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Research Article

Histological Analysis and Images of the Cardiac Fulcrum

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Abstract

Objective: During myocardial dissection, the discovery of the *cardiac fulcrum* as the insertion point of the myocardium led us to further questions: What are its characteristics? Where is it located? What is its histology? Is its presence analogous in different species? How is the myocardial muscle inserted into this structure we have called the *cardiac fulcrum*? What are its properties? Does the *fulcrum* have any functional relationship with the AV node, which is adjacent, located between it and the septal valve of the tricuspid valve?

Material and Methods: Seventy-one hearts from the morgue and slaughterhouses were used: a) 54 two-year-old cattle weighing 1300-1900g (average 1650g); b) 17 humans (three at 8, 16 and 23 weeks of gestation respectively; four infants at 30 days, 36 days, 10 weeks and 27 weeks; one 4-year-old child; one 10-year-old child and eight adults with an average weight of 300g). Anatomical, histological, histochemical, and radiological studies were performed. The hearts were fixed in 10% buffered formalin. Histology was performed with hematoxylin and eosin, Masson's trichrome staining, and 4-micron sections. 10% formalin was used as a buffer. Immunostaining (s100-neurofilaments) was also performed. All samples underwent histochemical analysis using Alcian blue staining, a reliable marker for identifying the presence of hyaluronic acid, as an anti-friction mechanism, and also providing a semiquantitative assessment.

Results: Anatomic, histological and radiological studies of the myocardium carried out in recent years in our research provide evidence that myocardial fibers constitute a continuous muscle that describes a double helix to form both ventricles and that, to fulfill its muscular function, it needs a support point that we have investigated, discovered, and called the *cardiac fulcrum*. Thus, the myocardium has the following characteristics derived from the anatomical, histological and radiological analysis performed.

Conclusions: We have found in anatomy, histology and radiological studies of bovine and humans hearts (pregnant, pediatric, and adult) that the *cardiac fulcrum* is a structure that grows in density toward a more solid center. In this scaling from lesser to greater density of the *fulcrum*, the fibers are inserted just as in a tendon matrix (equivalent to the insertion of skeletal muscle tendons into bone).

Keywords: Cardiac anatomy, Cardiac fulcrum, Myocardial insertion, Cardiac images

Introduction

The existence of a bony formation called "os cordis" in mammals is a well-known fact in veterinary science. Beyond its mere mention, until our research, no function or meaning for its presence had ever been assigned to it, nor had it been described in humans [1,2]. The article we published in 2021 entitled "*Myocardial torsion and cardiac fulcrum (Torsion myocardique et pivot cardiaque)*" was the first human observation of the *cardiac fulcrum* and its functional importance [3]. During myocardial dissection, the discovery of the *cardiac fulcrum* as the insertion point of the myocardium led us to further questions: What are its characteristics? Where is it located? What is its histology? Is its presence analogous in different species? How is the myocardial muscle inserted into this structure we have called the *cardiac fulcrum*? What are its properties? Does the *fulcrum* have any functional relationship with the AV node, which is adjacent, located between it and the septal valve of the tricuspid valve? All of these requirements were investigated by us and disseminated in numerous publications [2-10]. The purpose of this presentation is to properly establish the histology of the *cardiac fulcrum* and its radiological images.

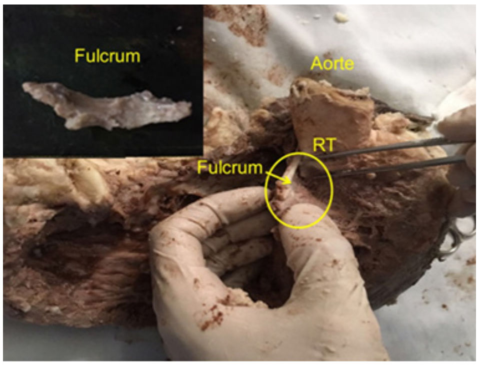
Material and Methods

Seventy-one hearts from the morgue and slaughterhouses were used: a) 54 two-year-old cattle weighing 1300-1900g (average 1650g); b) 17 humans (three at 8, 16 and 23 weeks of gestation respectively; four infants at 30 days, 36 days, 10 weeks and 27 weeks; one 4-year-old child; one 10-year-old child and eight adults with an average weight of 300g). Anatomical, histological, histochemical, and radiological studies were performed. The hearts were fixed in 10% buffered formalin. Histology was performed with hematoxylin and eosin, Masson's trichrome staining, and 4-micron sections. 10% formalin was used as a buffer. Immunostaining (s100-neurofilaments) was also performed [11]. All samples underwent histochemical analysis using Alcian blue staining, a reliable marker for identifying the presence of hyaluronic acid, as an anti-friction mechanism, and also providing a semiquantitative assessment [12,13].

Results

Histological Analysis of the *Cardiac Fulcrum*. Myocardial Insertion

The consistency of the *cardiac fulcrum* in bovine hearts, osseous on palpation (Figure 1 and 2), has been confirmed by histology (Figures 3 and 4). The microscopic analysis of the bovine *cardiac fulcrum* shows a trabecular osteochondral matrix with segmental lines. Its general structure resembles the metaphyseal growth of long bones, and increased magnification reveals bone trabeculae with osteoblasts and segmental lines secondary to bone apposition. The same histological findings have been encountered in chimpanzees [14]. The sequential insertion of myocardial fibers in the bovine *fulcrum* can be seen in Figure 5 and 6 (Figures 1-6).



***Note:** RT: Right Trigone.

Figure 1: *Cardiac fulcrum* below the aorta (bovine heart). The insertion shows the resected piece.

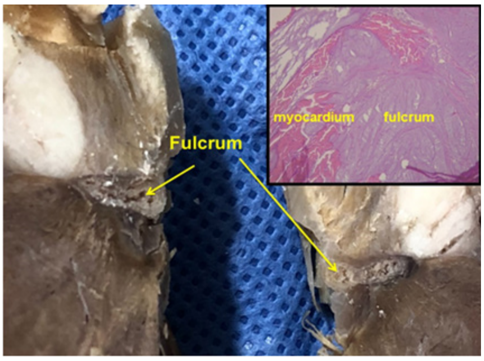


Figure 2: *Cardiac fulcrum* in the bovine heart. The right inset shows the microscopic image of myocardium insertion in the osseus matrix.

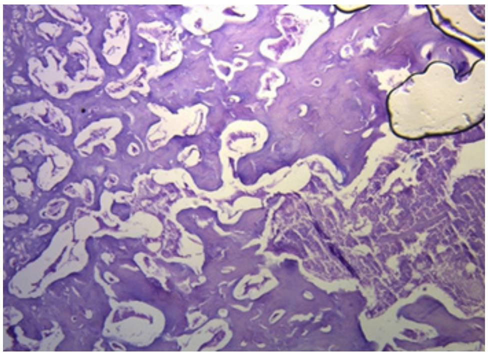


Figure 3: The microscopic field shows trabecular bone tissue with osteologic segmental lines corresponding to the *cardiac fulcrum* (bovine heart). H&E technique (40x).

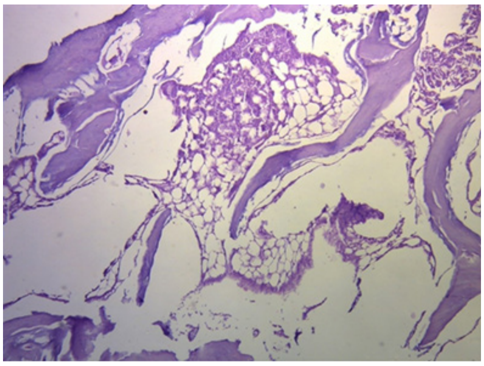
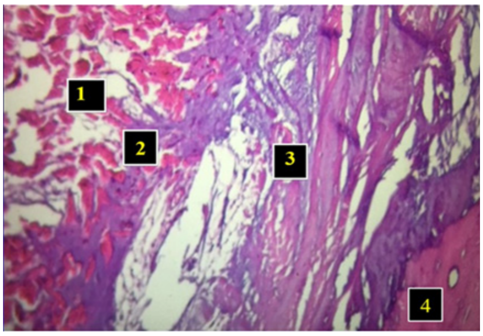


Figure 4: Mature osseus trabecula forming the *cardiac fulcrum* tissue (bovine heart). H&E technique (10x).



***Note:** 1: Myocardial fibers and myxoid stroma; 2: Myocardial strips in a chondroid stroma (insertion); 3: Fibrous bone tissue of the fulcrum; 4: Bone tissue. H&E technique (15x).

Figure 5: Myocardial insertion in the *cardiac fulcrum* (bovine heart). References.

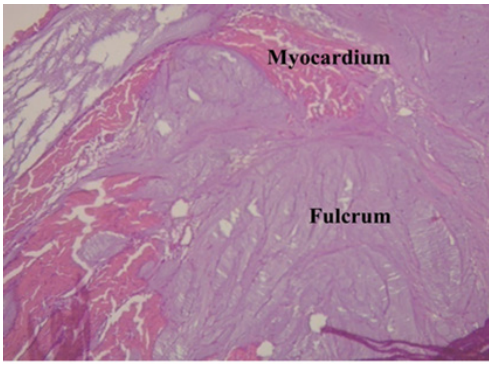


Figure 6: Insertion of myocardial fibers in the *fulcrum* chondroid tissue of a bovine heart. H&E technique (40x).

In the 10-year-old human heart, the histological description of the cardiac fulcrum is related with that early age, since the sample shows a central fulcrum zone formed by chondroid tissue. Given the age, its smaller size is logical, and characterized by more chondroid than osseus tissue (Figures 7,8). This finding was repeated in the 23-week-old human fetus with the characteristic prechondrial bluish areas in a myxoid stroma (Figures 9,10).

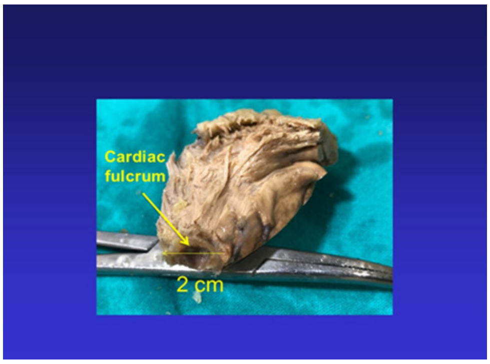


Figure 7: *Cardiac fulcrum* in a ten-year-old human explanted heart.

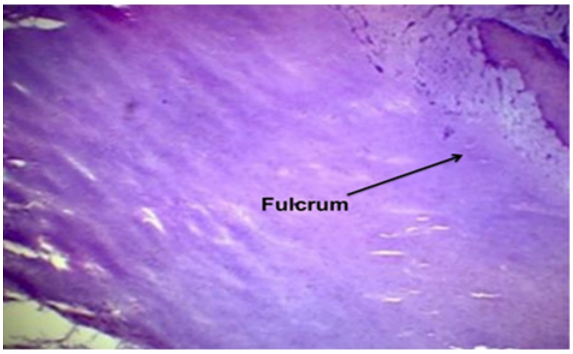
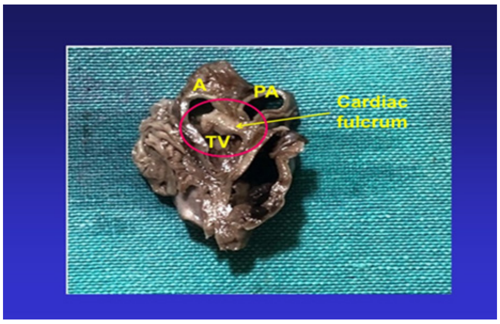


Figure 8: 10-year-old human heart. H&E technique (15x). Central area of the *fulcrum* formed by chondroid tissue.



***Note:** A: Aorta; PA: Pulmonary artery; TV: Tricuspid valve.

Figure 9: *Cardiac fulcrum* in the 23-week gestation human embryo.

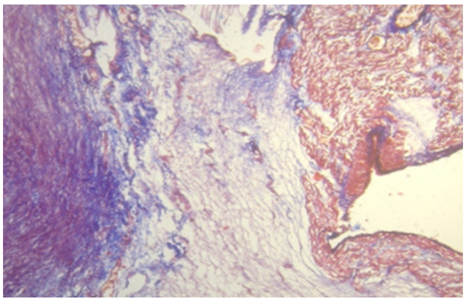
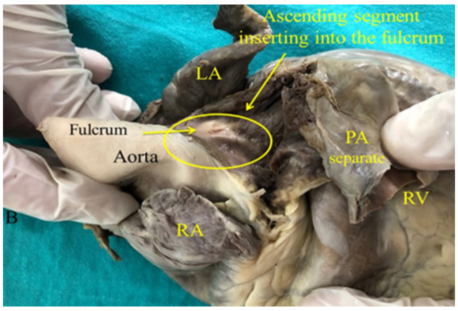


Figure 10: *Cardiac fulcrum* prechondrial bluish areas in a myxoid stroma (23-week gestation fetus). Masson's Trichrome Technique (15x).

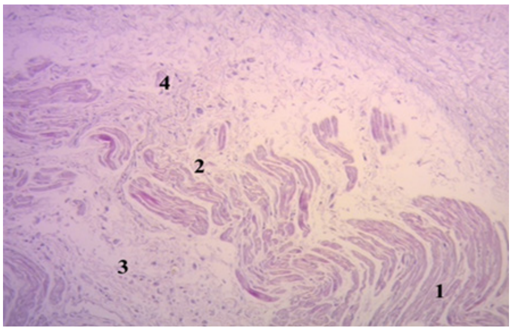
However, the histological analysis of the *fulcrum* in adult human hearts (approximate size 25mm long and 15mm wide) evidenced a chondroid-tendinous matrix, which needs additional clarification (Figure 11). As a rule, there is similar consistency in the detection, location and morphology of the *fulcrum* in all the hearts analyzed. They present myocardium insertion in the rigid fulcrum structure, forming a cardiomyocyte-matrix unit, independently of its osseous, cartilaginous or tendinous nature in the different specimens studied. As in any muscle, this point of attachment acts as a lever and also as a bearing, preventing the transfer of the ventricular rotation force, either by torque or torsion stress, to the great vessels, thus, dissipating the energy produced by the helical muscle movement. In this way, the energy of the myocardial torsion-detorsion movements is absorbed by the *cardiac fulcrum*, which is then shaped into the morphological characteristics of a helix (Figure 11).



***Note:** LA: Left atrium; RA: Right atrium; PA: Pulmonary artery; RV: Right ventricle.

Figure 11: Adult human heart. The ascending segment can be seen inserting into the *cardiac fulcrum*.

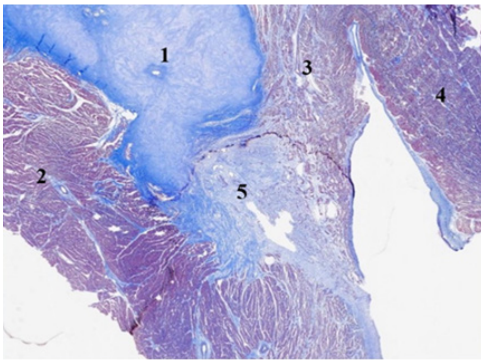
Having found an osseous structure in the bovine *cardiac fulcrum* and its relationship with the myxoid-chondroid texture in human hearts, even in embryos, is rational from the point of view of interpretation analysis. This disparity is associated with the different evolution given by age from chondroid to osseous material and with the greater power developed by bovine hearts, requiring a more rigid supporting point. In fact, tethering a heavy and powerful myocardium, such as that of a bovine heart, is not the same as tethering a myocardium of a human, which weighs only 270 grams. For the former, a very strong buoy, such as bone, is required. For humans, however, a cartilaginous-myxoid support is sufficient. Therefore, the histological analysis of the *fulcrum* in adult human hearts evidencing a chondroid-tendinous collagenous matrix, needs further clarification. The fact that it has been found in humans and different species implies that from a functional point of view its presence is synonym of myocardial insertion, as established in all histological analyses, becoming a solid point of reasoning to achieve its biomechanical function. And we find this demonstration when the histological examination is directed to the myocardial insertion in the *cardiac fulcrum*, be it of osseous, chondroid or tendinous nature. In all the hearts analyzed and according to the studies we have carried out in this investigation, this myocardial attachment was found to be as “ivy clinging to stone” in the rigid structure of the *fulcrum*, integrating an osseus, cartilaginous or tendinous cardiomyocyte-matrix unit, (Figure 12). In this concept there is analogy between skeletal and myocardial muscle. The former contracts between a fixed and a mobile supporting point, and this situation is found in the continuous myocardium, as there is greater solidity in the insertion between the *fulcrum* and the ascending segment compared with the attachment of the right segment in this support (Figure 12).



***Note:** 1: Festooned cardiomyocytes; 2: Cardiomyocyte fraying; 3: Atrophic cardiomyocytes; 4: Fibrocollagenous matrix (adult human heart). H&E technique (15x).

Figure 12: Festooned cardiomyocytes penetrating the fibrocollagenous matrix (*Cardiac fulcrum*).

At this point, fundamental questions arise: Why have we found that in adult human hearts the *cardiac fulcrum* has characteristics similar to a tendon despite it fulfills the same function of attaching the helical myocardium as in other species? Why does it not have the same structure as that found in the human embryo or child heart? Our interpretation is that perhaps the osseous-cartilaginous cardiac fulcrum is a vestigial organ specific of mammalian evolution. A vestigial structure must be understood as the preservation during the evolutionary process of genetically established attributes which have lost all or part of their ancestral function in a certain species [3]. As a result, it is found in the initial process of human gestation, but later loses its osteo-cartilaginous histology, remaining as a tendinous matrix sufficient to achieve myocardial insertion and accomplish a muscle power which is much lower than that of larger mammals. Let us recall that in bovines the fulcrum found in this investigation is of osseus nature. In Figure 13, a histological section of the fulcrum and its relationships can be seen in a porcine heart (Figure 13).



***Note:** 1: fulcrum; 2: ascending segment inserting into the left end of the fulcrum; 3: right loop segment; 4: interatrial septum; 5: AV node (right segment cardiomyocytes intermingle with neurofilaments).

Figure 13: Porcine heart. *Fulcrum* relationships.

To faithfully establish the identity of the *cardiac fulcrum*, a histological analysis has also been carried out on the trigones, trying to find cardiomyocytes as a probable cardiac muscle insertion in these structures. In our investigation, only collagenous tissue without cardiomyocytes was observed in the trigones, confirming that the fulcrum is the support of the myocardium, both at its origin and end.

Cardiac Fulcrum Images

Bovine hearts, studied with computed tomography (Figure 14,15), magnetic resonance imaging (Figure 16, 17) and x-rays (Figure 18) showed the osteochondral structure found in the dissections, evidencing the same morphology and analogous size. In computed tomography in humans, the analysis of the region where the *cardiac fulcrum* is located, through the dissections performed, revealed the presence of an intensity above 110HU (Hounsfield units), while the adjacent muscle has units below 80HU. Thus, in the image, the *fulcrum* structure reached an average of 132±4.5HU. In the adjacent areas, corresponding to the myocardial muscle, this value was between 47.96±12.5 and 77.59±21.64HU (Figure 19). Through echocardiography, recent and as yet unpublished works reveal the visualization of the *cardiac fulcrum* using the septum, the right coronary valve and the tricuspid septal valve as references for its location (Figure 20). The favoured views have been: modified 3-chamber parasternal long axis, modified apical 3-chamber and intermediate short axes parasternal and subxiphoid (between large vessels and short axis at the level of the AV valves). The intermediate apical 2-chamber view (between 4-chamber and pure 2-chamber) allows longitudinal insonation of the fulcrum. For their part, *Sosa Olavarría, et al.,* [15] found the *cardiac fulcrum* using echocardiography, which they published under the title "*Trainini's cardiac fulcrum in the fetal heart*" (2023). They studied 50 human pregnancies with fetuses between 18 and 37 weeks of gestation. Fetal cardiac ultrasound obtained 2D, Doppler, colour and three-dimensional, STIC, HD Flow and speckle tracking modalities (Figure 14-20).

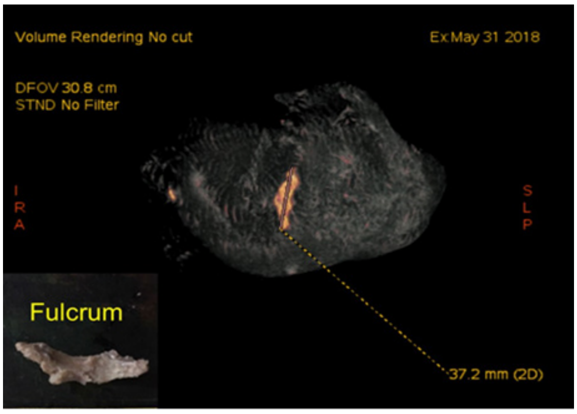


Figure 14: Computed tomography. A hyperdense image approximately 3.7cm long and 298HU density is seen in the interventricular *septum* topography adjacent to the aortic root (bovine heart). The resected fulcrum is shown in the box.

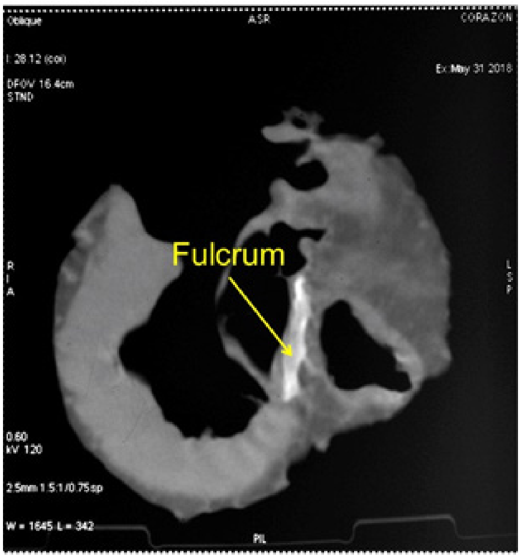


Figure 15: Computed Tomography: An image adjacent to the aortic root on the interventricular septum is observed in the area indicated by the arrow (bovine heart).

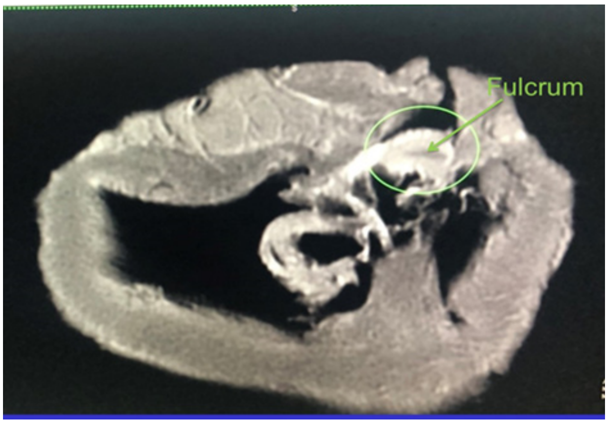


Figure 16: Nuclear magnetic resonance image in a bovine heart.

Figure 17: Diastole: Magnetic resonance imaging in adult human.

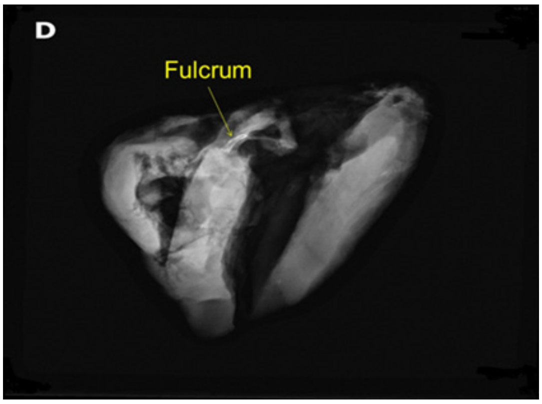
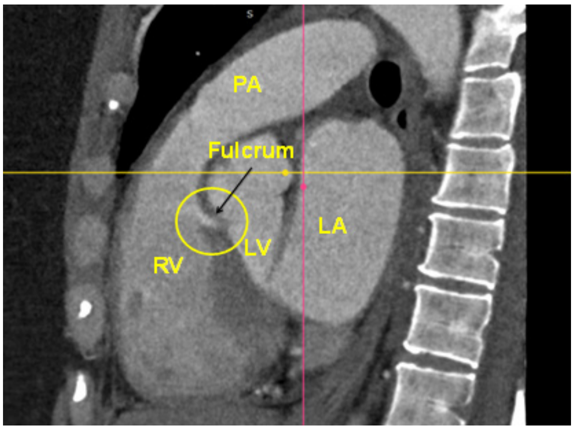
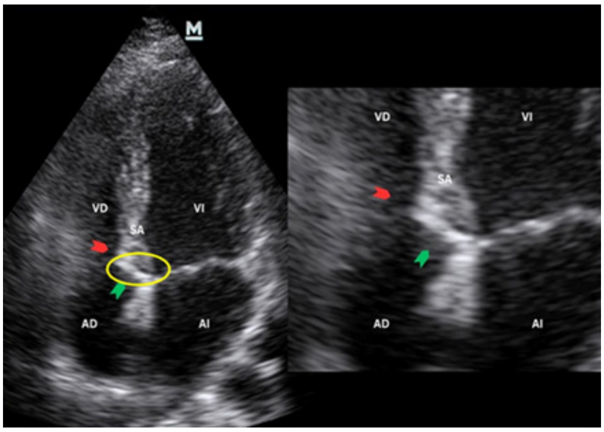


Figure 18: Radiological image of the *cardiac fulcrum* with mammography technique in a bovine heart.



***Note:** PA: Pulmonary artery; RV: Right ventricle; LV: Left ventricle; LA: Left atrium.

Figure 19: Computed tomography image in a patient showing the cardiac fulcrum.



***Note:** VD: right ventricle; AD: right atrium; VI: left ventricle; AI: left atrium; SA: ascending segment entering the fulcrum (green arrow, yellow circle); red arrow: septal leaflet of the tricuspid valve.

Figure 20: Four-chamber echocardiographic view on the left with a zoom in on the *septum* (human heart).

Discussion

The studies on the anatomy and histology of the myocardium carried out in recent years in our research [3,16-19] provide evidence that myocardial fibers constitute a continuous muscle that describes a double helix to form both ventricles and that, to fulfill its muscular function, it needs a support point that we have investigated, discovered, and called the *cardiac fulcrum*. Thus, the myocardium has the following characteristics derived from the anatomical and histological analysis performed:

1) It is a single, continuous and coiled muscle that forms a helix with two spirals.
2) The myocardium is attached at its origin and end, as any muscle, to a support that we have described and called the *cardiac fulcrum*. The muscle fibers surrounding the atrioventricular rings have no insertion into them.
3) The spatial helical arrangement forces the muscle to overlap segments in its spatial configuration.
4) This anatomical condition has marked correspondence with myocardial movements and with the stimulation that runs throughout its segments.
5) The transverse interconnections between the muscle tracts do not invalidate the concept of continuous myocardium, since this compact arrangement is understood as the result of the evolutionary development to obtain solidity of its structure in strict relationship with function.
6) The *fulcrum* is contiguous to the AV node, which with its specialized fibers surrounds and invades it.
7) In all the investigated hearts, we have found hyaluronic acid in the cleavage planes between the myocardial bundles associated with Thebesian and Langer venous conduits (Figure 21).

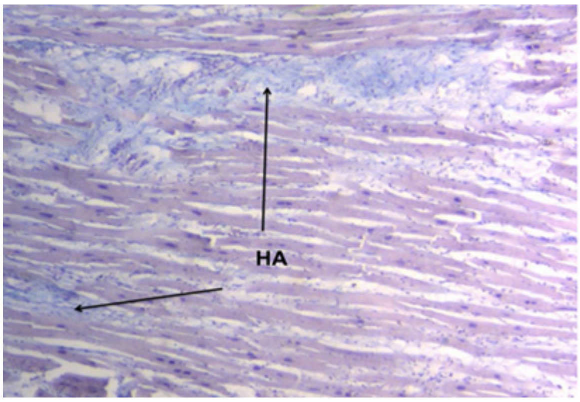


Figure 21: Interstitial space between cardiomyocytes showing Hyaluronic Acid (HA) stained with Alcian blue technique (15x) (adult human heart).

Therefore, the myocardium can be defined as a single muscle that in its longitudinal continuity adopts a spiral spatial conformation, inserted at its ends (origin and end) in an osteochondral-tendinous nucleus according to the specimens analyzed, called the *cardiac fulcrum*. This arrangement limits the two ventricular chambers [20]. The myocardium as a single, helical-coiled muscle is not accurately represented by the word "band," a term that has generated discussion from an anatomical strictly academic point of view. The concept of "band" does not correspond to the etymology of the word and to the full individuality of its spiraling pathway where it is forced to superimpose the segments. In contrast to the band concept, some authors have proposed the concept of myocardial fiber arrangement as a mesh [3]. This term is not acceptable either, since this mesh structure is not related to the functional anatomical organization of the heart, as analyzed in this section. There are solid criteria that support the concept of cardiac myocardium continuity as a single, continuous and spiraling muscle:

1) Muscle homogenization conceals the real spiral continuity of the fibers when its segments are overlapped. This implies considering that its structural solidity is required in birds and mammals to ensure that blood is ejected at a high velocity in a limited time span, through an organ that must supply two circulations (systemic and pulmonary). The anatomical investigation of the heart through adequate dissection, histological exploration, image analysis obtained through radiological and echocardiographic studies, electrophysiological studies carried out with 3D-EAM and diffusion tensor cardiac magnetic resonance imaging show the continuous muscular pathway that define the two ventricles.

2) Being able to unfold the myocardium and obtain a similar thickness throughout the muscle length shows that its continuity is real. When coiled, the thickness of the right ventricle is less than that of the left ventricle, since the former is composed of a single segment (right), while the latter presents attachment two segments (descendent and ascendent).

3) Its function leads it to have a supporting point as any skeletal muscle, both at its origin and end. If the myocardium did not have this helical spatial anatomical conformation, with an insertion at both ends in the cardiac base remaining free at the apex, that is, pendant in the thorax; and if it did not present a stimulation allowing torsion and detorsion, it would be unable to fulfill its extraordinary muscular power. Echocardiography with speckle-tracking techniques has demonstrated shortening and lengthening movements during the systolic and suction phases, respectively [21-24]. To calculate twist, the ultrasound system algorithm performs an algebraic subtraction (it adds the value of the positive apical rotation to the negative basal rotation). Our experience in normal subjects shows that this is around +19±9 degrees, always with a predominant apical rotation [25,26].

4) The trigones do not show cardiomyocyte insertion, confirming that the only myocardial attachment is the *fulcrum*.

5) Myocardial dissection, histological analysis, and cardiac function do not correlate with a mesh conformation.

6) The contiguity of the *cardiac fulcrum* with the AV node, surrounded by a rich plexus of neurofilaments, makes us consider an anatomical electromechanical unit where stimulation energy and muscle mechanics participate.

In this investigation, fresh bovine, porcine and human hearts were used to obtain detailed descriptions in order to elucidate the true spatial myocardial architecture.

Conclusions

To conclude, as previously reported, we find that the orientation and opposite rotational movement of the heart fibers, both at the base and at the apex, justify the continuous helical myocardium model. However, the question that arises from the logic of movement is that, to achieve torsion and the consequent detorsion, the muscle segments that in their continuity make up the ventricular chambers should do so on a supporting point as a skeletal muscle does on a firm insertion. It was found in our research and called the *cardiac fulcrum*. With the heart folded, we find the *fulcrum* embraced by the pulmotricuspid cord and the pulmonary artery on the right side of the aorta. The right ventricle is positioned anteriorly, so the fulcrum shows how the bundles emerging from it, when frontal, conceal the attachment of the ascending segment to said structure located below this view. When the pulmonary artery and the pulmotricuspid cord begin to unfold, the insertion of said ascending segment into the *fulcrum* is evident. The insertion of the myocardial fibers in the fibrous skeleton of the heart has been considered for three centuries. The development of the anatomical research reported in 1970 by Torrent Guasp [27-30] indicated that the myocardium originates and ends at the root of the great vessels, but that the fibers do not insert into the atrioventricular annuli, but merely attach to them, as confirmed by the images obtained by means of diffusion tensor magnetic resonance imaging.

In our anatomical investigations we found the nucleus called *cardiac fulcrum*, where the helical myocardium is inserted at both ends. Conversely, we have not found insertion of the cardiomyocytes in the collagenous matrix of the trigones; which confirms this finding. Our investigations have demonstrated that in the path of the aortic annulus septal segment, extending from the left to the right trigone, there is a solid structure that we have called *cardiac fulcrum* (below the origin of the right coronary artery) where the continuous myocardium is attached at its origin and end, since, as any muscle, it needs a supporting point to fulfill its function. Furthermore, we have not found any insertion of cardiomyocytes into the collagenous matrix of the trigones, a finding confirmed by histological studies. In all studies of animal and human hearts, the location of the *fulcrum* has been found to be contiguous but distinct from the classic fibrous core. The right and left trigones occupy the non-coronary sinus, the posterior half of the left coronary sinus, and the posterolateral part of the right coronary sinus. The *fulcrum* is located anteriorly, below the right coronary artery.

In our research, we always considered that there must be a fixation within the myocardium that would allow it to rotate in a helix to perform its fundamental movements and muscular power of shortening-twisting and lengthening-detwisting. This situation of investigating a continuous myocardial support correlates with an organic machine, such as the heart, which, without a solid anchor to a resistant nucleus, would lack the mechanical faculties necessary for its considerable power. This fixation point involves, as in any muscle, exercising the function of supporting the muscular lever and also allows it to act as a bearing or cushion, preventing the force of ventricular rotation, whether due to torque or torsional stress, from being transferred to the aorta. This way, it manages to dissipate the energy produced by the movement of the muscular helix and preventing the artery from becoming strangled or kinked during the systolic ejection period [2,18]. In the human hearts studied, the findings are surprising from the interpretation point of view, based on the fact that it is logical to consider its presence throughout the evolutionary chain of mammals. It should be considered that this structure, when analyzed in different specimens, has in common its function of supporting the helical myocardium to be able to generate the power required by any muscle, which is different in different mammals. Therefore, its presence is constant in all the hearts studied, both bovine and human, but its structural characteristics are distinct. And this difference in the intimate analysis of the *cardiac fulcrum* is undoubtedly related to the resistance it must oppose to the energetic action of the myocardium in hearts of different sizes.

It should be noted that what makes the concept of the *fulcrum* (support) important is the interweaving of the myocardial fibers and the chondroma. It is this functional element that gives value to this structure that supports and stabilizes myocardial movements. The *fulcrum* should not be considered a nucleus with sharp, rigid edges. The insertion of the myocardium into a structure with such characteristics would be inconvenient, as it would generate sudden tension at that point upon movement, causing tears at the insertion, given the force exerted by the myocardial band to eject the ventricular contents. Furthermore, its consistency decreases between bovines and humans, given that the force exerted is different depending on body weight. What we have found both in macroscopy and in the histology of bovine and human hearts (pregnant, pediatric, and adult) is a structure that grows in density toward a more solid center. In this scaling from lesser to greater density of the *fulcrum*, the fibers are inserted just as in a tendon matrix (equivalent to the insertion of skeletal muscle tendons into bone). This should be understood as a need to dissipate energy gradually with the least possible traction (bearing mechanism), avoiding a sudden and repetitive action-reaction principle, and also preventing the aorta from being dragged in the helical movement performed by the band.

We believe that a structure is only as good as its function. The fulcrum's function as a support for the myocardium is important. Without this insertion, it is impossible to conjecture the movements and energy of the myocardial band to sustain the necessary circulatory physiology. Finally, regarding this important topic, we would like to transcribe what *Best Adam, et al.,* [1] published in 2022 in "*Anatomy, Histology, Embryology*", supporting the priority of our finding regarding the cardiac fulcrum:

"In human cardiac anatomy, in addition to trigones and atrioventricular rings, the heart has a cardiac fulcrum (Figure 1). Works by Trainini and coauthors elucidated the value of this structure in humans and proposed its function and importance once they had observed the attachment of the continuous myocardium to the fulcrum and naming the structure the 'cardiac fulcrum' [5,6]. They proposed that the fulcrum, a thickening at the base of the aorta made up of a collagen matrix, is essential for anchoring the myocardial band allowing the ban to contract and relax maintaining efficient cardiovascular blood flow" [5,6].

"Anatomy, histology, developmental functions of Ossa cordis. A review".

Best Adam et al. University of Nottingham, UK; University of Tirol, Austria, University Colleague of London, UK; University of Montevideo, Uruguay. Anat, Histol, Embryol 2022; 00:1.13

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Conflict of Interest

None.

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