SPECIAL ARTICLE

Myocardium Dissection

Disección del miocardio

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I. BACKGROUND

Classical anatomy of the heart considered that the muscular structure forming the myocardium was homogeneous and compact. Based on this concept, it was described with an external and internal surface enclosing a uniform muscle mass. This structural notion does not explain cardiac mechanics, and hence, it is essential to establish its true internal anatomy. Historically, very little importance was attributed to the spatial arrangement of the fibrous tracts shaping the myocardium. In 1980, Francisco Torrest Guasp (1) defined the anatomy of the heart adapted to physiological reality. For this study, the cardiac structure is correlated with an organic machine presenting outstanding characteristics, such as being a propelling-suction pump with the size of a human fist and an average weight of 270 grams, which drives 4-6 liters/minute at a speed of 300 cm/s, consuming only 10 watts, working without interruption during 80 years without maintenance, almost without noise, and no smoke. Its work is equivalent to the daily extraction of 1 ton of water 1 m deep with a mechanical efficiency (work/energy relationship) of 50%, not achieved by man-made machines which only attain 30%. Its efficacy allows ejecting 70% of the left ventricular volume with only 12% shortening of its contractile unit, the sarcomere.

Torrent Guasp showed through numerous dissections of hearts from different species, including humans, that the ventricular myocardium is formed by an assembly of fibers twisting unto themselves similarly to a rope (rope model) (Figures 1 and 2) and flattened laterally as a band, which by producing two spiral turns defines a helix delineating both ventricles and setting their functionality. (2, 3) This structure is supported by the evolutionary process taking place from the primitive circulatory tube of the annelids to that of mammals, whose arterial circuit forms a loop or twist that coils unto itself giving rise to the

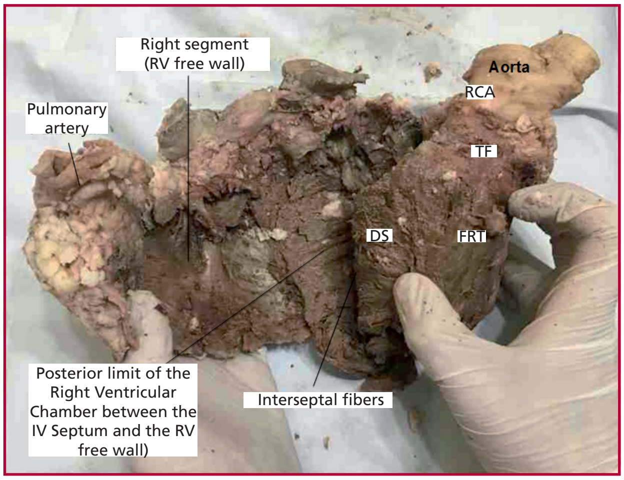

Fig. 1. Torrent Guasp's muscle band. The right ventricle has been separated from the left ventricle along the anterior interventricular (IV) sulcus. This maneuver allows seeing the fibers of the right trigone (FRT) which are inserted below the origin of the right coronary artery (RCA). These fibers insert into the aorta passing under the transverse fibers (TF). DS: Descending segment- RV: Right ventricular.

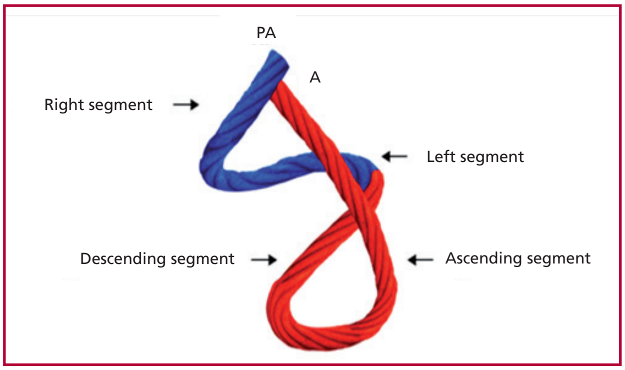

Fig. 2. Rope model of the muscle band, showing its different components. In blue: basal loop. In red: apical loop (see color image on the website). PA: Pulmonary artery. A: Aorta

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ventricular chambers. The primary tube lumen establishes a secondary communication between both adjacent chambers (ventricles) formed by the loop, assuming that the side of the tube where the interconnection takes place must have caved in along the tube to achieve this purpose. Based on these facts, we find that the spatial organization and the rotational movement of the ventricular fibers in their anatomical arrangement, both at the base and the apical region, correspond to the myocardial muscle band. However, this anatomy which allows unfolding the heart to form a muscle band was not considered valid until its original description.

In view of the criticism or indifference to the helical myocardial band proposed by Torrent Guasp, which we believe is due to lack of information and the necessary anatomical technique to perceive it, we can oppose its confirmation through: 1) heart dissection; 2) the evolutionary concept emerging from phylogeny; 3) new imaging procedures obtained with magnetic resonance by diffusion tensor (4-6); and 4) recent electrophysiological studies performed with three-dimensional electroanatomic mapping. (7-11) Regarding the argued difficulty to dissect the myocardium, which is apparent, we should consider that as the myocardial band developed as a loop in the arterial semicircle of amphibians and reptiles to adapt to the physiological demands of aerial life, the layers of muscle bundles became firmly attached to their contact surfaces, hampering the achievement of the necessary cleavage planes necessary for its dissection.

An explanation for this muscular homogeneity, more apparent than real, implies considering the required functionality in birds and mammals to drive blood at a high speed in a limited time by an organ that must provide two circulations (systemic and pulmonary). Despite these considerations, the myocardium dissection finds a structure with defined planes where the successive and related physiological heart movements of narrowing, shortening-twisting, lengthening-untwisting and widening take place, depending on the propagation of the electrical stimulus along its muscle pathways. (7)

The myocardial fibers forming the myocardium cannot be considered as independent entities within a defined space. Despite the intricacy of fiber bundles with polygonal shape, which in addition receive and give off collateral fibers, a predominant trajectory of central fibers is defined with sliding planes, together forming the myocardial muscle band. It should be remembered that the myocardium constitutes a spiral continuum in its fibers responding to a helical pattern in its muscle bundles. This arrangement indicates the need of generating a mechanical work that dissipates little energy. Therefore, the layers of fibers very gradually shift their orientation, with more or less acute angles, to avoid that abrupt changes in the spatial organization waste the necessary work for cardiac function.

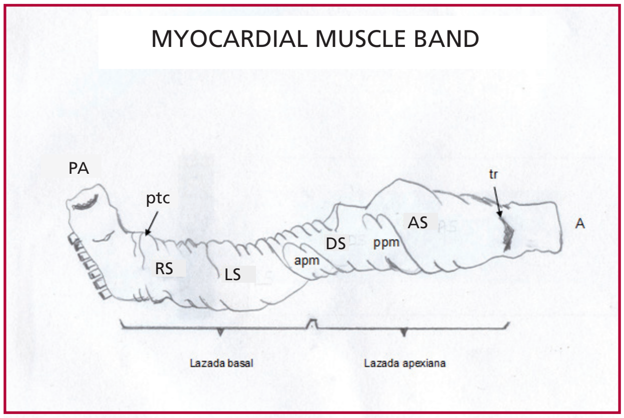


Fig. 3. Explanatory diagram of the muscle band segments. A: Aorta. PA: Pulmonary artery. RS: Right segment. LS: Left segment. DS: Descending segment. AS: Ascending segment. ptc: Pulmo-tricuspid cord. tr: Trigones. apm: Anterior papillary muscle. ppm: Posterior papillary muscle.

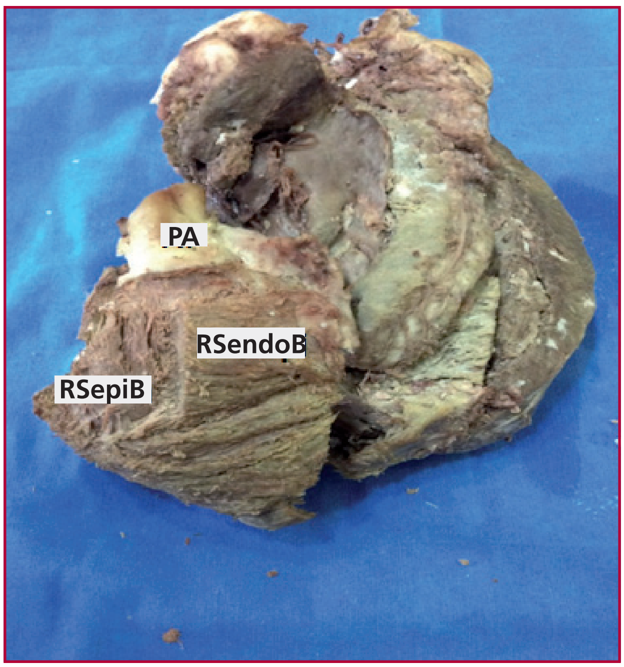


Fig. 4. PA: Pulmonary artery. RSepiB: Right subepicardial bundle. RSendoB: Right subendocardial bundle.

Beyond this complexity it is necessary to establish the concept of linear and laminar trajectories. Myocardial muscle bundles and bands, derived from phylogenetic development, essentially form a master axis of precise dynamic requirement. The spatial muscle structure adopted by the myocardial muscle band has a double function: a) to limit the ventricular chambers; and b) fulfill the suction and ejection action in its role of cardiac pump.

II. MYOCARDIUM DISSECTION

The heart to be dissected (the bovine heart is a good model) must be boiled in water with acetic acid (15 cc per liter) for approximately two hours and a half, except if a pressure cooker is used, in which case the time is reduced by half. Prior work before unfolding the muscle band consists in separating the atria from the ventricles in a very simple maneuver that demonstrates the different evolutionary origins between both types of chambers. Then, the aorta and the pulmonary artery are cut three centimeters from their origin, separating the attachment between them; finally, a longitudinal incision is done on the superficial fibers (interband or aberrant fibers) (2, 7) extending transversally along the anterior wall of the ventricles. Prior boiling of the anatomical piece allows the easy performance of all these steps.

The key maneuver to unfold the myocardial band is to enter into the anterior interventricular sulcus separating the tissue with a blunt instrument, leaving on the left side of the operator the end of the band corresponding to the origin of the pulmonary artery and its continuity with the right ventricular free wall (right segment). Next, traction is applied towards the same left side, separating the right fibrous trigone (belonging to the aorta), which completely frees the pulmonary artery from the rest of the myocardial band. The progression of the dissection implies finding the whole extent of the right segment, the beginning of the left segment and, at the posterior border of the right ventricular chamber, the dihedral angle formed by the interventricular septum and the right ventricular free wall (right segment).

The next step (the most delicate one) consists in entering the aforementioned dihedral angle between the right ventricular and intraseptal fibers. This separation from the right ventricle allows entering a cleavage between the anterior septal band and the intraseptal band (final segment of the myocardial muscle band), at the ventral part of the septum. Then, the dorsal part of the septum is dissected between the posterior septal band and the left descending segment to remove and separate the aorta.

Finally, the trajectories of the descending segment muscular layers are separated in blunt fashion, leaving the trigones attached to the aorta at the opposite end of the muscle band, to the right of the operator, allowing the band to be extended in all its length.

Figure I (Supplementary Material) shows the sequence of myocardial uncoiling until it becomes a muscle band. The drawing in Figure 3 details the different segments comprising it, as well as the insertions of the pulmonary artery in the pulmonary-tricuspid cord and of the aorta in the right and left trigones, which are the extremities constituting the beginning and end of the band, very close to each other in the intact heart. The length of the unfolded band in the adult bovine heart is approximately 61 cm.

The right ventricular free wall is made up of two groups of muscle fibers (Figure II, Supplementary Material) that cross their trajectory in the form of an X. One is the subepicardial right bundle that descends from the posterior interventricular sulcus towards the apex. The second is the subendocardial right bundle that extends from the root of the pulmonary artery to the posterior interventricular sulcus. Between the two bundles other intermediate fibers can be seen which gradually deviate from their direction according to the spiral plan of the myocardium in its functional integrity.

The transverse subepicardial right bundle defines the tricuspid orifice posteriorly and laterally. It is formed by two bands. The ventral one, called the anterior septal band ends in the pulmo-tricuspid cord. The

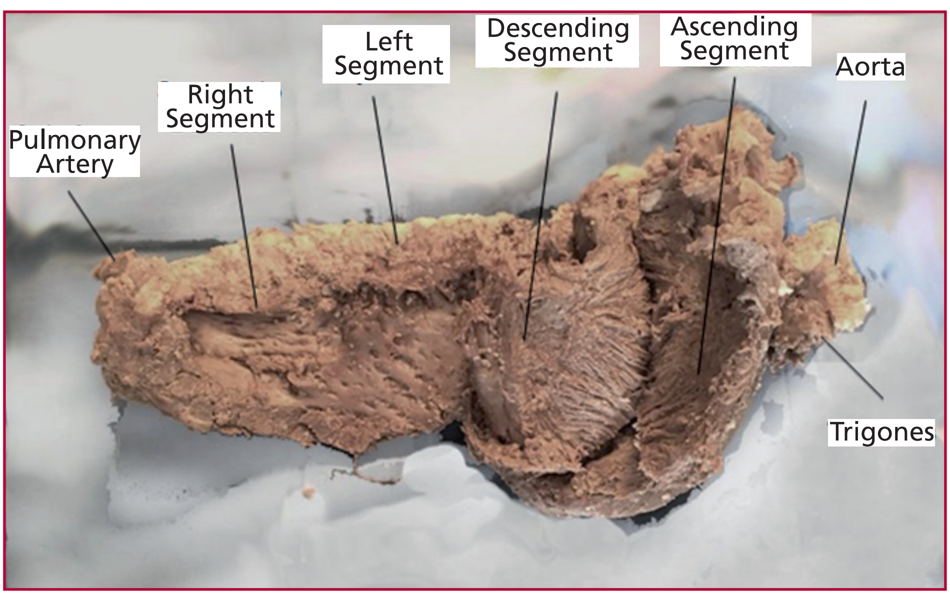


Fig. 5. Descending and ascending segment fibers. It can be seen how the fibers spiral according to the helical structure.

dorsal one, called the posterior septal band ends at the border of the tricuspid orifice and the free wall of the right ventricle. A small triangle of superior tricuspid base is delimited between both terminal insertions, constituting the membranous septum.

If the right subepicardial bundle (Figure 4) is resected, the subendocardial right bundle is observed deeper, almost in a vertical position, consisting also of two groups of fibers: a) the pulmonary band (inserted in the pulmonary artery) and b) the septal band (also called the bridge). (Figure III, Supplementary Material) The latter ends in the interventricular septum, forming a raphe, the pulmo-tricuspid cord, in a trajectory between the pulmonary artery and the tricuspid artery.

Thus, this defines that the muscle structure of the right ventricle (right band segment), consisting of four groups of fibers (pulmonary, septal, anterior septal and posterior septal), originates at the root of the pulmonary artery, in the pulmo-tricuspid cord and at the border of the tricuspid valve, giving origin to the muscle band of Torrent Guasp.

When addressing the dissection outside the left ventricle there are two groups of fibers (Figure IV, Supplementary Material) consisting of ascending muscle bundles (belonging to the ascending segment). One group reaches the left trigone, called left trigone band (below the left coronary artery). The second group of muscle fibers follows a direction parallel to the former and when they run in the anterior interventricular sulcus they pass between the right ventricle and the septum to reach the aorta below the origin of the right coronary artery (right trigone), corsing underneath a group of fibers called transversal fibers. This bundle is called right trigone band. If the right ventricle is separated from the left ventricle, the fibers that reach the right trigone are more clearly evident. (see Figure 1)

Figure 5 shows in detail the muscle fibers of the descending and ascending segments, to achieve the mechanical effect of ventricular torsion through their spiral direction.

In Figure V, Supplementary Material, by artificially separating the anterior surface of the left ventricle, the root of the aorta (trigones) may be identified, where the final end of the muscle band is inserted. In Figure 6, Supplementary Material, by removing the septal cusp of the mitral valve located between the two trigones, the right and left trigones are observed

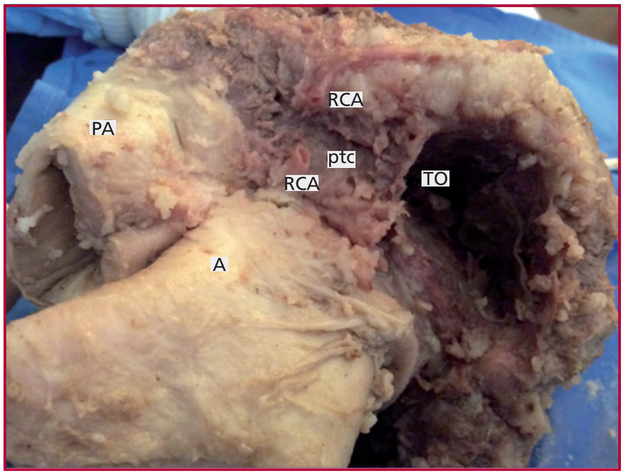
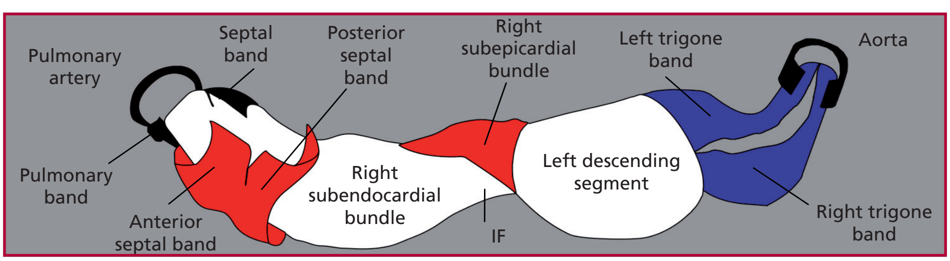


Fig. 6. Detail of the pulmo-tricuspid cord (ptc) between the tricuspid orifice (TO) and the pulmonary artery (PA), where the myocardial muscle band originates. The right coronary artery (RCA) has been removed to show the cord trajectory. A: Aorta.

in detail, with a fibrous consistency and homogeneous solidness different to those of the muscular trajectory. This insertion should be understood as a final point of support for the muscle band at the level of its ascending segment, same as the origin of the band with its right segment (Figures VII, Supplementary Material and 6) is attached to the pulmo-tricuspid cord (trajectory between the pulmonary artery and the tricuspid annulus). In contrast, the posterior cusp of the mitral valve should be considered an extension of the ventricular endocardium. Figure 7 shows a synthesis of the bands that form the muscular cord.

The adherence and consistency of the pulmo-tricuspid cord and the trigones allow a fixed point for the band to rotate as a helix with its fundamental shortening-twisting and lengthening-untwisting movements. Torrent Guasp (1) considered that the cardiac muscle lacks a fixed point of support like those depicted by the skeletal muscle system to fulfill its force function. In this sense, he analyzed that the muscle band would act in the same way as the circular muscle of the arteries, and that therefore, it would support itself on the proper contents of the cavity (hemoskeleton). Beyond this possible mechanism, we consider that the muscle band, when attaching to the great vessels at

Fig. 7. Composition of the myocardial muscle band. IF: Interventricular fibers.



both its origin and end, through the right and left trigones, the pulmo-tricuspid cord and the tricuspid annulus, of fibrous consistency and different from the muscle consistency, finds its insertion point to achieve the necessary lever just like a muscle with its bone insertion. This fixing point could be considered similar to the function exerted by a bearing, preventing the ventricular rotation force, either by torque or twisting effort, to be transferred to the aorta, thus dissipating the energy produced by the helical movement. In relation with this point, the analyzed fixing points become a single piece that supports and allows the band to exercise the fundamental rotation movements of the left ventricle. Let us not forget that the heart is a pendulum within the ribcage without restraints except for those points at the beginning and the end of the muscle band, very close to one another, slightly juxtaposed to the origin of the aorta.

In conclusion, the spatial arrangement and the rotational movement of the ventricular fibers correspond to the architectural plan of the muscle band. Until now, a classic interpretation of blood circulation along the different chambers of the heart has been made, which does not bear correlation with its muscular dynamics. And this, basically, is the circulatory engine established by the cardiac band, which also defines with its musculature the limits of the chambers through which the blood flows. This spatial arrangement of the band, mainly at the level of the descending and ascending segments, is what gives the ventricular chambers the fundamental shortening-twisting and lengthening-untwisting movements of cardiac function.

III. INTERPRETATION

Segmentation of the muscle band. The ventricular chambers are defined by the muscle band of Torrent Guasp. This describes two spiral loops with insertion of one of its ends in the trajectory that extends from the pulmonary artery to the orifice of the tricuspid valve in the so-called pulmo-tricuspid cord, anterior to the aorta, while the other is inserted in the aortic root, in the right and left trigones. In its trajectory the band takes a helical arrangement thus forming the two ventricular chambers. The myocardial band is made up of two bands called descending and ascending bands. The first one includes the right, left and descending segments; while the second one is formed by the remaining segment, the ascending segment.

The figure in 8 outlined by this course defines two loops: a basal and an apical loop (see Figures 2 and 3). The basal loop extends from the root of the pulmonary artery to the central crossing of the band. On the other hand, the apical loop courses from this crossing to the aortic root. In turn, each loop is formed by two segments. The **basal** loop is composed of the right and left segments and the **apical** loop by the descending and ascending segments (see Figure 2). In the general loop configuration, the basal loop surrounds the apical loop, so that the right ventricular chamber is more an open indent in the muscle mass thickness forming both ventricles (see Figure 1). Regarding the segments, they are defined by anatomical features.

Basal loop. The posterior interventricular sulcus shows a trough that determines the limit between the right and left segments of the basal loop. The right segment constitutes the right ventricular free wall and outlines the external aspect of the tricuspid valve orifice. The left segment located in the free wall of the left ventricle defines externally, the orifice of the mitral valve. The fibers pass in one direction from the subepicardium to the subendocardium following a counterclockwise helical trajectory (heart in its anatomical position, on its diaphragmatic surface, seen at the front from the apex).

Apical loop. The descending segment extends from the folding of the band to the apex. From there, it is called ascending segment to end at the aortic root. Both segments mainly constitute the interventricular septum and are separated by the anterior papillary muscle. As in the basal loop, the fibers run from the subepicardium to the subendocardium, but in this case following a clockwise helical trajectory (heart in its anatomical position, on its diaphragmatic surface, seen at the front from the apex).

From these concepts it can be inferred that the free wall of the right ventricle consists of a single loop (basal) and the free wall of the left ventricle consists of two loops (basal and apical). The fundamental fact for cardiac mechanics is that the muscle fibers of the base and the apex of the heart move in opposite direction. This disparity in the course of movement has a correlation with the trajectories reached by the fibers and the helical pattern of the muscle band limiting the ventricles.

Interband fibers. When the ascending segment of the apical loop reaches the anterior interventricular sulcus, some fibers instead of following their intraseptal course towards the end of the aortic root band, coat the right ventricular free wall and reach the anterior left ventricular surface after crossing the posterior interventricular sulcus. These fibers are inserted along the whole extension of the ventricular base comprising the pulmonary valve, tricuspid and mitro-aortic annuli. (see Figure II, Supllementary Material) These muscle bundles were called "aberrant fibers" by Torrest Guasp. He even pointed out: "Owing to their spatial arrangement they surround the basal loop in all its extension, thus enveloping both ventricles". (3) Torrent Guasp also believed that the function of these fibers was to separate the right and left ventricular walls to widen both chambers. He ended his report expressing with certain skepticism "This widening, due to its relatively low magnitude, has less importance than was normally assigned". (3)

Origin and end of the myocardial muscle band. The phylogenetic study allows elucidating, over 600 million years of evolution of the circulatory system, that the ends of the muscle band are located at the root of the great vessels, since it is formed by a loop of the primitive circulatory tube.

The muscular arrangement forming the right ventricle corresponds to the origin of the muscle band (right segment) originating in fibrous structures related to the pulmonary artery and the tricuspid annulus (pulmo-tricuspid cord). (Figures VII, Supplementary Material and 6) Regarding the autochthonous muscle bundles forming the left ventricle, they end at the root of the aorta in the right and left trigones. Figure VII, Supplementary Material shows that the aortic annulus is not continuous. (8) There is at this level a fibrous reinforcement in the circumference region that includes the right coronary cusp and a part of the noncoronary cusp and the left coronary cusp, where the fibers of the ascending segment insert.

The trigones and the pulmo-tricuspid cord establish the fibrous connection between the roots of the aorta and the pulmonary artery with the muscle band. By attaching to fibrous and fixed structures in the origin of the great vessels, this anatomical condition should be considered, from a functional approach, an insertion point to impel the mechanics of the muscle band. At the edges of the mitral and tricuspid valves only some superficial fibers are inserted.

Cardiac apex. The apex –formed exclusively by the left ventricle- is a region situated in a twist of the descending band in its ascending trajectory. This helical rotation of its fibers, which from subepicardial become subendocardial, form a coil of circularly interdigitating muscle layers that create a virtual rather than a real tunnel, as systolic contraction narrows it similarly to the mitral orifice. The apical cul-de-sac is lined by the endocardium and externally is covered by the epicardium. This can be seen through transillumination (Figure VIII, Supplementary Material).

Of the three twists made by the descending band in relation to the ascending band, the first two successively pass anteriorly and posteriorly. The last twist is again posterior. The spatial configuration of the double consecutive passage of the descending band posteriorly to the ascending band (see Figure 2) allows the apex to turn first to the left during systole (seen from the apex) and then to the right, at the onset of the isovolumic diastolic phase, with persisting contraction of the ascending segment. The prolongation of the descending band with the ascending band is a continuum that in that vertex allows the apical loop to act as a bellows that shortens during systole and lengthens during the isovolumic diastolic phase. The result of this anatomo-functional process is an apex capable of facilitating the transfer from the base to the apex during systole (shortening) and its separation during suctioning, thereby achieving ventricular elongation. (9) At this point we consider that the descending bundle by passing twice posteriorly to the ascending band allows part of the cardiac volume (30% of total diastolic volume) not to be ejected at the end of systole and to remain as residual volume. (10) This remaining fluid acts as a limiting layer for correct suction during the isovolumic diastolic phase. (7)

The apex does not make any measurable movement. It remains practically immobile throughout he whole cardiac cycle producing only a certain pressure on the chest wall (apical beat). It is the base of the heart which effects movements as it descends (systole) and ascends (suction). During systole, the heart undergoes a jet propulsion motion (principle of action and reaction). The apex is the main subordinate region of the retrograde force affecting the ventricular chamber when blood is ejected during systole. Similar to other body regions with stress overload it lacks a muscle (11) In addition, it is submitted to a final pressure in its cul-de-sac when the aortic valve closes. This apical region with no interposed muscle, relatively immobile (see Figure VIII, Supplementary Material), becomes the place where ventricular wall aneurysms originate in 90% of cases.

IV. CONCLUSIONS

Phylogenetic evolution determines an anatomy of the heart that has correspondence with ventricular mechanics. Electrical propagation with three-dimensional electroanatomical mapping researched by us in humans (7, 12-14) explains this correspondence between structure and cardiac function.

Briefly, the myocardium consists of three regions: 1) the free wall of the right ventricle; 2) the free wall of the left ventricle and 3) the interventricular septum. The wall of the right ventricle is formed by the right segment of the basal loop whereas that of the left is formed by both the basal loop (left segment) and the descending and ascending segments of the apical loop; hence, the smaller structural thickness of the right ventricular wall.

The interventricular septum consists of a ventral and a dorsal part. The first portion consists of the left descending segment, the intraseptal band (final segment of the muscle band) and the anterior septal band. The first two belong to the left ventricle and the last one to the right ventricle. The posterior region of the septum is composed of the left descending segment (dependence of the left ventricle) and the posterior septal band, corresponding to the right ventricle.

Historically, the interpretation of blood trajectory along the atrial and ventricular chambers has been made with no correlation between structure and function. The torsion action of the ascending and descending segments, from the evolutionary point of view, allows generating pressure with less energy expenditure and better work effectiveness. Linear propulsion through a circulatory tube would not have this effect. Finally, muscle dynamics is the engine of blood flow. This condition supported by the myocardial anatomy in strict correlation with cardiac function establishes a unit between the ventricles very different from the concept of atrio-ventricular unit which precluded the correct understanding of cardiac physiology. The horizontal arrangement of the atria (venous dependent chambers) became attached to the ventricular muscle component (arterial dependent chambers) where the suction and impulse to produce blood movement resides.

Conflicts of interest

None declared
(See authors' conflicts of interest forms on the website/Supplementary material)

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