01$) – 2.09 times, in horses ($p \leq 0.01$) – 2.19 times, compared to the right ventricle: in ($p \leq 0.05$) 1.67 times, in ($p \leq 0.05$) 1.49 times, in ($p \leq 0.05$) 1.28 times, in ($p \leq 0.01$) 2.06 times, in ($p \leq 0.05$) 1.48 times, in ($p \leq 0.05$) 1.47 times, respectively.

According to karyometric studies, the average volumes of cardiomyocyte nuclei in the myocardium of the ventricles and atria in all experimental animals had different values, depending on their species characteristics: the smallest volumes were characteristic of rabbit cardiomyocytes, the largest – of horse

cardiomyocytes (Fig. 4.86), which is associated with the species characteristics of the organism.

However, in terms of individual animal development, the average volume of cardiomyocyte nuclei in the right and left ventricles and atria was similar in all experimental animals (Fig. 4.86).

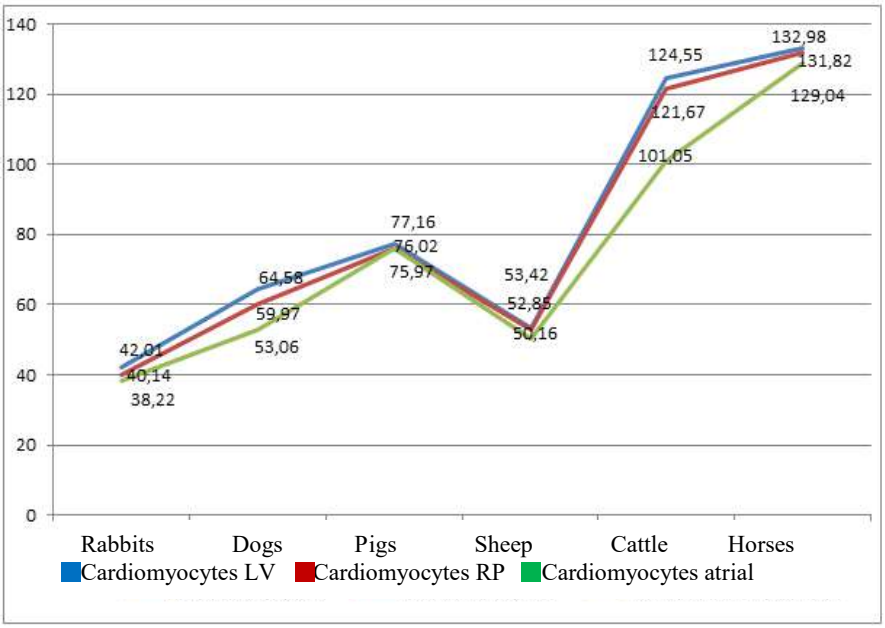

Fig. 4.86. Nuclear volume of contractile (typical) cardiomyocytes in the ventricles and atria of the hearts of domestic mammals.

Given such ambiguous quantitative indicators of cardiomyocyte volume (differences between them in the corresponding chambers of the heart-ventricles, atria), and, accordingly, similar quantitative values for the volume of their nuclei in a specific animal species, cardiomyocytes were found to have different YCV coefficients (Fig. 4.87) [261, 265, 230, 436,

437, 187, 559], which indicated a functional feature of the muscular membrane of the ventricles and atria during spontaneous and rhythmic contractions of cardiomyocytes when performing a certain task.

The nuclear-cytoplasmic ratio of LV cardiomyocytes, compared to that in the RV and atria, was the smallest in all experimental animals. At the same time, in a comparative species aspect, the NCR was higher for cardiomyocytes of the LV of the dog heart (0.0224±0.0076) and 1.4 times lower in rabbits (0.0161±0.0054).

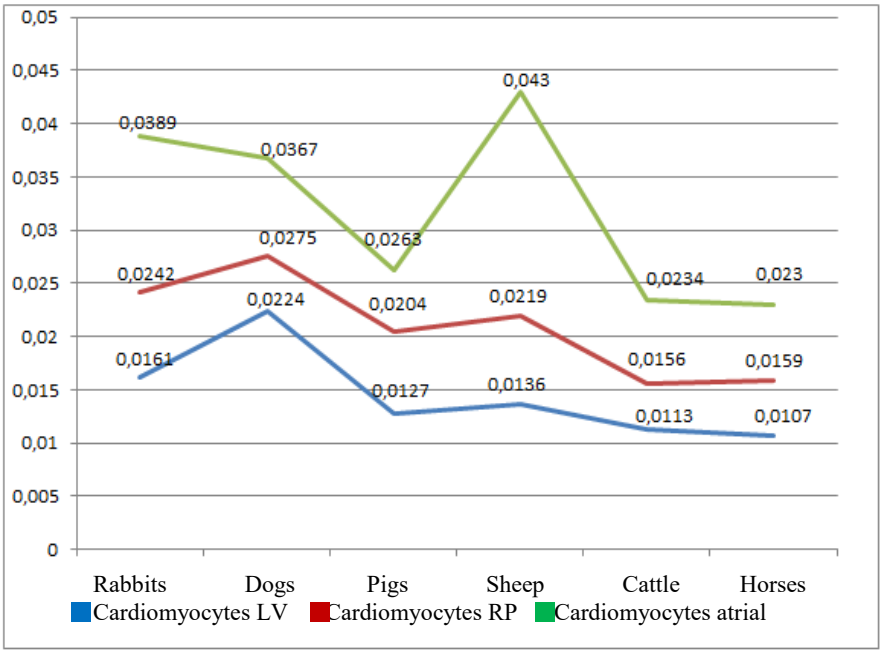

Fig. 4.87. Nuclear-cytoplasmic ratio of contractile (typical) cardiomyocytes of the heart of domestic mammals.

A lower nuclear-cytoplasmic index was characteristic of large animals (cattle – 0.0113±0.0068 and horses – 0.0107±0.0074), which is direct evidence of the high level of morphofunctional state of cardiomyocytes in representatives of these species of domestic animals of the mammalian class. After all, the most functionally active somatic cells are those characterized by a low NC-CI [226]. This is associated with the intensification of the functional activity of the left ventricle of the heart: cardiomyocytes of the left ventricle of the heart pump blood through a closed system of vessels of the large (somatic) circle of blood circulation to the body of animals, which starts from the left ventricle of the heart, from which arterial blood enters the capillaries through the aorta (gas exchange occurs) of the organs and animals throughout the body, then venous blood flows from the organs and tissues through the hollow veins into the right atrium. Thus, in order to perform such an increased load, blood circulates in the following direction: heart – arteries – arterioles – precapillaries – capillaries – postcapillaries – venules – veins – heart, performing the greatest load [25, 467, 575, 626].

Cells with a higher YACV index are less functionally active. That is why the YACV of cardiomyocytes in the right ventricle of the heart in all studied animals was significantly ($p \leq 0.05$) higher than in the left ventricle: in rabbits (0.0242±0.0048) – 1.5 times, in dogs (0.0275±0.0081) – 1.23 times, in pigs (0.0204±0.0068) – 1.61 times, in sheep (0.0219±0.0079) – 1.61 times, in cattle (0.0156±0.0054) – 1.38 times, in horses (0.0159±0.0098) – 1.48 times. This is due to the fact that right ventricular cardiomyocytes, compared to LV, perform less work, facilitating blood flow through the vessels of the small (pulmonary) circle of blood circulation, which begins in the right ventricle of the heart, where venous blood is delivered to the alveoli of the lungs through the pulmonary artery (gas exchange occurs through the walls of the

alveoli and pulmonary capillaries between the air contained in the alveoli and the blood), then from the lungs, arterial blood enters the left atrium through the veins, performing a significantly lower workload [25, 467, 575].

The highest value of the nuclear-cytoplasmic ratio coefficient is characteristic of atrial cardiomyocytes. In terms of species, these parameters manifested themselves as follows: the highest value was found in sheep – 0.0430±0.0096, intermediate values were found in rabbits (0.0389±0.0062) and dogs (0.0367±0.0105), the lowest values, which were close to each other, were characteristic of pigs (0.0263±0.009), cattle (0.0234±0.0058), and horses (0.0230±0.0066) (Fig. 4.86). Such high YACV values, which we found in atrial cardiomyocytes compared to those in the ventricles of the heart, indicate a lower morphofunctional load on atrial cardiomyocytes compared to ventricular cardiomyocytes during rhythmic and spontaneous contractions. This is due to the fact that the atria receive blood returning to the heart from the body of animals, closing the circulatory circles: the left atrium closes the small circle of blood circulation, the right atrium closes the large circle of blood circulation, performing a significantly lower load, as evidenced by the correspondingly high YACV index of atrial cardiomyocytes [261, 230, 436, 437, 187, 559]. After all, less functionally active and mature somatic cells are those characterized by a high YAC index.

Thus, according to the results of cytometric studies, cardiomyocytes of the muscular membrane of the heart and its components in domestic mammals are different and have different quantitative characteristics depending on the species of experimental animals, their body weight, absolute and relative heart weight, and physiological load on the corresponding organs. We associate the increase in the volume of cardiomyocytes and

their nuclei in the phylogenetic series with the adaptive features of the animal organism to the conditions of existence. It is known that the most developed organs are found in animals that are subject to significant physical and physiological stress on the corresponding organs and systems [228].

At the same time, the highest cytometric parameters of cardiomyocytes (length, width, volume of cardiomyocytes, their nuclei, low YCV-cardiomyocytes value) are found in the myocardium of the left ventricle of the heart and, accordingly, lower quantitative values in the myocardium of the right ventricle and especially in the myocardium of the atria of mammals, are associated with the functional characteristics of the myocardial muscle tissue, which is capable of spontaneous, rhythmic contractions, promoting blood flow through the closed system of vessels of the large and small circulatory systems.

Thus, our studies have shown that the macro- and histological structure of the heart in clinically healthy domestic animals studied by us in a comparative species aspect has a similar histoarchitectonics characteristic of other species of animals of the Mammalia class, but differs in morphometric indicators. Such studies are not only of cognitive importance, but also form the basis for clinical veterinary medicine in the field of veterinary cardiology.

CONCLUSIONS

In scientific work using macro- and microscopic, organ-, histo- and cytometric research methods, a new solution to the current scientific problem has been theoretically generalized and presented, which consists in establishing the patterns of the structure and development of the heart, taking into account the formation of morphological features (markers) in clinically healthy six species of domestic animals, class Mammalia – Mammals: Orictolagus cunicalus L., 1758 – European rabbit; Canis familiaris L., 1759 – domestic dog; Sus scrofa, forma domestica L., 1758 – domestic pig; Ovis aries L., 1758 – domestic sheep; Bos Taurus L., 1758 – domestic cattle; Equus ferus Caballus L., 1758 – domestic horse.

The morphoarchitectonics of the heart in experimental animals are similar to each other, but have certain morphometric features. Taking into account the macroscopic structure and development index of the organ, three types of heart shape have been identified in domestic mammals: the first type is enlarged-shortened (IRS = 140–150%), the second is enlarged-elongated (IRS = 151–160%), and the third is elongated-narrowed (IRS = 161–170%). The rabbit's heart is oval in shape, enlarged-shortened (IRS = 145.8 ± 4.16%) type; the dog's heart is round (elliptical) in shape, enlarged-shortened (IRS = 145.9 ± 6.56%) type; the pig's heart is relatively large, ellipsoidal-conical in shape, enlarged-elongated (IRS = 155.06 ± 6.32%); the sheep's heart is conical in shape, enlarged-shortened (IRS = 145.5 ± 4.02%); the heart of cattle is cone-shaped, elongated-narrowed (IRS = 166.04 ± 5.14%); the heart of a horse is cone-shaped, enlarged-shortened (IRS = 147.52 ± 7.36%).

The absolute mass of the heart in domestic mammals (the smallest in rabbits – 10.3 ± 0.86 g, the largest in horses – 2987.6 ±

96.84 g) synchronously obeys the well-known and recognized fact of phylogenetic development of animals: the higher the species of animals in systematic terms (their size, live body weight, etc.), the greater the organometric indicators of the organ.

The relative mass of the heart varies asynchronously, depending on the body weight of animals and the absolute mass of the heart (the percentage of the organ's mass relative to the body weight of animals). The highest heart WM is in dogs – 0.72±0.005% and horses – 0.59±0.012%, the lowest is in pigs – 0.29±0.004%.

The thickness of the walls of the ventricles and atria of the heart in domestic mammals depends on the functional load of the corresponding chambers of the heart and the species characteristics of the cardiovascular system of the experimental animals:

– the heart walls are more developed in rabbits – 5.91± 0.11 mm, dogs – 15.92±0.34 mm, pigs – 26.7±0.51 mm, sheep – 164.08±16.17 mm, cattle – 36.54±0.64 mm, horses – 40.14± 0.88 mm. The wall thickness of the right ventricle of the heart is significantly smaller than that of the left ventricle: in rabbits ($p \leq 0.01$) by 1.9 times, in dogs ($p \leq 0.05$) by 1.52 times, in pigs ($p \leq 0.01$) by 1.85 times, in sheep ($p \leq 0.01$) – 1.98 times, in cattle – ($p \leq 0.01$) – 1.98 times, in horses ($p \leq 0.01$) – 1.98 times;

– the walls of the left atrium are less developed: in rabbits – 3.82±0.04 mm, in dogs – 4.37±0.08 mm, in pigs – 7.81±0.06 mm, in sheep – 7.05±0.09 mm, in cattle – 8.24±0.12 mm, in horses – 11.02±0.16 mm. The thickness of the PP walls, compared to the LP, is significantly ($p \leq 0.05$) smaller: in rabbits by 1.46 times, in dogs – 1.32, in pigs – 1.3, in sheep – 1.39, in cattle – 1.14, in horses – 1.1 times.

The absolute mass of the ventricles and atria of the heart in domestic mammals varies and is determined by the formation and

functional load of cardiomyocytes of the corresponding anatomical structures during their rhythmic contraction:

– the LV has the largest AM mass: in rabbits – 4.6±0.37 g, in dogs – 76.2±1.02 g, in pigs – 250.9±5.37 g, in sheep – 90.3±5.21 g, in cattle – 984.91±19.52 g, in horses – 1484.12±28.74 g. The absolute mass of PS, compared to LS, is significantly lower: in rabbits ($p \leq 0.01$) by 1.84 times, in dogs ($p \leq 0.05$) by 1.75 times, in pigs ($p \leq 0.001$) by 2.22 times, in sheep ($p \leq 0.001$) – 1.98 times, in cattle – ($p \leq 0.05$) – 1.78 times, in horses ($p \leq 0.001$) – 1.92 times;

– lower absolute weight is characteristic of LP: in rabbits – 1.5±0.14 g, in dogs – 24.2±2.88 g, in pigs – 59.6±2.16 g, in sheep – 27.9±3.31 g, in cattle – 255.02±8.04 g, in horses – 338.67±14.52 g. The absolute mass of PP, compared to LP, is significantly lower: in rabbits ($p \leq 0.05$) by 1.36 times, in dogs ($p \leq 0.001$) by 2.52 times, in pigs ($p \leq 0.01$) by 1.56 times, in sheep ($p \leq 0.001$) – 2.49 times, in cattle ($p \leq 0.01$) – 1.79 times, in horses ($p \leq 0.01$) – 1.59 times.

The relative mass of the left and right ventricles and the left and right atria in relation to the AM of the heart is directly proportional to the AM of the organ and the body weight of the animals:

– the largest percentage of the total net mass of the heart is occupied by the LV, the indicators of which are similar in all animal species: in rabbits – 47.42±2.76%, in dogs – 49.45±2.86%, in pigs – 54.38±3.18%, in sheep – 51.6±3.06%, in cattle – 50.87±1.32%, in horses – 52.87±4.08%. A lower VM relative to the pure AM of the heart is characteristic of PS: in rabbits – 25.77±1.28%, in dogs – 29.29±1.79%, in pigs – 24.45±1.62, in sheep – 26.06±1.32%, in cattle – 28.62± 0.64%, in horses – 27.49±0.82%;

– the relative mass of the left and right ventricles relative to the pure absolute mass of the heart in all experimental animals is the smallest: the VM LP in rabbits is 15.46±0.88%, in dogs – 15.7±1.86%, in pigs – 12.91±0.09%, in sheep – 15.94±1.49%, in cattle – 13.17±0.21%, in horses – 12.06±0.47%, respectively, VMPP – 11.34±0.62%, 6.23±0.94%, 8.26±0.11%, 6.4±0.82%, 7.34±0.09% and 7.58±0.11%.

In domestic mammals, the species stability of the ventricular-cardiac index (VCI) – the ratio of ventricular AM to pure heart weight – has been established: in rabbits – 1:0.73, in dogs – 1:0.78, in pigs – 1:0.79, in sheep – 1:0.78, in cattle – 1:0.79, in horses – 1:0.79, and the atrial-cardiac index (ACI) – the ratio of atrial mass to net heart mass: in rabbits – 1:0.27, in dogs – 1:0.21, in pigs – 1:0.21, in sheep – 1:0.22, in cattle – 1:0.21, in horses – 1:0.20. Accordingly, the atrioventricular index (AVI) – the ratio of atrial mass to ventricular mass in rabbits is 1:0.37, in dogs – 1:0.28, in pigs – 1:0.27, in sheep – 1:0.29, in cattle – 1:0.26, in horses – 1:0.24, which indicates a certain peculiarity in the formation of the myocardium of the ventricles and atria depending on the species characteristics of domestic mammals.

According to cytometric studies, the largest volume is found in the cardiomyocytes of the left ventricle: in rabbits – 2834.59±319.99 μm^3, in dogs – 2941.76±127.44 μm^3, in pigs – 6130.98±922. 18 μm^3, in sheep – 3982.99±423.96 μm^3, in cattle – 11225.73±824.42 μm^3, in horses – 12554.36±877.52 μm^3. The volumes of right ventricular cardiomyocytes are significantly smaller than those of the left ventricle: in rabbits ($p \leq 0.05$) by 1.76 times, in dogs ($p \leq 0.05$) by 1.32 times, in pigs and sheep ($p \leq 0.05$) by 1.62 times, in cattle ($p \leq 0.05$) by 1.41 times, and in horses ($p \leq 0.05$) by 1.49 times. The smallest volume is found in atrial cardiomyocytes: in rabbits – 0.0389±0.0062 μm^3, in dogs – 0.0367±0.0105 μm^3, in pigs – 2964.20±412.02 μm^3, in sheep –

1215.93±176.94 μm^3, in cattle – 5361.50±583.91 μm^3, in horses – 1215.93±176.94 μm^3.

The lowest nuclear-cytoplasmic ratio of typical (contractile) cardiomyocytes in domestic mammals, indicating the morphofunctional characteristics of muscle tissue due to spontaneous rhythmic contractions of the myocardium, characteristic of the left ventricle of the heart: in rabbits – 0.0161±0.0054, in dogs – 0.0224±0.0076, in pigs – 0.0127±0.0056, in sheep – 0.0136±0.0062, in cattle – 0.0113±0.0068, in horses – 0.0107±0.0074. The nuclear-cytoplasmic ratio of right ventricular cardiomyocytes is significantly higher than that of left ventricular cardiomyocytes: in rabbits – 1.5 times, in dogs – 1.23 times, in pigs and sheep – 1.61 times, in cattle – 1.38 times, in horses – 1.48 times. The highest nuclear-cytoplasmic ratio is characteristic of atrial cardiomyocytes: in rabbits – 0.0389±0.0062, in dogs – 0.0367±0.0105, in pigs – 0.0263±0.0097, in sheep – 0.0430±0.0096, in cattle – 0.0234±0.0058, in horses – 0.0230±0.0066.

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