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MORPHOFUNCTIONAL BASIS OF THE FORMATION OF CARDIAC OUTPUT

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The article is devoted to the study of the morphological basis of the formation of systolic blood ejection from the left ventricle into the systemic circulation. The myocardium is a continuous syncytium-like structure with multidirectional muscle fibers; however, different segments of the left ventricle during systole are allowing the myocardium to move along a certain trajectory in the absence of fulcrums. The mechanisms of myocardial movement in a certain direction remain unknown. The aim of our study was to study the morphological basis of the formation of systolic blood flow from the left ventricle into the great circle of blood circulation. Macroscopic, microscopic methods and speckle-tracking echocardiography were used in the study. The results of our study showed that the compact myocardium of the upper segments of the left ventricle of the heart is formed by connecting the strands of muscle fibers that change direction from "clockwise" to "counterclockwise". The vector of movement of each segment of the myocardium depends on the direction of its muscle fibers and the sequence of contractions. The trabeculae contract first and are the fulcrum for compact myocardial cardiomyocytes, which determines the direction of movement of each segment of the left ventricular myocardium. Changes in myocardial architecture, as well as abnormal cardiomyocyte contractions, may lead to decreased stroke volume with symptoms of heart failure, which should be considered when making a diagnosis.

Key words: myocardium, left ventricle, morphology, speckle-tracking echocardiography, cardiac output.

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МОРФОФУНКЦІОНАЛЬНІ ОСНОВИ ФОРМУВАННЯ СЕРЦЕВОГО ВИКИДУ

Стаття присвячена вивченню морфологічних основ формування систолічного викиду крові з лівого шлуночка в системний кровообіг. Міокард представляє собою суцільну синцитіоподібну структуру з різноспрямованими м'язовими волокнами, при чому під час систоли різні сегменти лівого шлуночка забезпечують рух міокарда за певною траєкторією при відсутності точок опори. Механізми руху міокарда у певному напрямі залишаються невідомими. Метою нашого дослідження було вивчення морфологічної основи формування систолічного викиду крові з лівого шлуночка серця у велике коло кровообігу. У дослідженні були використані макроскопічні, мікроскопічні методи та спекл-трекінг ехокардіографія. Результати нашого дослідження показали, що компактний міокард верхніх сегментів лівого шлуночка серця формується в результаті з'єднання тяжів м'язових волокон, які змінюють напрям з «за годинниковою стрілкою» на «проти годинникової стрілки». Вектор руху кожного сегмента міокарда залежить від спрямованості його м'язових волокон і послідовності скорочень. Трабекули скорочуються першими і є точкою опори для кардіоміоцитів компактного міокарда, що визначає напрям руху кожного сегмента міокарда лівого шлуночка. Зміна міокардіальної архітектоніки а також порушення послідовності скорочень кардіоміоцитів можуть призводити до зниження ударного об'єму крові з симптомами серцевої недостатності, що потрібно враховувати при постановці діагнозу.

Ключові слова: міокард, лівий шлуночок, морфологія, спекл-трекінг ехокардіографія, серцевий викид.

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As is known, the myocardium is a continuous three-dimensional syncytium-like structure with multidirectional muscle fibers, which never lose contact with each other [1, 8]. Histologically, the myocardial cord shows its linear orientation in accordance with the segmental continuity of its spatial organization, when the cord is coiled both on the inner and outer surface [15]. The introduction of the latest diagnostic technologies (in particular, vector echocardiography) into healthcare practice has shown that blood from the left ventricle (LV) of the heart enters the aorta due to a very complex trajectory, but the most effective movement of the myocardium [3, 9]. It was shown that during systole the segments of the basal and middle sections of the LV move along the longitudinal axis towards the apex, and simultaneously the basal segments rotate clockwise, and the middle section contracts radially towards the center. The apical part practically does not move along the longitudinal axis, but rotates counterclockwise [2, 13]. The structure of the myocardium determines its function, but does not explain the mechanics of the heart, so the question remains open about the mechanisms that ensure the movement of the myocardium in a strictly defined direction in the absence of points of support which are characteristic for skeletal muscles. Also, there is still no clear idea about what each LV segment contributes to the formation of a complex trajectory of myocardial movement.

The purpose of the study was to clarify the morphological basis of the formation of systolic blood ejection from the left ventricle into the systemic circulation.

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Materials and methods. The macroscopic examination was performed by dissecting pig hearts (n=10), the structure of the myocardium of which most closely matches the structure of the human heart [5, 11]. Hearts were dissected according to the F. Torrent-Guasp method [12] and according to the method of A.S. Gulyaeva and I.M. Roschevskaya [4] in our modification: from the top to the bottom. The microarchitectonics of the myocardium was studied on 15 human fetal hearts of 20–22 weeks of gestation, obtained during abortion for medical reasons due to changes incompatible with life and not related to the cardiovascular system. Sheets were cut out from the myocardium, fixed in 10 % neutral formalin, then fragmented into pieces, carried out in alcohols of increasing concentration and embedded in paraffin according to the generally accepted method. Serial paraffin sections 5 μm thick were made on a Leica SM 2000 R microtome, made in frontal, sagittal and transverse projections (5 hearts per projection) and stained with hematoxylin and eosin. Microscopic examination was performed using an Olympus RX41 microscope, which gave an idea of the fine details of the intramural structure of the myocardium. The trajectory of myocardial movement was studied in 35 healthy volunteers (age 32.5±4.2 years). By using speckle-tracking echocardiography, the indices of rotation (°), longitudinal displacement (mm) and deformation (%) were determined segment by segment. Statistical processing of the results was carried out after the creation of the database in the Microsoft Excel program, using the method of variation statistics for average values. All indicators are presented as mean value and standard error. To determine the statistical significance of differences between the mean values, the Student's coefficient was used. Differences were considered statistically significant at $p<0.05$.

Results of the study and their discussion. When dissecting the myocardium, it was seen that the outer bundles of cardiomyocytes (CMCs), oriented clockwise, are directed from the base to the apex, where they twist and plunge into the LV cavity, changing their direction from “clockwise” to “counterclockwise”.

Fig.1. Microspecimen. Cross section of the LV (apical part) of the fetal heart at 22 weeks of gestation. The inner side of the subendocardial layer has a fringed appearance with separated bundles of muscle fibers, each of which is directed obliquely counterclockwise and is woven into the nearest trabecula with its free end. The hematoxylin and eosin staining, magnification x 20.

As a result of the connection at an angle of two differently directed arrays of muscle fibers, a compact myocardium of the apical segments of the LV is formed. CMCs that have entered the LV also form trabeculae with longitudinally oriented fibers (non-compact part of the myocardium). These trabeculae are woven into scattered bundles directed counterclockwise, fibers of the inner part of the compact myocardium (fig. 1).

This architectonics of the apex ensures the rotational movement of the apical segments counterclockwise due to the fact that the trabeculae contract first and the inner part of the compact myocardium is pulled up to them. The outer part of the compact myocardium, connected to the inner one at an angle (“palm branch” in transverse sections), following the internal bundles, is deformed, as if layering on them.

A functional reflection of this are the indicators of myocardial deformation obtained using vector echocardiography. Table 1 shows that the maximum myocardial deformation is observed precisely in the apical segments of the LV.

Table 1.

Indices of maximum longitudinal deformation of LV myocardial segments on longitudinal sections in the norm (%) (n=35)

Slices	Segments	compartments of the LV					
		apical		middle		basal	
		M	m	M	m	M	m
4S	lateral	-25.4	2.5	-22.5	2.1	-21.6	2.2
	inferior septal	-26.9	2.9	-23.3	2.5	-20.4	2.1
3S	anterior septal	-25.6	3.5	-22.2	2.1	-20.1	2.3
	posterior	-25.8	5.2	-22.5	2.9	-20.5	3.1
2S	anterior	-25.7	3.9	-22.3	2.2	-21.5	2.3
	inferior	-27.4	2.9	-23.6	1.8	-22	2.1
	THE AVERAGE	-26.1	3.5	-22.7	2.3	-21.0	2.4

Note: Negative values correspond to the narrowing of the contours of the segments.

The same segments demonstrate the maximum values of the angular displacement of the myocardium (table 2).

□bl□2

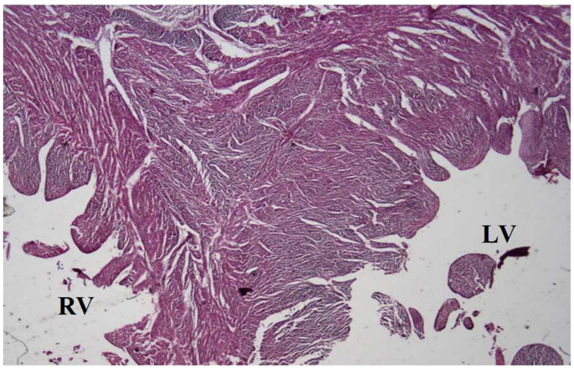
Indices of rotation of segments of the LV myocardium in transverse sections (n=35) (º)

Segment	Slice (M± m)		
	Basal at the level of mitral valve	Middle at the level of papillary muscles	Apical
anterior septal	-3.2±1.8	0.6±2.0	11.0±1.9*
anterior	-1.4±2.3	2.3±1.9	11.4±2.0*
lateral	-2.3±2.1	1.7±1.9	11.5±2.0*
posterior	-5.7±1.9	-0.9±2.2	12.2±2.1*
inferior	-8.9±1.8	-3.8±2.8	11.4±2.0*
inferior septal	-7.7±2.3	-2.9±2.6	11.2±1.9*

Notes: 1. Negative values correspond to clockwise movement, positive – to counterclockwise. 2. * Statistically significant difference relative to slices: basal at the level of the mitral valve and middle at the level of papillary muscles ($p < 0.05$).

In contrast to the apex, the inferior septal, inferior and posterior segments of the basal region rotate as much as possible, but in a clockwise direction. If we add up the angle of rotation of the basal segments clockwise (-8.9±1.8) and the apical segments counterclockwise (12.2±2.1), then the total angle of twisting of the LV at the moment of systole is 21.1±1.9º. It is the moment of twisting that contributes to the formation of the most effective ejection of blood from the LV. In the middle compartment, where the most of the muscle fibers were located circularly, some of the segments moderately rotated clockwise, others in the opposite direction, which created the effect of constriction.

In a macroscopic examination of porcine hearts, we found a vertical muscle cord running in the posterior part of the interventricular septum from the base to the middle section of the heart, giving off lateral circular branches to both ventricles (fig. 2A).


A.


B.

(Fig. 2). Descending muscle cord in the basal part of the posterior interventricular septum (IVS) with circular branches. (A). Macrospecimen of a porcine heart. (B). Microspecimen of a transverse section of the posterior-basal part of the IVS and the adjacent myocardium of the ventricles of the fetal heart (RV-right ventricle, LV-left ventricle of the heart). The hematoxylin and eosin staining, magnification x40.

The presence of this anatomical structure was also documented on serial transverse histological sections of fetal hearts (fig. 2B), which also show that in the LV, muscle bundles oriented obliquely clockwise extend inward from the indicated circular branches to the trabeculae, which probably ensures rotational component of systolic movement in this direction of the basal LV. On sagittal histological sections, the architectonics of the myocardium of the posterior basal part of the LV wall looks even more complicated due to the fact that here the CMCs of the outer layer of the myocardium is turned inward and bending around the circular branches of the posterior vertical muscle cord, are connected to the trabeculae (fig. 3A). With their contraction, a displacement of the posterior basal compartment of the LV along the longitudinal axis occurs.

In the lateral and anterior basal segments of the LV, longitudinal fibers dominate. Under the atrioventricular sulcus, they turn with their whole mass into the LV and connect there with trabeculae (fig. 3B).

Therefore, the entire myocardium of the basal segments during systole is displaced towards the apex.

The fibrous ring of the mitral valve moves in the same direction due to the presence of special trabeculae attached to it (Fig. 4A.), which contributes to the creation of the effect of suction of blood from the pulmonary veins into the left atrium. Of particular interest are the muscle layers we found that run in the LV outflow tract from the fibrous ring of the aortic valve to the trabeculae of the anterior and anterior septal segments (fig. 4B.).

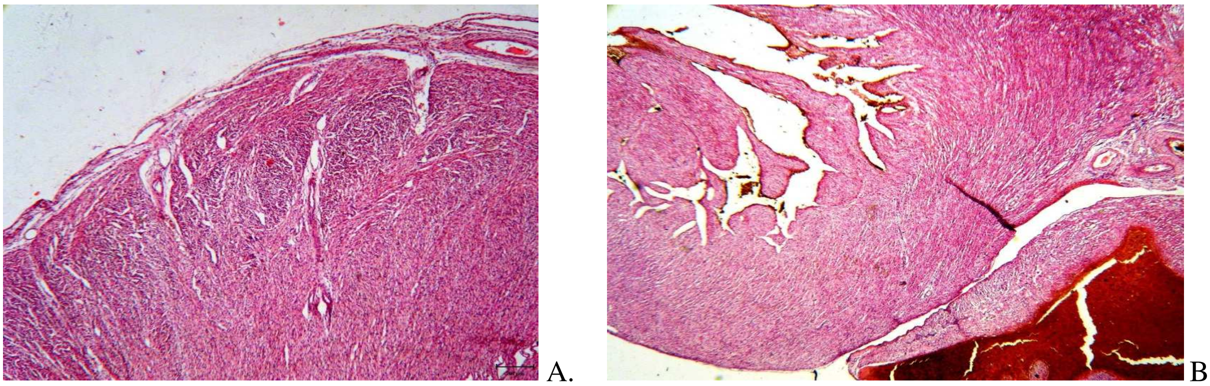


Fig. 3. Microspecimens of the sagittal section of the posterior-basal segment of the LV (A) and the anterior section of the anterolateral wall of the LV (B). The hematoxylin and eosin staining, magnification x20.

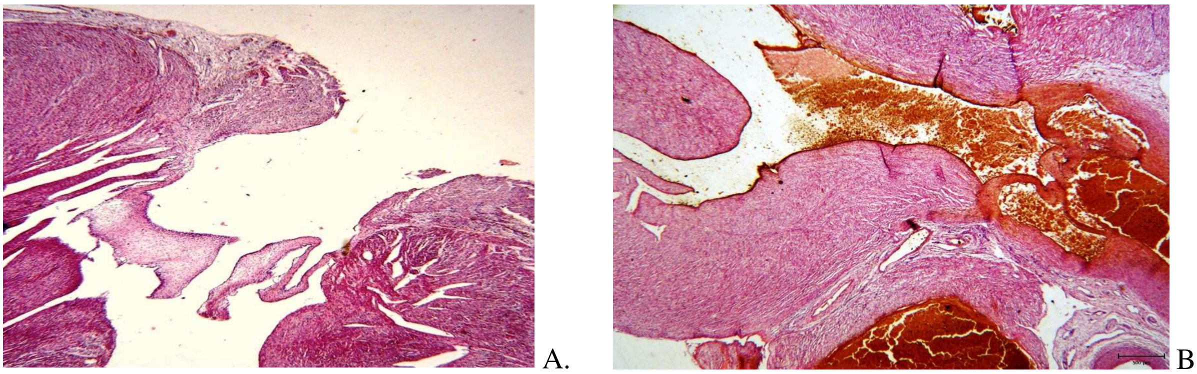


Fig. 4. Microspecimens of frontal sections of the LV. A. Mitral valve with trabeculae connecting its fibrous ring with the LV wall. B. Aorto-trabecular bundles of CMCs. The hematoxylin and eosin staining, magnification x20.

At the moment of expulsion of blood from the LV into the aorta, these muscles, as it were, plant the aortic root on the vortical (clockwise) blood flow, increasing the efficiency of systolic contraction of the myocardial outflow tract.

In the middle section of the LV, muscle fibers are located mainly circularly, which creates a constrictor component of the movement of the walls of this area. However, among the circular fibers, separate small longitudinal CMCs bundles are differentiated, providing a shift of the middle section of the LV towards the apex by 9.7±2.1–13.5±2.1 mm. The maximum values of the longitudinal displacement were recorded in the basal segments (from 19.2±1.8 to 20.1±2.5 mm), the minimum values – in the apical region (3.0±1.5–5.0±1.4 mm).

In general, the results of our study are consistent with those of other scientists [2, 3, 5, 7, 9]. We can confirm that the compact myocardium of the upper segments of the LV of the heart is formed as a result of the connection at an angle of two strands of muscle fibers that change direction from clockwise to counterclockwise [13]. In recent years, scientists have been busy studying the morphological and functional correlations of the dynamics and mechanics of the heart, however morphological studies of the human heart are extremely limited, as it is difficult to obtain intact, well-preserved hearts [7, 15]. The results of our microscopic analysis showed that the CMCs of the inner part of the compact myocardium are woven into trabeculae in separate bundles, which has its own reflection in the speckle-tracking study (the total LV twist angle at the time of systole is 21.3±2.5). According to our data, the myocardium of the basal segments shifts towards the apex during systole, while the trabeculae are the first to receive excitation, given the fact that the Purkinje fibers are transformed into working CMCs in the trabeculae [6, 10]. This structure of the myocardium of the LV provides rotation and twisting, which form the effective cardiac output [13, 15]. The muscle layers that run in the LV outflow tract from the annulus fibrosus of the aortic valve to the trabeculae of the anterior and anterior septal segments impinge the aortic root on the vortex blood flow, increasing the efficiency of systolic contraction of the myocardium of the outflow tract [14].

Thus, each segment of the LV myocardium during the cardiac cycle has its own trajectory. The result of the integration of these trajectories is the movement of all LV walls, which provides the most efficient cardiac output. A change in myocardial architectonics, as well as a violation of the CMCs contraction sequence, can cause a decrease in stroke volume of blood with symptoms of heart failure. This must be taken into account when diagnosing specific patients. In addition, the morphofunctional approach to the study of various pathological conditions of the myocardium can be very productive for clarifying the pathogenesis of many heart diseases.

Conclusions

1. Systolic movement of the LV myocardium is provided by a consolidated contraction of its various segments in the longitudinal, radial and circular directions.

2. The vector of movement of each segment of the myocardium depends on the direction of muscle fibers and the sequence of their contraction.

3. Trabeculae contract first and therefore they are the fulcrum for the CMCs of the compact myocardium, determining along with the orientation of muscle fibers, the direction of movement of each segment of the myocardium and the LV as a whole.

References

1. Zaharova VP, Trembovetskaya EM, Savchuk TV, Batsak BV, Rudenko KV, Rudenko EV. Novyie aspekty stroeniya miokarda zheludochkov serdtsa. Sertse i sudini. 2014; 3: 35–43. [in Russian]

2. Obrezan AG, Baranov DZ. Deformatsiya miokarda u bolnyih hronicheskoy serdechnoy nedostatochnostyu. Kardiologiya. 2019; 59(8): 88–96. DOI: 10.18087/cardio.2019.8.2579 [in Russian]

3. Sohibnazarova VH, Saidova MA, Tereschenko SN. Primenenie novykh ekhokardiograficheskikh tehnologiy nedopplerovskogo izobrazheniya miokarda v dvumernom i trekhmernom rezhimakh u bolnykh HSN s sokhrannoy i snizhennoy fraktsiey vyibrosa levogo zheludochka. Evraziyskiy kardiologicheskiy zhurnal. 2017; 2: 42–47. [in Russian]

4. Trembovetskaya EM, Knyishov GV, Zaharova VP, Rudenko EV, Moroz MN. Morfologicheskie osnovyi dinamicheskikh kharakteristik miokarda levogo zheludochka serdtsa. Sertse i sudini. 2015; 3: 51–60. [in Russian]

5. Baehr A, Klymiuk N, Kupatt C. Evaluating Novel Targets of Ischemia Reperfusion Injury in Pig Models. Int. J. Mol. Sci. 2019; 20(19): 47–49. DOI: 10.3390/ijms20194749

6. Boyden PA, Dun W, Robinson RB. Cardiac Purkinje fibers and Arrhythmias; The GK Moe award Lecture 2015. Heart Rhythm. 2016; 13(5): 1172–1181. DOI: 10.1016/j.hrthm.2016.01.011

7. Buckberg GD, nanda NC, Nguen C, Kocica MJ. What is heart? Anatomy, Function, Pathophysiology, and Misconceptions. J. Cardiovasc. Dev. Dis. 2018; 5; 33. DOI: 10.3390/jcdd5020033

8. Carmeliet E. Conduction in cardiac tissue. Historical reflections. Physiol. Rep. 2019; 7 (1): 1–13. DOI: 10.14814/phy2.13860

9. Daae AS, Wigen MS, Fadnes S, løvstakken L, Støylen A. Intraventricular vector flow imaging with blood speckle tracking in adults: feasibility, normal physiology and mechanisms in healthy volunteers. Ultrasound in Medicine & Biology. 2021; 47(12): 3501–3513. DOI: 10.1016/j.ultrasmedbio.2021.08.021

10. Garsia-Bustos V, Sebastian R, Izquierdo M, Molina P, Chorro FJ, Ruiz-Sauri A. Aquantative structural and morphometric analysis of the Purkinje network and the Purkinje–myocardial junctions in pig hearts. J. Anat. 2017; 230: 664–678. DOI: 10.1111/joa.12594

11. Helke HL, Ezell PC, Duran-Struuck R, Swindle MM. Biology and diseases of swine. Laboratory Animal Medicine. 2015: 695–769. DOI:10.1016/B978-0-12-409527-4.00016-X

12. Maclver DH, Stephenson RS, Jensen B, Agger P, Sanchez-Quintana D, Jarvis JC et al. The end of the unique myocardial band: Part I. Anatomical considerations. European Journal of Cardio-Thoracic Surgery. 2018; 53: 112–119. DOI: 10.1093/ejcts/ezx290

13. Mora V, Roldan I, Romero E, Sauri A, Romero D et al. Myocardial Contraction during the Diastolic Isovolumetric Period: Analysis of Longitudinal Strain by Means of Speckle Tracking Echocardiography. J. Cardiovasc. Dev. Dis. 2018; 5; 41. DOI: 10.3390/jcdd5030041

14. Sundström E, Jonnagiri R, Gutmark-Little I, Gutmark E, Critser P, Taylor MD, Tretter JT. Effects of Normal Variation in the Rotational Position of the Aortic Root on Hemodynamics and Tissue Biomechanics of the Thoracic Aorta. Cardiovasc. Eng. Technol. 2020; 11(1): 47–58. DOI: 10.1007/s13239-019-00441-2

15. Trainini J, Lowenstein J, Beraudo M, Wernicke M, Trainini A, Labata VM, Carreras CF. Myocardial torsion and cardiac fulcrum. Morphologie. 2021; 105: 15–23._DOI:10.1016/j.morpho.2020.06.010

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