P.A. Kobeza
I.V. Tverdokhlib

Dnipro State Medical University
Dnipro, Ukraine

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HISTOGENETIC AND MORPHOFUNCTIONAL ASPECTS OF MUSCLE TISSUE CLASSIFICATION (review and research perspectives)

Kobeza P.A. ✉, Tverdokhlib I.V. Histogenetic and morphofunctional aspects of muscle tissue classification (review and research perspectives).
Dnipro State Medical University, Dnipro, Ukraine.
ABSTRACT. Introduction. Novel methods for determining the developmental pathways and formation of muscle tissue, whose main feature is the contraction mechanism, are gaining widespread use. Muscle tissue is a highly specialized structure responsible for the motor activity of an organism. Understanding its structure and histogenesis is critically important for studying both normal and pathological conditions. Research in embryology and histology, enhanced by modern methods of microscopy and molecular biology, allows for a new look at the fundamental mechanisms of muscle tissue development, which opens up new perspectives in the field of individual developmental biology, cytology and histology. **The objective** of this article is to systematize and integrate current scientific data on the histogenetic and morphofunctional aspects of muscle tissue classification. The aim is to expand the understanding of the developmental origins and key differences in the formation processes of each type of muscle tissue. **Methods.** A systematic scientific search was conducted in the Scopus, Web of Science Core Collection, and PubMed databases. The analysis covered the period from 2015 to 2025. The search was performed using keywords such as "myogenesis," "cardiogenesis," "smooth muscle development," "muscle tissue histology," and "embryonic myogenesis." In total, over 100 scientific publications were analyzed, including review articles and the results of primary experimental studies. **Results**. The literature analysis confirms that the three types of muscle tissue have different origins and unique histogenetic mechanisms. Skeletal muscle develops from the myotomes of somites through the fusion of myoblasts into multinucleated muscle fibers. Cardiac muscle is formed from the visceral leaf of the splanchnotome; however, cardiomyocytes do not fuse but form a single network, functionally connected by intercalated discs. Smooth muscle has the most variable origin (from the splanchnotome mesenchyme or the ectoderm of the neural crest) and is formed from individual spindle-shaped cells that retain the ability to proliferate. **Conclusion.** The fundamental morphofunctional differences between the three types of muscle tissue are directly determined by their histogenesis. Modern research methods allow for the detailed study of these processes, confirming that the formation of multinucleated structures, specific intercellular contacts, and the variability of embryonic origin are key events that determine the final structure of muscle tissue. The systematization of this knowledge is the basis for further research in developmental biology and tissue engineering.
Key words: histogenesis, muscle tissue, myogenesis, cardiogenesis, myoblast, cardiomyocyte, smooth muscle.

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Kobeza P.A. 0000-0003-1113-4007
Tverdokhlib I.V. 0000-0002-8672-3773
✉ kobeza.pavel@gmail.com

Introduction

Muscle tissue is a highly specialized biological structure that is key to ensuring the motor activity of an organism and its individual components. Its unique characteristic is the ability to contract, which is realized on the basis of the mechanisms of interaction between actin and myosin filaments. This fundamental feature leads to the diversity of its morphological structure and functional characteristics. In the human

body, three main types of muscle tissue are distinguished, each with a different origin and histogenesis. According to studies, Myosin heavy chain-embryonic plays a critical role in skeletal muscle tissue differentiation during mammalian development, as shown by Agarwal M, Sharma A et al. [1]. This protein, according to them, is not just present, but is an active regulator that influences the formation of muscle fibers. Understanding this regulatory function can be key to further studying skeletal muscle morphogenesis. Their work sheds light on the specific molecular mechanisms that control cell differentiation in the early stages. The authors emphasize that identifying such regulatory proteins is an important step in studying histogenesis. This study is a valuable contribution to understanding the fundamental processes underlying muscle tissue formation. It provides new data for future research in the field of developmental biology.

Skeletal muscle tissue originates from the myotome of somites, which, in turn, differentiate from the paraxial mesoderm. This process involves the differentiation of myoblasts and their subsequent fusion to form multinucleated muscle fibers, which is a characteristic feature of this tissue. Cardiac muscle tissue is formed from the visceral leaf of the splanchnotome, and its morphogenesis is aimed at forming a functionally integral myocardium. Smooth muscle tissue has the most variable embryonic origin, developing from both the splanchnotome mesenchyme and the ectomesenchyme of the neural crest, which is characteristic of some anatomical structures.

The latest single-cell cartography methodology, applied by Giordani L, He GJ et al., allowed the identification of previously unknown populations of cells resident in skeletal muscles [2]. This study fundamentally expands our understanding of the cellular composition and heterogeneity of this tissue. According to the authors, these newly discovered cell populations may play an important role in the function and maintenance of muscle tissue. Their work emphasizes that traditional methods of histological analysis may not always reveal the full complexity of the cellular composition. This discovery has a significant impact on our understanding of embryonic development and muscle morphogenesis. It also provides new objects for further morphological and histological research. The data obtained in this study can be used to create more detailed maps of cell lineages.

Understanding these histogenetic pathways is the basis for the correct classification and functional analysis of muscle tissues. Studying the features of their development and structure is important for analysis both in normal conditions and in pathological states. This review article is dedicated to the systematization of modern scientific data concerning the histogenetic and morphofunctional aspects of muscle tissue classification.

The study by Wu P, Zhou K et al. identifies key circular RNAs (circRNAs) that play an important role in the development of chicken skeletal muscles at the embryonic stage [3]. The authors found a significant number of differentially expressed circRNAs that are associated with growth and metabolic processes. According to their conclusions, some of these circRNAs influence the organization of the actin cytoskeleton and the assembly of myofibrils, which is critical for the formation of muscle structure. This study emphasizes the complexity of the molecular regulation of muscle histogenesis, demonstrating that not only proteins, but also non-coding RNAs play an important role. The use of RNA sequencing allowed the authors to gain a deep understanding of molecular mechanisms. The discovered regulatory networks, according to them, can serve as a basis for future research in the field of developmental biology.

The review by Scaal M, Marcelle C. focuses on the contribution of chicken and quail embryos as models for studying cell lineages, muscle morphogenesis and tissue interaction [4]. The authors emphasize that, despite a large number of genetic studies on mice, it was avian models that provided the basic knowledge about cellular processes. According to their analysis, these models are indispensable for studying skeletal muscle morphogenesis *in vivo*. The work focuses on the importance of classical embryological approaches combined with modern molecular methods. They argue that understanding these processes is key to a general understanding of the development of skeletal muscles in vertebrates. This review is valuable for the systematization of knowledge obtained over many decades of research. The authors believe that the combination of different model organisms allows for a more complete picture of histogenesis.

The work of Hernández-Hernández J.M., García-González E.G. et al. focuses on the role of myogenic regulatory factors (MRFs) as key determinants of muscle cell development, identity and regeneration [5]. The authors argue that these transcription factors initiate and control a cascade of events necessary for myoblast differentiation. According to their conclusions, MRFs not only initiate the formation of muscle fibers, but also maintain their cellular identity in the mature organism. The review emphasizes that understanding the role of these factors is critically important for studying the fundamental aspects of histogenesis. They also note that MRFs play a key role in maintaining the satellite cell population, which is the basis for muscle regeneration.

The objective of this review article is to systematize and integrate current scientific data regarding the histogenetic and morphofunctional aspects of muscle tissue classification. We aim to expand the understanding of the developmental origins of each type of muscle tissue and identify key differences in their formation processes based on embryological, histological, and molecular-biological studies.

Muscle tissue is a biological structure composed of cells, or myocytes, that are capable of contraction.

These cells contain myofibrils, which are contractile proteins—actin and myosin. Their function is to convert chemical energy, obtained from metabolic processes, into mechanical energy. This unique characteristic is the basis for all of its functions, including movement, posture maintenance, and the regulation of internal processes.

The relevance of the study is driven by the continuous expansion of knowledge in embryology and histology, which allows for a new perspective on the fundamental mechanisms of tissue development. A detailed study of muscle tissue histogenesis is critically important for understanding both the normal functioning of the body and the pathogenesis of congenital or acquired diseases related to disorders in their development and regeneration. The integration of new findings, obtained with modern methods of microscopy and molecular biology, allows for the formation of a holistic view of the formation of muscle structures, which, in turn, opens new perspectives for research in the field of regenerative medicine.

Materials and methods

For the preparation of this review article, a systematic scientific search was conducted in leading global scientometric databases, such as Scopus, Web of Science Core Collection, and PubMed. The chronological scope of the search covered the last ten years (2015-2025), which allowed for a focus on the most relevant and recent studies. The search was performed using relevant keywords such as “myogenesis,” “cardiogenesis,” “smooth muscle development,” “muscle tissue histology,” “embryonic myogenesis,” “skeletal muscle differentiation,” and “muscle progenitor cells.” Special attention was paid to scientific publications that included the results of embryological studies, high-resolution microscopy (including transmission and scanning electron microscopy), and data from immunohistochemical and molecular-biological analysis. In total, more than 100 scientific publications were analyzed, including review articles, primary research, and the results of long-term experimental work. This approach provided a comprehensive and multifaceted evaluation of current concepts regarding the histogenesis and morphofunctional aspects of muscle tissue classification.

Results and discussion

The structure of muscle tissue is unique and differs depending on its type: striated (skeletal and cardiac) and non-striated (smooth). This distinction is determined by the specific arrangement of actin and myosin filaments, which form myofibrils. In their review, Chal J and Pourquié O. elaborate on the mechanisms of skeletal myogenesis both in vivo and in vitro, providing a comprehensive analysis of the muscle tissue formation process [6]. They emphasize that studying these processes outside the organism allows for their observation and control with high precision. According to the authors, these studies help to identify the key factors that drive differentiation. The work highlights the importance of understanding the relationship between cellular signals and morphological changes. This review is valuable for understanding how knowledge gained in laboratory settings can be extrapolated to the complex systems of a living organism. This research is important for our article because it integrates experimental data obtained by various methods. According to their analysis, skeletal myogenesis is a highly organized process regulated on many levels.

Striated muscles are characterized by the presence of sarcomeres—the basic contractile units that give them their typical striated appearance. This high level of organization ensures rapid and powerful contraction. In contrast, in smooth muscle tissue, the filaments are arranged less orderly, allowing it to contract more slowly and for longer periods, maintaining the tone of internal organs. In general, the functional properties of muscle tissue include excitability, contractility, extensibility, and elasticity. Pourquié O.'s review focuses on the formation of somites in the chicken embryo, emphasizing that this process is the foundation for the development of skeletal musculature [7]. The author describes in detail the mechanisms of paraxial mesoderm segmentation. According to his conclusions, somitogenesis is regulated by a complex mechanism known as the "clock-and-wavefront" model. This mechanism ensures the synchronous formation of paired somites, which is critical for the correct positioning of muscles. The work highlights that somites are precursors not only of muscles but also of other structures such as the spine and skin. This study is fundamental to understanding the initial stages of skeletal muscle histogenesis. The author believes that studying somitogenesis is key to understanding the entire development of vertebrates.

The histogenesis of skeletal muscle tissue, known as myogenesis, is a complex, multi-stage process that begins early in embryonic development. This tissue originates from the paraxial mesoderm, which forms segmented structures called somites. The ventrolateral part of the somites, known as the myotome, is the main source of muscle fiber progenitor cells. Cells from the myotome migrate to become myoblasts, which are mononucleated and have high proliferative activity. This process of migration and proliferation occurs under the influence of numerous signaling molecules, such as fibroblast growth factors (FGFs) and hepatocyte growth factors (HGFs), secreted by cells of the neural tube, ectoderm, and other adjacent structures.

Weldon S.A. and Münsterberg A.E. review the development of somites and the regionalization of the vertebrate axial skeleton, which is closely related to the formation of skeletal muscles [8]. Their review emphasizes that the correct segmentation of somites is critical for the subsequent differentiation of myotomes. The authors analyze the role of signaling pathways that control somite differentiation. According to them, these processes are the basis for the formation

of a functional locomotor apparatus. This study provides important data on the interaction between the skeleton and muscle tissue in the early stages of development. They believe that disruptions at this stage can have serious consequences for the final morphology. The review is a valuable contribution to our understanding of the embryonic foundations of muscle development.

The review by Bertrand S, Aldea D et al., focusing on the evolution of FGF and retinoic acid (RA) signaling pathways that control somitogenesis in chordates, demonstrates the evolutionary conservativeness of these mechanisms [9]. The authors argue that these signaling pathways are fundamental for the correct formation of segmented structures. Their work emphasizes that understanding the evolutionary origins of these processes helps to better understand their importance for muscle histogenesis. This study provides a broader evolutionary context for our data, showing that the mechanisms we are studying are ancient and universal. According to the authors, studying these signaling pathways in primitive chordates helps to reveal their role in higher vertebrates.

After the proliferation period, myoblasts begin to differentiate. This stage is accompanied by the expression of specific transcription factors belonging to the MRF (Myogenic Regulatory Factors) family, particularly MyoD and Myf5. These factors initiate a cascade of genetic events that trigger the synthesis of contractile proteins and other components of the muscle fiber. After differentiation, myoblasts lose their ability to divide and fuse with each other, forming multinucleated cellular structures known as myotubes. This fusion is a key and unique stage in the formation of skeletal muscle tissue, which fundamentally distinguishes it from other muscle tissues. Inside the myotubes, the active synthesis of myofibrils begins, which are arranged in an orderly fashion along the cell.

The next stage is the maturation of myotubes into mature muscle fibers. This process includes the further organization of myofibrils into sarcomeres, the formation of a complex sarcoplasmic reticulum and T-tubule system, and the migration of nuclei to the periphery of the cell. Mature muscle fibers are surrounded by a basement membrane that ensures their structural integrity and interaction with the surrounding environment. In addition, at this stage, connective tissue sheaths are formed: the endomysium, which surrounds each individual fiber, the perimysium, which unites the fibers into fascicles, and the epimysium, which covers the entire muscle. These sheaths not only maintain the mechanical strength of the muscle but also contain blood vessels and nerve endings, which are vital for its function. The features of skeletal muscle histogenesis, namely the formation of multinucleated syncytia, are the basis for its high contractile ability and rapid response to nerve impulses. Remnants of undifferentiated myoblasts that remain in the mature tissue in the form of satellite cells play an important role in its regeneration after damage. Thus, the histogenesis of skeletal muscles is not just a process of formation, but also the basis for their further function and restoration.

In their review, Miao Y and Pourquié O. describe the cellular and molecular control of somitogenesis in vertebrates, providing updated data on this key process [10]. The authors emphasize that somites are the source not only of skeletal musculature but also of cartilage and dermis. Their work analyzes the complex mechanisms that ensure mesoderm segmentation, including the role of biological clocks. According to their analysis, the correct formation of somites is critical for the entire body's development. This study provides a comprehensive overview of the molecular regulators that govern morphogenesis in the early stages. They believe that the details of these processes are the basis for understanding tissue formation.

The review by Onai T. is dedicated to the evolutionary origin of chordate segmentation, revisiting the enterocoel theory, which is important for understanding the origin of somites [11]. The author argues that segmentation is one of the oldest and most important features of chordates. His work provides an evolutionary context for our study, showing that the mechanisms we are studying are deeply rooted in evolution. According to the author, understanding evolutionary origins helps to explain modern morphology. This study helps us place our analysis in a broader context.

Piatkowska A.M., Evans S.E. and Stern C.D. review in detail the cellular aspects of somite formation in vertebrates, focusing on cell dynamics and their interaction [12]. The authors emphasize that somitogenesis is a highly organized process that involves precise cell movements and shape changes. Their work analyzes the mechanisms that ensure the formation of segments from the unsegmented mesoderm. According to their conclusions, these cellular aspects are critical for the correct development of muscle tissue. This study provides a deep insight into the cell biology of muscle formation.

Meister L., Escriva H., and Bertrand S. study the functions of the FGF signaling pathway in cephalochordates, which provides insight into the evolution of the prechordal plate and, accordingly, somites [13]. The authors argue that this signaling pathway is a fundamental regulator of development. Their work emphasizes the evolutionary conservativeness of the mechanisms that govern the formation of basic structures. This study is important for understanding the evolutionary basis of muscle histogenesis.

In their study, Miao Y, Djeffal Y et al. performed the reconstruction and deconstruction of human somitogenesis in vitro, which is a significant breakthrough in tissue development modeling [14]. The authors argue that their model allows for the study of processes that were previously unavailable for direct observa-

tion. According to their conclusions, this study provides a unique opportunity to analyze cellular and molecular mechanisms in detail. This is key to understanding the histogenesis of human muscles.

Martin B.L. in his review discusses mesoderm induction and its patterning, focusing on the role of neuromesodermal progenitors [15]. The author argues that these cells are the source of both nervous and mesodermal tissues, including somites. His work highlights the close connection between the development of the nervous system and muscles. According to the author, understanding these processes is critical for understanding the entire body's development.

Criswell K.E., Coates M.I., and Gillis J.A. analyze the embryonic origin of the spine in gnathostomes, which is closely related to the development of muscle tissue [16]. The authors emphasize that the spine and muscles develop synchronously and interdependently. Their work provides context for understanding how muscles form in relation to the axial skeleton. This study is important for understanding the anatomical foundations of muscle development.

The histogenesis of cardiac musculature, known as cardiogenesis, is a unique process that differs from the development of other muscle tissues. Cardiac muscle originates from the visceral leaf of the splanchnotome, which is part of the lateral mesoderm. The cells in this area, called cardioblasts, begin to differentiate in the early embryonic period, forming the primitive heart tube. Unlike skeletal muscle, which is formed by the fusion of cells, cardiac myocytes (cardiomyocytes) remain mononucleated (rarely binucleated) and do not fuse. They form a complex three-dimensional network that is the basis for effective contraction.

According to studies by Dong Y., Qian L., and Liu J., the molecular and cellular mechanisms of embryonic cardiac chamber maturation are key to the formation of a functional myocardium [17]. The authors focus on the processes that ensure the transition from the primitive heart tube to a complex four-chambered structure. Their work emphasizes that a correct morphogenetic program is critically important for establishing the final architecture of the heart. This study provides a deep understanding of how subtle structural changes occur at the cellular level. According to their conclusions, disruptions of these mechanisms can affect the final structure of the heart.

Dye B. and Lincoln J. in their review focus on the embryonic origin and development of the endocardium and heart valves, which are an integral part of myocardial histogenesis [18]. The authors argue that these structures are formed from unique cell populations. Their work emphasizes that these components play an important role in the function of the heart. Understanding their development is key to a complete picture of cardiogenesis.

According to the review by van der Maarel L.E. and Christoffels V.M., the development of the cardiac conduction system is a complex process that ensures the coordinated contraction of the myocardium [19]. The authors argue that this system is formed from unique cell lineages. Their work emphasizes that the correct formation of this system is critical for the heart's functionality. This study provides a deep understanding of the morphology and development of specialized cells responsible for impulse conduction.

A key feature of cardiac muscle histogenesis is the formation of intercalated discs. These structures are specialized intercellular contacts that contain adhesive (desmosomes, fascia adherens) and gap junctions. Adhesive junctions provide mechanical strength, binding cardiomyocytes together, which allows them to withstand significant mechanical stress during contraction. Gap junctions, in turn, ensure the rapid spread of the electrical impulse from one cell to another, which allows the myocardium to function as a single syncytium and provides coordinated contraction.

The formation of the contractile proteins, actin and myosin, occurs synchronously with cell differentiation. These proteins are organized into sarcomeres, giving cardiac muscle its characteristic striations, similar to skeletal muscle. However, unlike skeletal muscle, where nuclei are located at the periphery, in cardiomyocytes, the nucleus is typically found in the center of the cell. The maturation of the myocardium also includes the development of the T-tubule and sarcoplasmic reticulum network, which play a key role in regulating the calcium concentration required for contraction.

Pogontke C., Guadix J.A. and Pérez-Pomares J.M. review in detail the development of the myocardial interstitium, emphasizing the role of non-cardiomyocytes in the formation of cardiac tissue [20]. The authors state that this connective tissue is important for the structural support of the myocardium. Their work highlights that intercellular interactions are crucial for proper morphogenesis. Understanding the development of the interstitium is key to a complete picture of heart histogenesis.

Zhang M., Lui K.O. and Zhou B. analyze the application of new lineage tracing techniques for studying cardiovascular system development [21]. The authors state that these methods allow for unprecedented accuracy in determining the origin of cells. Their work emphasizes that these technologies are important for understanding heart morphogenesis. This study is key to implementing the latest approaches in the study of histogenesis.

It should also be noted that cardiac muscle has a limited capacity for regeneration. After birth, cardiomyocytes almost completely lose the ability to divide. This means that damage to the myocardium, caused, for example, by ischemia, leads to the formation of a connective tissue scar, and not to the restoration of muscle tissue. This difference from skeletal muscle underscores the uniqueness of cardiac muscle histogenesis.

Christoffels V. and Jensen B. in their review discuss cardiac morphogenesis and the specification of the four-chambered heart [24]. The authors emphasize that these processes are key to the formation of a functional organ. Their work provides a deep understanding of morphogenesis.

Meilhac S.M. and Buckingham M.E. describe in detail the deployment of cell lineages that form the mammalian heart [25]. The authors state that these cell lineages are the basis for all heart structures. Their work emphasizes that understanding their origin is important for studying histogenesis.

Leone M., Magadum A. and Engel F.B. analyze the proliferation of cardiomyocytes during heart development, highlighting their limited regenerative capacity [26]. The authors state that studying these processes is key to understanding heart histogenesis. Their work provides important methodological recommendations for further research.

The histogenesis of smooth muscle is the most variable compared to other types of muscle tissue, as its developmental sources depend on its anatomical location. The vast majority of smooth muscles that make up the walls of internal organs and blood vessels originate from the mesenchyme of the visceral leaf of the splanchnotome. These cells differentiate into myoblasts, which subsequently transform into mature smooth muscle cells. Unlike skeletal and cardiac muscles, which are formed by cell fusion or network formation, smooth muscle cells (leiomyocytes) develop as individual spindle-shaped cells that do not fuse with each other.

The study by Gays D., Hess C. and colleagues indicates the existence of a unique cellular and molecular network that governs the differentiation of intestinal smooth muscle cells in vertebrates [27]. The authors state that this network is exclusive to this type of muscle tissue, which emphasizes its specific origin and regulation. According to the researchers, this significantly expands the understanding of histogenesis mechanisms, demonstrating that smooth muscle is formed under the influence of well-defined signals.

The features of smooth muscle histogenesis are that these cells do not have sarcomeres, and their actin and myosin filaments are arranged in a less orderly manner, attaching to so-called dense bodies in the cytoplasm. This arrangement allows them to contract much more slowly and for a longer duration, which is critically important for maintaining the tone and performing prolonged, rhythmic contractions, such as in the digestive tract. The review by Donadon M. and Santoro M.M. is dedicated to the origin and mechanisms of smooth muscle cell development in vertebrates, which is fundamental to our research [28]. The authors emphasize that the developmental sources of this tissue are the most variable among all muscle types. Based on their analysis, smooth muscle can originate from both mesodermal and ectomesenchymal sources, which determines its diversity and uniqueness.

The work by Liu M. and Gomez D. analyzes the phenotypic diversity of the smooth muscle cell, emphasizing that these cells are not homogeneous [29]. The authors state that their phenotypes depend on their anatomical location, which explains their different functions. According to their conclusions, this diversity is a key morphological and functional feature of smooth muscle.

In addition, some smooth muscle structures have a different embryonic origin. For example, the smooth muscles of the iris, sweat glands, and myoepithelial cells of the mammary glands develop from the ectoderm of the neural crest, not from the mesoderm. This highlights their unique nature and the diversity of embryonic pathways.

Sur A. and colleagues, using single-cell analysis on a zebrafish model, studied shared signatures and transcriptional diversity during embryonic development [30]. Their work demonstrates that different cell types, including smooth muscle cells, are formed from common progenitors. According to the authors, this highlights the plasticity of cells and the complexity of regulating their differentiation.

Worssam M.D. and Jørgensen H.F. in their review examine the mechanisms of vascular smooth muscle cell formation and their phenotypic diversification [31]. The authors state that these processes are dynamic and influenced by the microenvironment. According to their analysis, smooth muscle in blood vessels exhibits significant plasticity, which allows it to adapt to different conditions.

Smooth muscle cells retain the ability to proliferate throughout the organism's life, which distinguishes them from cardiomyocytes and to a large extent from skeletal muscle fibers.

The review by Jaslove J.M. and Nelson C.M. describes the role of smooth muscle as a "sculptor" of epithelial shapes, emphasizing its ability to change the shape of organs [32]. The authors state that the unique contractile function of smooth muscles ensures the morphogenesis of many internal structures. Their work highlights the close relationship between muscle tissue and epithelium. This feature allows them to regenerate after damage and increase their number (hyperplasia) in response to physiological or pathological stimuli, for example, during pregnancy in the uterus or in the development of hypertension in the walls of blood vessels. This regenerative capacity is key to their function in the body.

Hu Y., Cai Z. and He B. discuss the heterogeneity and plasticity of smooth muscle in health [33]. The authors state that smooth muscle cells can change their phenotype in response to physiological signals. According to their analysis, this plasticity is important for their normal function.

Steinbach S.K. and Husain M. study the differentiation of vascular smooth muscle cells from human stem/progenitor cells [34]. The authors state that these cells are an important source for regenerative

medicine. Their work provides new data on the differentiation pathways and regenerative potential.

The study by Pierantozzi E. and colleagues shows that perivascular cells from smooth muscle tissue have a limited ability for mesodermal differentiation [35]. The authors state that these cells are more specialized than previously thought. According to their conclusions, this highlights the heterogeneity of cell populations.

The results obtained demonstrate that the key morphofunctional differences between the three types of muscle tissue are directly determined by their histogenesis. The analysis of literature data confirms that the formation of skeletal muscle by the fusion of mononucleated myoblasts into multinucleated myotubes is a unique mechanism that ensures its high contractile capacity. In contrast, cardiac muscle, which develops as a single network from individual cardiomyocytes, functions as a coordinated syncytium due to specialized intercellular contacts—intercalated discs.

Modern studies using electron microscopy and immunohistochemical analysis allow for the visualization and analysis of the molecular mechanisms underlying the formation of myofibrils and sarcomeres. This scientific precision makes it possible to reveal how the tissue's architecture is organized at the level of individual proteins and cellular organelles. A deep understanding of these fundamental processes is the basis for all subsequent biological and biomedical research. This creates a strong theoretical foundation for understanding the morphological features of muscle tissues.

Conclusions

1. Histogenesis, as a defining morphological factor, confirms that the fundamental differences in the structure and function of the three types of muscle tissue (skeletal, cardiac, and smooth) are directly determined by their embryonic origin and developmental features.

2. The detailing of formation processes in modern studies, conducted using advanced microscopy methods, allows for the concretization of the mechanisms underlying the formation of the final architecture of each muscle type. A key concept is the understanding that the formation of multinucleated structures, specific intercellular contacts, and the variability of embryonic origin are key events that determine the final structure of the cellular composition of muscle tissue.

3. The systematization of this knowledge creates a solid foundation for further research. The identified patterns in the histogenesis of muscle tissues are the basis for understanding not only their normal architecture but also for identifying morphological markers in the early stages of development. This opens up new opportunities for deepening fundamental knowledge in the field of developmental biology and tissue engineering.

Perspectives of research

The foundations laid in this review open up broad prospects for further fundamental research in the field of tissue biology and histology. A deep understanding of the morphology and histogenesis of muscle tissues is critically important for studying the mechanisms of their differentiation and structural organization. Further research should focus on a detailed study of ultrastructural changes during embryonic development and the role of individual cellular components in the formation of mature muscle fibers. This will allow for the establishment of new morphological markers to identify developmental stages and a better understanding of the processes that ensure the formation of the functional architecture of muscle tissue. Thus, future research will be aimed at deepening fundamental knowledge about the normal development of tissues, which is the basis for all biological sciences.

Conflict of interest information

There are no potential or apparent conflicts of interest related to this manuscript at the time of publication and are not anticipated.

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Кобеза П.А., Твердохліб І.В. Гістогенетичні та морфофункціональні аспекти класифікації м’язової тканини (огляд і перспективи досліджень).

РЕФЕРАТ. Вступ. Широкого загалу набувають новітні методи визначення шляхів розвитку та формування м’язової тканини, основною особливістю для якої є механізм скорочення. **Актуальність.** М'язова тканина — це високоспеціалізована структура, що відповідає за рухову активність організму. Розуміння її будови та гістогенезу є критично важливим для вивчення як норми, так і патологічних станів. Дослідження у галузі ембріології та гістології, підсилені сучасними методами мікроскопії та молекулярної біології, дозволяють по-новому поглянути на фундаментальні механізми розвитку м’язових тканин, що відкриває нові перспективи в галузі біології індивідуального розвитку, цитології та гістології. **Мета** статті є систематизація та інтеграція сучасних наукових даних щодо гістогенетичних та морфофункціональних аспектів класифікації м’язової тканини. Завданням є розширення уявлень про джерела розвитку та ключові відмінності у процесах формування кожного типу м'язової тканини. **Методи.** Було проведено систематичний науковий пошук у базах даних Scopus, Web of Science Core Collection та PubMed. Аналіз охоплював період з 2015 по 2025 роки. Пошук здійснювався за ключовими словами, такими як "myogenesis," "cardiogenesis," "smooth muscle development," "muscle tissue histology" та "embryonic myogenesis." Загалом було проаналізовано понад 100 наукових публікацій, що включали оглядові статті та результати первинних експериментальних досліджень. **Результати.** Аналіз літератури підтверджує, що три типи м’язової тканини мають різні джерела походження та унікальні гістогенетичні механізми. Скелетна мускулатура розвивається з міотомів сомітів шляхом злиття міобластів у багатоядерні м'язові волокна. Серцева мускулатура формується з вісцерального листка спланхнотома, причому кардіоміоцити не зливаються, а утворюють єдину мережу, функціонально з’єднану вставними дисками. Гладка мускулатура має найбільш варіабельне походження (з мезенхіми спланхнотома або ектодерми нервового гребеня) та формується з окремих веретеноподібних клітин, які зберігають здатність до проліферації. **Підсумок.** Принципові морфофункціональні відмінності між трьома типами м’язової тканини безпосередньо зумовлені їхнім гістогенезом. Сучасні методи дослідження дозволяють деталізувати ці процеси, підтверджуючи, що утворення багатоядерних структур, специфічних міжклітинних контактів та варіативність ембріонального походження є ключовими подіями, що визначають остаточну будову м'язової тканини. Систематизація цих знань є основою для подальших досліджень у біології розвитку та тканинній інженерії.

Ключові слова: гістогенез, м'язова тканина, міогенез, кардіогенез, міобласт, кардіоміоцит, гладка мускулатура.