ORIGINAL PAPER

Trainini cardiac fulcrum in the fetal heart

Fulcro cardíaco de Trainini en el corazón fetal

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Declaration of ethical aspects

Acknowledgement of authorship: The authors declare that they have made contributions to the idea of the researchers mentioned in the bibliography, being the authors' own the design of the study, specimen collection, dissection, imaging, analysis and interpretation of data.

Ethical responsibilities: Protection of persons. The author and collaborators declare that the procedures followed conformed to the ethical standards of the responsible human experimentation committee and in accordance with the World Medical Association and the Declaration of Helsinki.

Right to privacy and informed consent: The author has obtained the informed consent of the patients and/or subjects referred to in the article who donated biological specimens to fulfill the objectives of the present study, and pregnant women who underwent fetal echocardiographic examination.

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ABSTRACT

Objective: To demonstrate by dissection of anatomical specimens and prenatal ultrasonographic images of the fetal heart the presence of the cardiac fulcrum as a fixation structure supporting the helical myocardial band. Methods: Six hearts of fetuses between 20-24 weeks of gestational age resulting from spontaneous abortions were dissected, finding the cardiac fulcrum in the proximity of the aorta and connections with myocardial fibers. In 50 singleton pregnancies with fetuses between 18-37 weeks of gestation, fetal cardiac ultrasonography was used to obtain 2D, Doppler, color and three-dimensional modalities, STIC, HD Flow and speckle tracking, images, fulcrum measurements and its kinetics. Results: With the described strategy, the presence of the cardiac fulcrum or myocardial lever was identified and demonstrated, establishing its anatomical characteristics, connections with myocardial fibers of the cardiac loop and the biometry according to gestational age. A hypothesis on the biomechanics or kinetics of the fulcrum during the cardiac cycle is formulated. Conclusions: In order for the heart to fulfill its function as an aspirating and impelling pump, it must have a support point, a lever or fulcrum, which constitutes a sort of muscle-tendon unit. This lever presents mixed displacements during myocardial torsion and detorsion. Its diameters increase progressively as gestation advances.

Key words: Fetal heart, Heart fulcrum, Myocardial lever, Biomechanics, Cardiac kinetics, Cardiac bone, Ossa cordis

RESUMEN

Objetivo. Demostrar mediante la disección de piezas anatómicas y de imágenes ultrasonográficas prenatales del corazón fetal la presencia del fulcro cardíaco como estructura de fijación que sirve de soporte a la banda miocárdica helicoidal. Material y métodos. Se disecaron 6 corazones de fetos entre las 20 y 24 semanas de edad gestacional productos de abortos espontáneos, logrando encontrar el fulcro cardíaco en la proximidad de la aorta y conexiones con fibras miocárdicas. En 50 embarazos simples con fetos entre las 18 y 37 semanas de gestación, mediante ultrasonografía cardíaca fetal se obtuvieron las modalidades 2D, Doppler, color y tridimensión, STIC, HD *Flow y speckle tracking*, imágenes, medidas del fulcro y su cinética. Resultados. Con la estrategia descrita se identificó y demostró la presencia del fulcro cardíaco o palanca miocárdica, estableciendo sus características anatómicas, conexiones con fibras miocárdicas del asa cardíaca y la biometría según la edad gestacional. Se formula una hipótesis sobre la biomecánica o cinética del fulcro durante el ciclo cardíaco. Conclusiones. Para que el corazón cumpla su función de bomba aspirante e impelente debe poseer un punto de apoyo, una palanca o fulcro, que constituye una especie de unidad músculo-tendinosa. Dicha palanca presenta desplazamientos mixtos durante la torsión y detorsión del miocardio. Sus diámetros aumentan progresivamente a medida que avanza la gestación.

Palabras clave. Corazón fetal, Fulcro cardíaco, Palanca miocárdica, Biomecánica, Cinética cardíaca, Hueso cardíaco, *Ossa cordis*

Introduction

In 1973, Torrent-Guasp[1,2] considered the myocardium as a cardiac muscular band, demonstrating through dissections that it is constituted by a set of muscular fibers twisted on themselves that resemble a cord, flattened laterally, which when turning twice in a spiral defines a helicoid that delimits the basic architecture of the two ventricles. Furthermore, the sequential contraction initiated from the limit of the basal loop at the base of the pulmonary artery to the ascending portion of the apical loop that reaches the aorta guarantees the cardiac function as an aspirating, impelling pump, described centuries ago by Erasistratus of Alexandria (400 B.C.).

The architecture underlying Torrent-Guasp's proposal, independent of the three-dimensional arrangement of the cardiomyocytes considered individually, divides the myocardium into two loops that form the base (basal loop) and the apex of the heart (apical loop). Both loops are separated by a 180° central fold that determines macroscopically identifiable helical directions (spirals within spirals), recalling the principle of self-similarity and fractal dimension described by Mandelbrot[3]. Its overall three-dimensional structure resembles a non-orientable geometric surface of triple torsion, like a Moebius strip[1,4,5].

The findings and proposals of Torrent-Guasp were confirmed in the fetal heart by us[6], managing to unfold the helical band in its two components, basal and apical, following the standardized dissection also continued by Antúnez-Montes[4]. Each of these components has two segments: the basal - with anterior and posterior segments - which originates in the root of the pulmonary artery and the apical loop with descending and ascending segments towards the aorta, in a three-dimensional arrangement[3,6-10].

MacIver DH et al.[11] point out that the band does not exist as an anatomical entity with defined borders and conclude that the discussion on the existence of a single double helix myocardial band should come to an end. Other authors who question its existence are Anderson et al.[12] Resonance imaging (MRI) techniques using diffusion tensor imaging[9] have been providing evidence for the Torrent-Guasp findings and, independently of the planes of the cardiomyocytes in the multiplanar system, these are arranged on a double helix helical architecture.

To understand how the myocardium can fulfill its mission, which requires a significant energetic force, the question that arises is, what point of support does it resort to in order to perform its contractile function? In this sense, it is essential to quote Trainini et al.[13,14] 'The inevitable reflection that arises is that, in order to perform torsion, the myocardium should perform it on a support point, just as a skeletal muscle does on a firm insertion'. Consideration followed by two questions: Does such a structure exist in the human heart? If this support is real, how do the cardiac muscle fibers insert into such a structure?

The veterinary literature[15-19] refers to the existence of a formation called *os cordis* in bovids, sheep and chimpanzees, this structure being located in the same place where Trainini et al.[20] have found it in both bovids and humans. No function or significance has ever been assigned to its presence. Likewise, there is no description and function in humans, except that provided by Trainini et al.[13,14,21-23] These authors conclude that this structure, which they call fulcrum or myocardial lever, 'constitutes the support point where fibers of the myocardial cardiac loop described by Torrent-Guasp are inserted' and is located in a plane in continuity with the aorta, below and in front of it, but independent of the trigones. Its location is equidistant to these. It is a structure of osseous, cartilaginous and tendinous characteristics, and hence its denomination as *os cordis* or *ossa cordis* should be replaced by that of fulcrum or myocardial lever.

Objectives

In this research we wish to demonstrate and describe through dissections the existence of the fulcrum in fetal hearts. Likewise, to achieve that the participants experts in fetal echocardiography demonstrate ultrasonographically the visibility of the fulcrum, as well as the technique and windows for its optimal visualization and measurement in order to register its dimensions according to gestational age. Also, to record its kinetics during the cardiac cycle, using techniques such as 2D ultrasound, TM mode, color Doppler, spectral, tridimension with STIC software, HD Flow and speckle-tracking. Finally, to present a hypothesis about its mechanics during synchronized ventricular torsion and detorsion in the cardiac cycle.

Methods

An observational, prospective and longitudinal investigation was carried out in which 6 hearts from fetuses between 20-24 weeks of gestational age, products of spontaneous abortions, were studied. The main author proceeded to the fixation and meticulous and progressive dissection of the specimens, visualizing the fulcrum and its connections with segments of both basal and apical loops by means of directed dissection in different planes. Subsequently, the images of the dissections were sent to the collaborators, who, following the anatomical findings, performed a search directed towards the fulcrum, thus describing the echocardiographic technique for its visualization, its shape, kinematics and dimensions according to gestational age. To meet these objectives, 50 patients with normal pregnancies were studied, from 18 to 37 weeks of gestation, using US2D, TM mode, and three-dimensional with STIC software, HD Flow and strain and speckle-tracking technique.

Results

In all the fetal heart specimens dissected, the location of the fulcrum was macroscopically verified. Dissection of the myocardium revealed it below and in front of the aortic root, in a plane inferior to the right trigone, implanted as a complementary structure between the elements of the atrioventricular junction, without continuity with the aortic valve. Anatomical images are presented in Figures 1 and 2.

The presence of the fulcrum was demonstrated ultrasonographically starting from the tetrachamber plane and locating the outflow tract of the left ventricle (long axis of the aorta), adjacent to the right wall of the arterial trunk, below its valve. It was also visualized in the short axis of great vessels below and to the right of the aortic annulus. Its shape varies according to the plane of section, between rounded, rectangular, or triangular. And in the atrioventricular plane, in M-mode scanning, its vertical displacement wave was observed. The plane showing its triangular shape was used to obtain the largest and smallest diameters (Figure 3 A and B). The insertions of myocardial fibers on the fulcrum (Figure 2) were detected in ultrasound images. Those of the basal loop start (in their right segment) towards the anterior border and right end of the fulcrum; those inserted in the posterior wall of the fulcrum come from the fibers of the descending endocardial segment and, finally, fibers of the ascending segment of the apical or apex loop are inserted in its left end (Figure 3 B and C).

Figure 1. Anatomical pieces showing the fulcrum (F) inside the red circle. Pulmonary artery (PA) and aorta (Ao), tricuspid (TV) and mitral (MV) valve annuli, right atrium (RA) and left ventricle (LV).

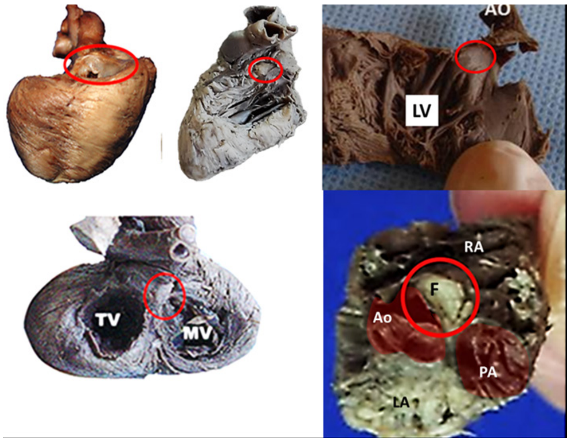
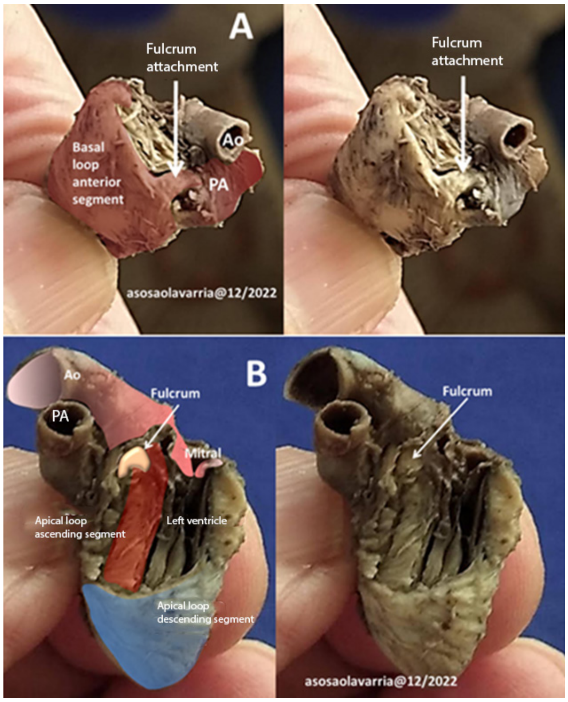


Figure 2. (A) Dissection aimed at demonstrating the fixation of fibers of the basal loop (anterior segment) to the right end of the fulcrum. (B) Dissection aimed at demonstrating the attachment of fibers of the apical loop (ascending segment) to the lower end of the fulcrum (inside the red circle).



The relationship of the fulcrum with the right coronary artery is shown in Figure 4. The displacement recorded with TM mode is shown in Figure 3E. Its rotational dynamics in the 2D plane was determined by STIC 3D and 4D HDL Flow, and speckle-tracking (Figure 5).

The measurements obtained (maximum and minimum) from 18 weeks of gestation to 37 weeks, calculating their average and standard deviation for each one, are shown in Table 1.

A hypothesis is presented about the mixed movement of the fulcrum (Figure 3D), in see-saw, with longitudinal displacement towards the apex with repositioning towards its initial position (base); and also, its bidirectional rotation, following the sequential contraction (torsion-detorsion) of the helical myocardial band (BMH). Its rotational dynamics were identified during systole and diastole using ultrasonographic (3D) and speckle methods (Figure 5). It was demonstrated that the fulcrum initially presents a clockwise rotation and subsequently, when ascending segment contraction begins, the fulcrum rotates counterclockwise, with the end of the rotation coinciding with the opening of the mitral valve. This allows rapid filling of the left ventricle. In addition to the rotation, there is also a longitudinal displacement of the fulcrum following the approach of the base to the apex and subsequently its ascent to its original position.

Table 1. Fetal cardiac fulcrum. Diameters (in mm), average maximum and minimum values and their respective standard deviations according to gestational age in weeks.

Weeks of gestation	Minimum average diameter	Standard deviation	Maximum average diameter	Standard deviation
18	1.93	0.53	3.28	0.89
20	2.13	0.33	3.33	0.40
22	2.20	0.21	4.32	0.76
24	2.40	0.34	4.40	0.83
26	2.46	0.36	4.54	0.52
28	2.51	0.37	4.76	0.93
30	2.56	0.46	4.82	0.95
32	2.93	0.91	5.05	1.33
33-37	4.10	0.85	7.37	1.96

Discussion

In 2022, Best et al.[15] listed the proposed functions of the ossa cordis noting that research in mammals has suggested two main and two complementary theories. In cattle and camels, it has been proposed that cardiac muscle is anchored in ossa cordis enhancing contraction; in cattle, sheep and otters it has been suggested that it protects the heart from damage under circumstances of high mechanical stress; and in chimpanzees, horses, cats and dogs, its presence has been associated with cardiovascular disease.

Figure 3. (A, B, C, D, E). 2D US image of fetal heart showing cardiac chambers the aorta (Ao) and the fulcrum (F). Ultrasonographically it is distinguished starting from the tetrachamber plane (A) and locating the left ventricular outflow tract (LV), long axis of the aorta artery (Ao), (B) adjacent to the right wall of the arterial trunk, below its valve, but it is also visualized in the short axis of great vessels below and to the right of the aortic annulus. The first of the described planes is the optimal one for its triangular shape for its measurement in major and minor diameter. In (C) the image shows (red) the fibers that insert into the fulcrum (1, 2 and 3). (D) Diagram showing the movements of the fulcrum, and in (E) TM recording of this structure with displacement in two directions.

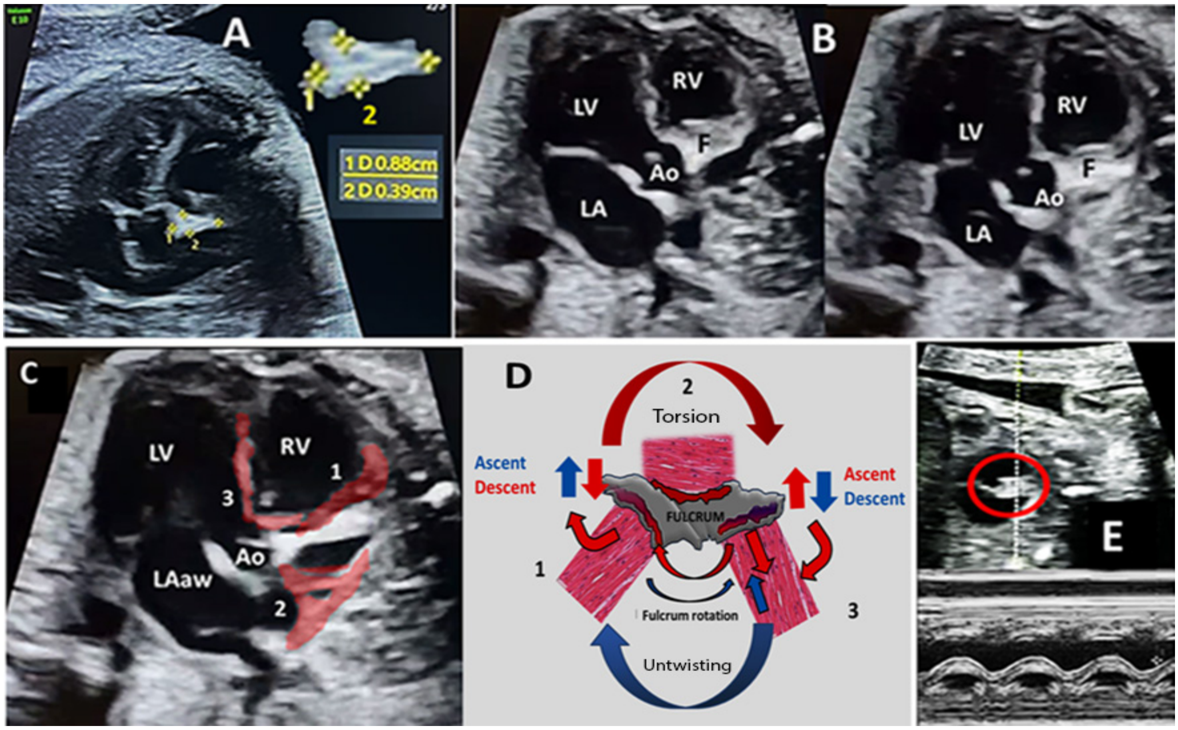


Figure 4. Color Doppler images showing the aorta (Ao), the fulcrum (red arrows) and right coronary artery (CA) (yellow arrow).

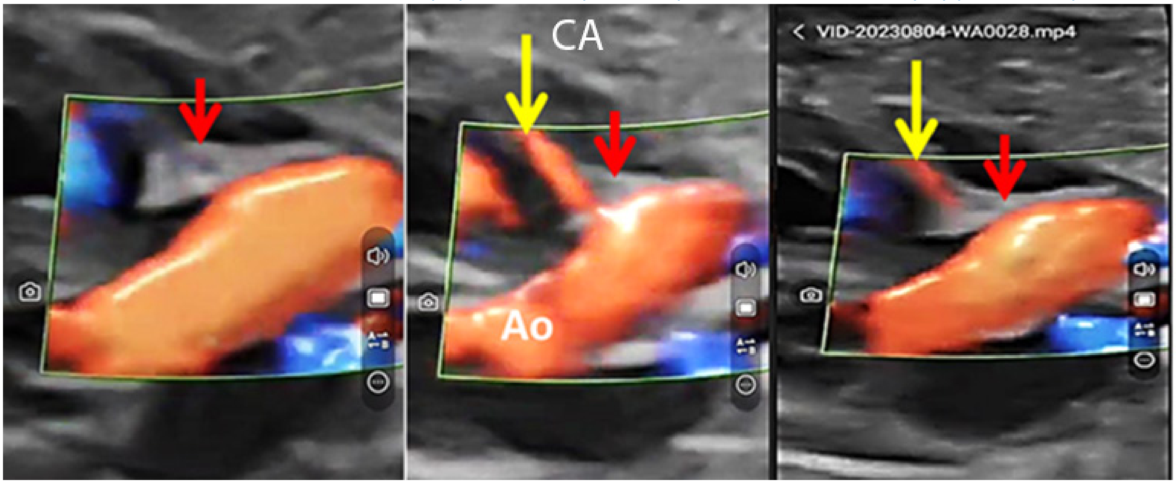
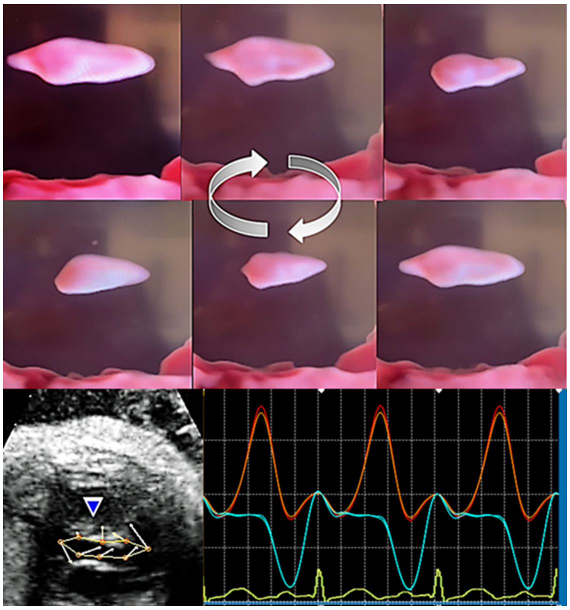


Figure 5. 3D images with STIC software, HD Flow (top) showing the fulcrum in different positions obtained frame by frame in video and demonstrating rotational motion. At the bottom, displacement of the fulcrum recorded by speckle-tracking.



In humans, the fulcrum, a small osteochondroid and tendinous structure within the heart, helps anchor the myocardial band to assist contraction. Located in front of the aorta, just below the right trigone, the myocardial band inserts part of its fibers into the aorta in the manner of a osteoid muscle tendon. Histological analysis of animal and human hearts[5,13,16-19,24-26] has shown the presence of cardiac myocytes within the fulcrum. Furthermore, it is suggested that the reason for this insertion into the *ossa cordis* may help to stabilize the hearts during contraction and relaxation. And there is no doubt from the work of Trainini et al.[25-28] of the existence of this structure in the human heart, from the prenatal, infant and adult stages, which serves as a support point for the heart to twist and untwist, displace and reposition the atrioventricular junction, thus actively alternating powerful compression and suction forces according to the momentum of displacement and torsion.

Previously, Torrent Guasp together with Kocica et al.[1,27] had suggested the need for a mechanical fulcrum in the heart. It was called 'dynamic hemoskeleton' by means of a physical explanation, applying the principles of the first degree lever; the volume of blood acquired in the ventricles as non-compressible fluid would be the support point. The same authors named this phenomenon as fulcrum radius, being that the support provided by the surrounding myocardium will vary according to consecutive changes in intraventricular blood volume. Hence the term 'dynamic', concluding that the larger the hemoskeleton, the lower the leverage effect and vice versa[1].

In the work of Trainini et al.[13,14,20-23] the investigation was completed with histological, plain radiographic, nuclear magnetic resonance and computed tomography imaging studies, finding in all the human and bovine hearts studied a nucleus underlying the right trigone with a histological bone-chondroid-tendinous structure. Microscopic analysis revealed in bovine hearts a trabecular osteochondral matrix. In all human hearts the fulcrum was found to be formed by chondroid tissue. In this structure, not described by other authors, there is insertion of myocardial fibers from the origin and end of the myocardial loops, and fibers from the right, descending and ascending segments, origin and end of the cardiac muscle, are inserted into it. There common function is to support the myocardium in order to generate the power, electrophysiological phenomenology required by any muscle. Therefore, its presence is constant in all hearts analyzed, both bovine and human, being torsion and detorsion responsible for the best cardiac filling and emptying[28-30].

The kinetics of the fulcrum we propose is as follows: when contraction of the basal loop occurs in its two segments (right and left), the right ventricle (RV) compresses and ejects its preload. At this moment, the fulcrum at its end where fibers of the anterior segment of the basal loop are attached moves downward and toward the external wall of the RV, while the opposite end where fibers of the ascending segment of the apical loop are inserted, rises; when this segment contracts, it lowers the left end and the final ejection is completed in the left ventricle (LV); thus the see-saw movement is fulfilled. When the heart twists and untwists, the fulcrum rotates in one direction and then resets. The third component of this mixed motion occurs when the atrioventricular (AV) junction moves toward the tip and then returns, the fulcrum descends and ascends. All this kinematics occurs sequentially and synchronously according to the duration of the cardiac cycle, and atrial activity is only a complement to the efficiency of the pump[30,31].

The inevitable reflection that arises is that, in order to perform torsion, the myocardium must perform it on a point of support, just like a skeletal muscle, and it does so on a firm insertion, the fulcrum or mechanical lever of the heart. If we accept as valid the arguments of Torrent-Guasp and complement them with the findings of Trainini et al.[13,14,20-23], we must conclude that new paths are opening up for the understanding of a new cardiac physiology or electro biomechanics that will have broad repercussions in the management of multiple conditions that affect cardiac performance[7]. The results provided by Torrent-Guasp, the contributions of Trainini and the theories of perfectly synchronized ventricular filling and emptying have allowed us to try to decipher some of the hieroglyphics of fetal cardiac Doppler[29].

Regarding the origin of the fulcrum tissue, so far the only accepted source of cartilage in the heart is the cardiac neural crest, a multipotent ectomesenchyme whose cardiac cell derivatives are mainly confined to the aorta-pulmonary septum, the developing pulmonary and aortic valves and surrounding tissues. However, recent reports have revealed that the embryonic epicardium, i.e., the layer of tissue overlying the cardiac muscle also contributes significantly to various cardiac connective tissues. The epicardium develops from the proepicardium, a mass of coelomic progenitors located at the venous pole of the embryonic heart. Duran et al.[24] point out that the presence of cartilaginous tissue in the embryonic and adult hearts of different vertebrate species is a well-documented fact. However, although the embryonic neural crest has historically been considered to be the main source of cardiac cartilage, recently published results on the broad connective potential of cells of the epicardial lineage suggest that they could also differentiate into chondrocytes. These results, like those of Palmquist-Gomez et al.[32] are relevant to the understanding of cardiac cellular complexity and cardiac connective tissue responses to pathological stimuli. Indeed, cartilage differentiation is initiated by condensation of mesenchymal connective tissue under instructive signaling provided by key growth factors such as BMPs and FGFs and master regulation of key Sox9 transcription factors. This differentiation process results in the active synthesis of a characteristic extracellular matrix (ECM) enriched in collagen II, chondroitin sulfate, hyaluronic acid and various proteoglycans.

Limitations

No obstacles were encountered in the execution of the present study, and the possible usefulness of the amplitude of the fulcrum movement as a function of cardiac performance and the presence of this structure in congenital cardiopathies, including structural and rhythm anomalies, remains to be evaluated.

Conclusions

The cardiac fulcrum is located at the intermediate point of the loops (basal and apical), guaranteeing a fulcrum or pivot point for effective contraction of the helical myocardium. Serving as a lever for cardiac fibers coming from the loops, it undergoes, as a consequence of sequential contraction, mixed type displacement, has clockwise and counterclockwise rotation following torsion and detorsion, descends, ascends and swings.

The hypothesis derived from this study is that when depolarization of the basal loop occurs in its two segments, the RV compresses and ejects its preload. At this moment the fulcrum, at its end where fibers of the basal loop are attached, moves downward while the opposite end, where fibers of the ascending segment of the apical loop are inserted, rises, facilitating final ejection in the left ventricle. When the heart twists and untwists, the fulcrum rotates in one direction and in the opposite direction until the atrioventricular junction is repositioned.

Both filling and emptying of the ventricles is the product of an active movement; in torsion it compresses and ejects, and at that moment exerts a powerful suction force on the atria, which then relax (atrial diastole). In ventricular detorsion, it sucks into this cavity and compresses the atria. These contribute to the acquisition of ventricular preload through atrial systole.

In the present work, these findings are confirmed morphologically and by ultrasonography, and through these we find a logical explanation from the physical and physiological point of view that enriches our knowledge of the capacity of the myocardium to fulfill its aspiring and impellent mission.

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