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Basic Research

Morphometric Parameters, Contractility and Architecture of the Left Ventricle Myocardium in Pigs

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Abstract

This study aims to reveal the interrelations found within the architecture of the muscular fibers, the morphometric parameters and contractility of the left ventricular myocardium in the Landrace breed of conventional pigs. The left ventricular morphometric parameters were investigated at three levels (basal, middle, apical) utilizing echocardiography, myocardial contractility was estimated by the ejection fraction, fractional shortening and fractional thickening. The fiber architecture of the working myocardium was studied following the method of the layer-by-layer splitting of muscular fibers. The fibers of the superficial and deep layers of the left ventricle showed an oblique orientation, while the muscular fibers of the middle layer were distinguishable as high-lying and low-lying fibers. During the cardiac cycle, the greatest reduction in the transverse dimension and the greatest thickening of the walls were observed in the middle level when compared with the basal and apical levels, that is related with more thick layer of muscular circumferential fibers in the middle section of the ventricle and large papillary muscles. A low contractile ability of the left ventricle myocardium was revealed in pigs. IJBM 2012; 2(1):50-57.
Key words: *echocardiography, cardiac cycle, muscular fibers, ungulate*

Introduction

In electrocardiology, the process of wave excitation distribution in the heart ventricles of warm-blooded animals and humans is assumed to proceed identically. The electrocardiograms registered in comparable leads are similar in form and polarity. Comparative-physiological research enabled us to discover the type of depolarization of the heart ventricles in ungulates was different from that observed in other warm-blooded animals, including humans. For ungulates, the class to which pigs belong, the "flash" type of activation of the heart ventricles is typical [1]. The polyfocality of the areas of initial depolarization of the ungulate heart ventricles is related to the location of Purkinje fibers in the myocardial wall from the endocardium to the epicardium [2]. A similar occurrence of the depolarization sequence [3] and distribution of terminals of the conducting system [4] is revealed in birds. Heart ventricles in humans [5] and predators [6, 7] depolarize successively from the endocardium to the epicardium because of the subendocardial location of the conducting system fibres [8]. The depolarization succession of the heart ventricles depends upon the working myocardium architecture, mutual location and interlacing of fibers [9].

Different concepts exist on the fiber architecture of the working myocardium of the heart ventricles. According to some authors [10, 11], the heart ventricles represent an interlacing network of muscular fibers, with the fibrous skeleton of the heart acting as the backbone, while others contend that [12, 13], the heart ventricles represent a single muscular bundle going from the pulmonary artery root to the aorta. However, the problem of the comparative characteristics of the fiber architecture and the contractile ability of the myocardium in vertebrates remains unsolved.

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During the cardiac cycle, the left ventricle of warm-blooded animals and humans experiences 3D deformation and successive movements, which are coordinated in time and space [14-16]. The change in ventricular form, the deformation of its walls, and the contraction of the myocardium during the cardiac cycle depend upon the orientation and interaction between the muscular bundles [17, 18].

Heart ventricles are characterized by structural and functional heterogeneity, including the architecture of the working myocardium [19] and the conducting system [20], depolarization sequence [21], regional wall contraction [22], biomechanics of the contraction [23], and a change in wall thicknesses during contraction [15].

Anatomic and functional regional heterogeneity of the myocardium facilitates the coordinated work of the heart as a whole organ, which makes it necessary to analyze the dynamics of wall movements, mutual location of the muscular fibers, and the change in the geometry and contractility of the various ventricular areas.

The purpose of this research, therefore, is to reveal the interrelations in the spatial orientation of the muscular fibers, the morphometric parameters and the contractility of the myocardium of the left ventricle in pigs.

Materials and Methods

The experiments were conducted based on the principles of the humane treatment of animals as provided by the clauses of "The European Convention for the Protection of Vertebrate Animals used for Experimental and Other Scientific Purposes" (ETS N 123), Convention No.123 of March 18, 1986.

The study of the morphometric parameters, contractile ability, and left ventricular myocardial architecture was performed on the Landrace breed of conventional pigs.

The morphometric parameters of the left ventricle were investigated using echocardiography in nine pigs (weight 25–30kg) under anesthesia, given intramuscularly (urethane 1.5 g/kg, Sigma, Germany). The echocardiographic research was done using a cardiac ultrasound system equipped with a 3.5-5.0 MHz transducer (SonoDiagnost 360; Philips, Germany). The echocardiographic images were obtained in the right parasternal long- and short-axes views and the four cardiac chambers by B-mode and M-mode tracing.

The dimensions and thicknesses of the left ventricle were measured in three parallel planes along the axis from the base to the apex: at the level of the mitral valve (basal), at the level of the papillary muscles (middle), and at the apical level, in the longitudinal direction (Fig.1).

The left ventricular contractility of the myocardium was evaluated by measuring the ejection fraction (EF), a decrease in the internal dimensions of the left ventricle in systolic or fractional shortening (%FS) and fractional thickening (%FT) by M-mode echocardiography employing the following formulae:

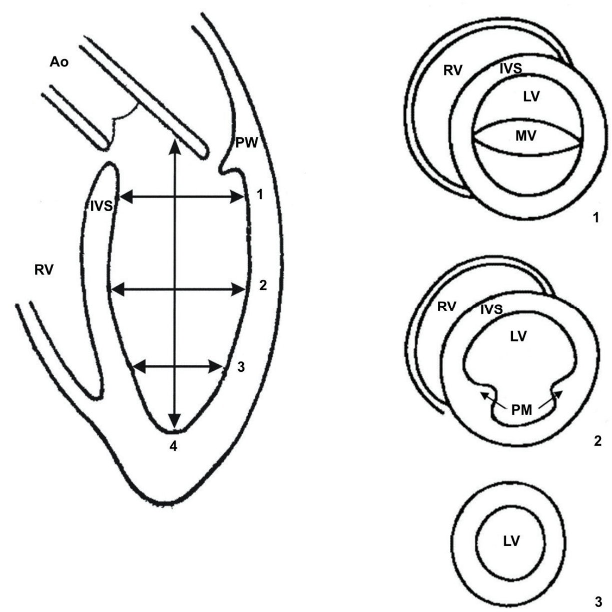
$$EF = \frac{EDV - ESV}{EDV} \times 100,$$

$$\%FS = \frac{LVEDD - LVESD}{LVEDD} \times 100 \text{ [24]},$$

$$\%FT = \frac{ESPWT - EDPWT}{LVEDD} \times 100 \text{ [25]},$$

where, ***EDV*** - left ventricle end-diastolic volume; ***ESV*** - left ventricle end-systolic volume; ***LVEDD*** - left ventricle end-diastolic dimension; ***LVESD*** - left ventricle end-systolic dimension; ***ESPWT*** - end-systolic posterior wall thickness; ***EDPWT*** - end-diastolic posterior wall thickness.

Figure 1
The scheme of measurement levels of the left ventricular morphometric parameters.



Note: *The left ventricular morphometric parameters of the heart were measured in three parallel planes, along the axis from the base to the apex, at the level of the mitral valve, (1) papillary muscles, (2) the apex, (3) in the longitudinal direction (4). LV − left ventricle; IVS − interventricular septum; PW − posterior wall of the left ventricle; MV − mitral valve; PM − papillary muscles; RV − right ventricle; Ao − aorta.*

The fiber architecture of the working myocardium of the left ventricle was studied in the hearts of 12 pigs (weight 60–70kg) employing the method of the layer-by-layer splitting of muscular fibers [26]. To study the superficial layer of the left ventricle, the atria, the pericardium and the coronary vessels were removed. To visualize the arrangement of the deep fibers, the right ventricle was removed, and the left ventricle was cut from the base of the left-lateral section to its apex. The orientation of the muscular fascicles was described relative to the apical-basal heart axis. The direction of the fibers was photographed using a digital video camera, which was part of the VideoTest system (ISTA-VideoTest, St. Petersburg, Russia).

The data were presented as the arithmetical mean ± mean - square divergence. The results were processed statistically using the *Wilcoxon* test. *p*-value less than 0.05 was considered significant.

Results

Morphometric characteristics of the left ventricle in pigs during the cardiac cycle

Echocardiography was performed on the pigs under general anesthesia, which produced no cardiodepressive effects. Echocardiographic images in humans are obtained usually in the left parasternal long- and short-axes views. However, high quality echocardiographic images in pigs are obtained from the right parasternal view due to the peculiarity of the location of the heart in the thorax. The long axis of the heart is “rotated” to the right in the thorax.

Table 1 shows the morphometric characteristics of the left ventricle in Landrace pigs in three parallel planes: basal, middle, apical, in the longitudinal direction. There were no significant differences observed in all three parallel planes for nearly every measured parameter, except the left ventricular posterior wall systolic thickness between the basal and middle levels ($p<0.05$) and the left ventricular internal end-diastolic and end-systolic transversal dimensions between the basal and apical levels ($p<0.05$).

Table 1.
Morphometric characteristics of the left ventricle in Landrace pigs (cm)

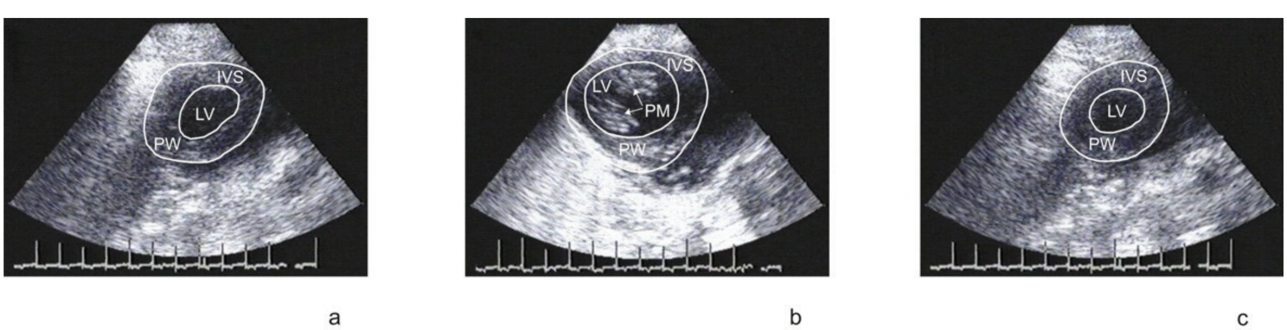
Parameters	**Planes**		
	basal	**middle**	**apical**
Left ventricular internal end-diastolic transversal dimension	3.20±0.81*	2.48±0.55	1.89±0.40*
Left ventricular internal end-systolic transversal dimension	2.40±0.62†	1.72±0.43	1.34±0.36†
Left ventricular posterior wall diastolic thickness	0.89±0.13	1.17±0.15	1.08±0.18
Left ventricular posterior wall systolic thickness	1.16±0.16‡	1.54±0.19‡	1.41±0.28
Interventricular septum diastolic thickness	0.88±0.14	0.92±0.14	0.88±0.14
Interventricular septum systolic thickness	1.12±0.13	1.27±0.15	1.07±0.12
Left ventricular internal end-diastolic longitudinal dimension		6.20±0.50	
Left ventricular internal end-systolic longitudinal dimension		5.30±0.70	

Note: **, †, ‡ - $p<0.05$*

The echocardiographic research has shown, that during the cardiac cycle the transverse dimension of the left ventricular cavity at the level of the mitral valve (Fig. 2a) decreases in relation to the diastole by 21±6% ($p<0.05$), at the level of the papillary muscles (Fig. 2b) by 29±4% ($p<0.05$), and at the level of the apex (Fig. 2c) by 26±7% ($p<0.05$). The fractional shortening of the longitudinal left ventricular dimension is equal to 14±6% ($p<0.05$).

The greatest thickness of the posterior left ventricular wall in pigs during diastole and systole is defined at the level of papillary muscles compared with the posterior wall thickness at the basal and apical levels. The least thickness of the posterior ventricular wall during the cardiac cycle is shown at the left ventricular base. The posterior left ventricular wall thickness in pigs in systole increases at the level of the mitral valve by 21±9% ($p<0.05$), at the level of the papillary muscles by 26±4%

Figure 2.
Ultrasound images of the left ventricle of heart in three parallel planes along the axis from the base to the apex with superimposition of outlines, in pig.



Note: *The left ventricular morphometric parameters of the heart were measured at the levels of the mitral valve (a), papillary muscles (b) and the apex (c) in diastole. LV − left ventricle; IVS − interventricular septum; PW − posterior wall of the left ventricle; PM − papillary muscles.*

($p<0.05$), and at the apical level by 22±5% ($p<0.05$) in relation to the diastole.

The maximum thickness of the interventricular septum in diastole and systole is shown in the area of the papillary muscles. In the end-diastole, the thickness of the interventricular septum at the level of the mitral valve showed the least value and was the same as the interventricular septum thickness at the apical level. The least thickness of the septum during systole is observed at the apical level. During contraction, the interventricular septum thickness in pigs at the level of the mitral valve level increases by 20±5% ($p<0.05$), at the middle and apical levels by 24±4% ($p<0.05$) and 15±3% ($p<0.05$) respectively. The posterior left ventricular wall thickness in pigs in the areas of the papillary muscles and the apex is significantly thicker ($p<0.05$) than the thickness of the interventricular septum during diastole and systole.

Thus, the transverse dimension of the left ventricular cavity in pigs during systole decreases unevenly, in three parallel planes. It shows maximum reduction at the level of the papillary muscles. The degree of thickening in the left ventricular posterior wall and the interventricular septum during the contraction period is observed more at the level of the papillary muscles than at the mitral valve and apical levels. The left ventricular longitudinal dimension in the contraction period shows less shortening when compared with the transverse dimension. The posterior ventricular wall thickness during systole and diastole is more pronounced at the papillary muscles and apical levels, compared with the interventricular septum thickness.

Muscular fiber architecture of the left ventricle in pigs

Three muscle layers in the left ventricle in pigs have been earlier described, the superficial (subepicardial), middle and deep (subendocardial) layers, which differ by muscular fiber orientation.

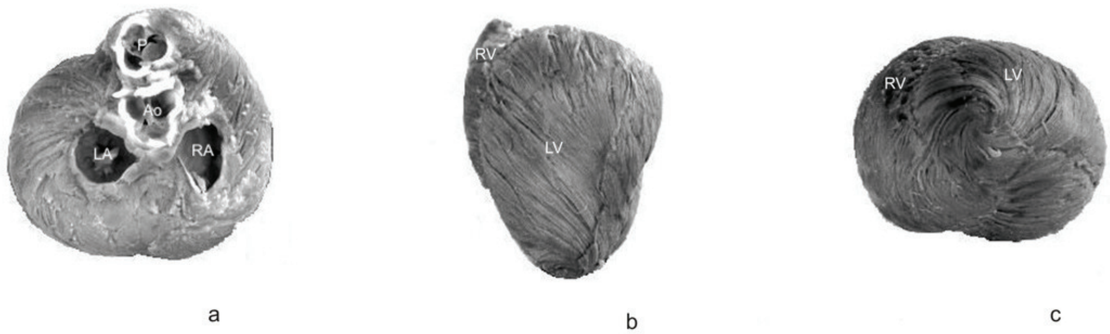
The superficial layer is common for the right and left ventricles. The muscular fibers begin from the fibrous skeleton at the base of the heart (Fig. 3a), continue across the anterior and posterior interventricular grooves and go down obliquely to the left ventricular apex (Fig. 3b). On reaching the apex, the fibers twist inside and give way to the beginning of the left ventricular subendocardial layer of the left ventricle (Fig. 3c).

The middle layer in the left ventricle, in pigs, is presented by the circumferential muscles. In the circumferential layer, the high-lying and low-lying muscular bundles were distinguished. The high-lying muscular fibers continue along the dorsal and lateral surfaces of the left and right ventricles (Fig. 4a); while from the ventral side, they continue deeper to form the interventricular septum (Fig. 4b). The low-lying muscular fibers on the dorsal side, however, are not continuous. In the left ventricle the fibers penetrate deep and twist into a spiral (Fig. 4c). At the left ventricular apex, in the area of the transition of the superficial fibers into the deep fibers, no circumferential layer of fibers is present.

The fibers of the superficial and low-lying middle layers together form the deep layer. The subepicardial fibers twist inside the apical area, rise in spiral form to the base of the heart and are attached to the fibrous ring of the mitral valve. The low-lying fibers of the middle layer gradually transform their circumferential orientation into an oblique orientation, passing into the deep layer (Fig. 5).

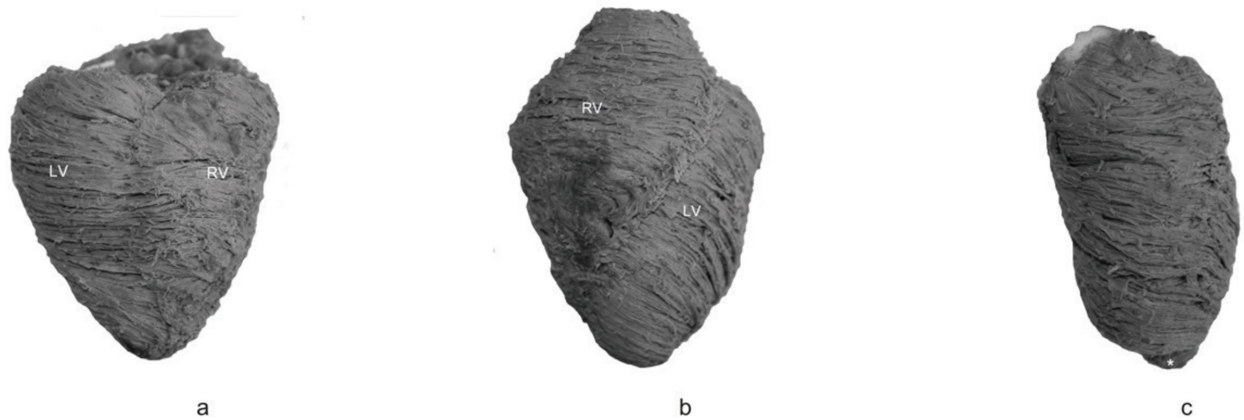
In the left ventricular cavity, there are two large papillary muscles located on the anterior and posterior wall (Fig. 6). The tendinous chords, which are attached to the edge of the mitral valve, move apart from their apices. The moderator bands divergently penetrate the left ventricular cavity forming a thin mesh structure. They are located between the interventricular septum and the papillary muscles, between the interventricular septum and the free wall and do not attach to the edge of the mitral valve. The internal surface of the left ventricle encloses a powerful trabecular apparatus.

Figure 3.
Orientation of the superficial fibers of the left ventricle of heart, in pig.



Note: *The basal view of the heart (a) shows the insertion of muscle fascicles in the fibrous skeleton. The lateral view of the heart (b) shows that myocardial fascicles go down obliquely from the base to the left ventricular apex. The apical view of the heart (c) shows the arrangement of the superficial layer in the vortex cordis. RV − right ventricle; LV − left ventricle; RA − right atrioventricular orifice; LA − left atrioventricular orifice; P − pulmonary artery; Ao − aorta.*

Figure 4.
The orientation of the middle layer of fibers of heart, in pig.

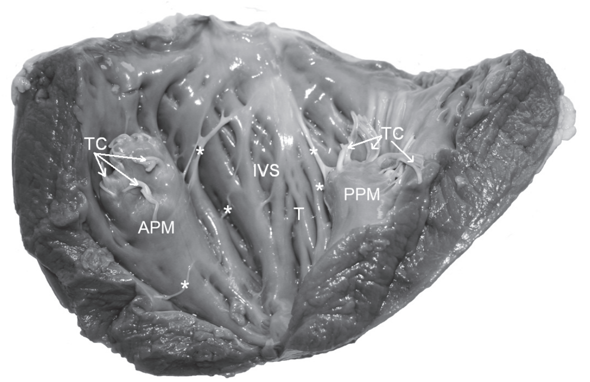


Note: *High-lying and low-lying muscular bundles are distinguished in the circumferential layer. High-lying muscular fibers continue along the dorsal (a) surface of both ventricles, while from the ventral surface (b) they continue deeper to form the interventricular septum. The lateral view of the left ventricle (c) shows the orientation of the low-lying circumferential fibers of the middle layer. In the area of the apex (*) no circumferential fibers are present. RV – right ventricle; LV – left ventricle.*

Figure 5.
The orientation of the deep layer of fibers of left ventricle in pig.

Note: *Subendocardial fibers spirally rise relative to the longitudinal heart axis from the apex to the base.*

Figure 6.
Internal view of left ventricle cavity in pig.



Note: *There are two papillary muscles located in the left ventricular cavity. From their apex tendinous chords (TC) move apart, being attached to the edge of the mitral valve. Moderator bands (*) divergently penetrate the left ventricular cavity. The internal surface of the left ventricle contains powerful trabeculars (T). APM – anterior papillary muscle; PPM – posterior papillary muscle; IVS – interventricular septum.*

Discussion

Comparison of the morphometric characteristics of the left ventricle in pigs and humans

The research conducted has shown that the ejection fraction indicator (Table 2), characterizing the general contractility of the left ventricular myocardium in pigs, is much lower than in humans. The ejection fraction in the conventional pigs studied were examined by us (weight 25 –30 kg) is 53±9% [27]. In the Yucatan micropigs (weight 29–33 kg) the ejection fraction is 58±8% [28], which indicates a low contractile ability of the left ventricular myocardium in conventional pigs and micropigs. The indicator of the ejection fraction in humans is 68±5% [29].

The transverse dimension of the left ventricular cavity in pigs during systole decreases non-uniformly in

Table 2.
Comparison of the parameters of conventional pigs, micropigs and normal humans measured by M-mode echocardiography (%)

Parameters	Landrace pig	Yucatan	Human
Left ventricular ejection fraction	53±9	58±8	68±5‡
Left ventricular fractional shortening:			
at the basal level	21±6	24±0.6	25-40§
at the middle level	29±4	-	-

Note: *†Lee MY et al., 2007 [18]; ‡Schmidt MA et al., 1999 [30]; §Henein MY, Gibson DG, 1999 [16]*

three parallel planes, with its maximum reduction being observed at the level of the papillary muscles, namely in the middle level (Table 2). The degree of shortening of the left ventricular transverse dimension at the mitral valve level in humans [30] is higher than in conventional pigs and micropigs.

According to our data, the longitudinal dimension of the left ventricle in pigs during systole shortens by 14±6% when compared with the diastole. The longitudinal dimension of the left ventricle in humans becomes shorter by more than 7% from the initial state in diastole [31]. The most essential changes of the dimension of the left ventricle in humans during contraction occur on a short axis, while on a long axis the dimension changes slightly [16]. In pigs, the longitudinal dimension of the left ventricle during the contraction period shows less shortening when compared with the transverse dimension, at different levels of measurement.

Thus, the researches of morphometric characteristics of the left ventricle in pigs using echocardiography revealed a low contractile ability of the myocardium, non-uniformity in shortening of the transverse dimensions, and a low degree of the longitudinal dimension reduction.

The comparative analysis of the left ventricle muscular fiber orientation in pigs and humans

The left ventricle both in pigs [32] and in humans [33] consists of three differently directed myocardial fiber layers.

The fibers of the subepicardial layer in pigs have an oblique orientation. A similar direction of the superficial layer is observed in humans [34].

The middle left ventricular layer in pigs is characterized by a circumferential orientation of the fibers. A similar direction of muscular fibers is also characteristic of the middle left ventricular layer in humans [35]. However, in pigs some peculiarities were observed in the spatial organization of the middle layer where the fibers of the middle layer were found to first surround both ventricles, and then, twisting more deeply, surround only the left ventricle, and are characterized by complicated spirally twisted coils. In humans, however, the circumferential fibers of the left ventricle form a muscular cylinder, in which the corner of spiral coils is almost identical to the longitudinal axis of the heart [33]. The difference in fiber spatial organization between pigs and humans may be connected with the absence [35] or insignificant thickness [33] of the middle layer in the right ventricle, in humans.

The direction of the deep fibers of the left ventricle in a pig's heart differs from that in a human heart: the subendocardial fibers in humans have a longitudinal orientation, while in pigs they have an oblique orientation [33, 34].

On comparing the internal surface of the left ventricular walls in pigs and humans, certain clear similarities and differences are observed. In pigs, two papillary muscles are found in the left ventricular cavity. According to Crick's data [36] the papillary muscles in pigs are larger than those in humans, although they are identical in form and arrangement. The cavity of the left ventricle in pigs, from the base to the apex, is penetrated by transverse bands, in different directions. In humans, moderator bands are seen crossing the left ventricular cavity, exclusively in the apical area, perpendicular to its longitudinal axis [37]. The internal surface of the left ventricular wall in pigs is characterized by a more powerful trabecular apparatus, when compared with that of humans [36].

Thus, the most essential differences identified in the architecture of the muscular fibers of the left ventricle in pigs and humans relate to the orientation of fibers of the middle and deep layers.

The interrelation of morphometric characteristics, the orientation of muscular fibers and the contractile ability of the left ventricular myocardium

In mammals, during the cardiac cycle, a spatial deformation of the myocardium occurs, causing a change in the longitudinal and transversal dimensions [14, 38]. The type of the deformation depends on the peculiarities of the architecture of the working myocardium fibers and the structural organization of the ventricular cavity [39].

During the cardiac cycle in humans, the longitudinal dimension of the left ventricle changes due to the contraction of the obliquely and longitudinally oriented fibers [40]. In humans, the subepicardial fibers are obliquely oriented, while the subendocardial fibers are oriented longitudinally [34]. In pigs, the muscular fibers are found in an oblique direction, in the superficial and deep layers. Based on the data resulting from our ultrasonic research, during the cardiac cycle, the longitudinal dimension of the left ventricle shortens less in pigs than in humans. The distinctions in the change in the longitudinal dimension of the left ventricle in pigs and humans during the cardiac cycle are assumed to be related to the differences in the orientation of the fibers of the deep layer.

Due to the asymmetrical arrangement of the muscular fibers of the superficial and deep layers, the rotations of the apex and base of the heart occur in opposite directions, because of which, the braiding effect is observed during systole. A study of the deformation of the fibers of these layers has revealed that, in systole the shortening and thickening of the deep fibers causes the lengthening and thinning of the superficial fibers, while during diastole, the opposite action is observed [15, 41]. In the apical area of the left ventricle in pigs, the subepicardial fibers pass into the subendocardial fibers, forming an “x”-like intersection, because of which an asymmetrical orientation of the fibers of these layers is observed.

The change in the transverse dimension, during the cardiac cycle, is caused by the papillary muscles and circumferential fibers of the middle layer of the left ventricular myocardium [16]. Research on the architecture of the working myocardium in the human heart has shown that in the left ventricle, the middle layer occupies 53–59% from the general thickness of the ventricular wall [35], which is the thickest at the base and becomes thinner towards the direction of the apex [42]. Therefore, the greatest shortening of the transversal dimension, in humans, is observed in the left ventricular base. Based on our data, in pigs, the maximum reduction of the left ventricular transverse dimension and the greatest increase in its wall thickness are observed at the level of the papillary muscles; also, more powerful papillary muscles were observed in pigs compared with humans. This indicates the presence of the thickest circumferential layer in the middle section of the left ventricle, in pigs.

The spatial deformation of the myocardial muscular layers during the cardiac cycle, the cavity and wall structure of the left ventricle define the changes in the longitudinal and transverse dimensions and wall thickness.

When the anatomic-physiological models of the myocardium are created, specific differences in the architecture of the working myocardium, the conducting system distribution, the types of depolarization and repolarization, and morphometric and contractile parameters of the heart in animals of different taxonomical groups must be considered.

This research has revealed that the left ventricle in pigs differs from that of predators and humans not only in the type of depolarization of the heart ventricles and the distribution of terminals of the conducting system but also in the low contractile ability of the myocardium, the complicated structure of the circumferential layer and the oblique orientation of the deep layers of the working myocardium, mainly in the middle level of the walls deformation.

Conclusion

The fibers of the superficial (subepicardial) and deep (subendocardial) layers of the left ventricle in pigs show an oblique orientation, while the muscular fibers of the middle layer are distinguishable into high-lying and low-lying fibers. During the cardiac cycle in the left ventricle, in pigs, the greatest reduction of the transverse dimension and the greatest thickening of the walls have been observed at the level of papillary muscles, compared with the base and the apex, which are connected by a thicker circumferential layer of muscular fibers in the middle section of the ventricle and also the large papillary muscles. In pigs, a low contractile ability of the myocardium of the left ventricle was revealed.

Acknowledgements

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