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Research Article

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The Cardiac Fulcrum and the Atrioventricular Node in the Transmission and Regulation of the Cardiac Cycle

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Abstract

Objective: Observe the anatomofunctional relationships of the Cardiac Fulcrum with the AV Node.

Material and Methods: The methods used in this research to explain consisted of:

i. The use of 84 hearts from a morgue and slaughterhouses: a) 17 human hearts (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 300 g) b) 57 two-year-old bovine hearts weighing between 1300 and 1900 g (average 1650 g) c) 10 porcine hearts (400 g)

ii. Histological and histochemical analysis of the anatomical samples.

iii. Immunostaining technique for neurofilaments.

Results: We observed that in all the species studied (human, bovine, and porcine), the fulcrum has a central area and two poles. It is in close contact with the atrioventricular node. The central area of the fulcrum forms the lever arm. This configuration allows the fulcrum to transmit a pulsatile tilting motion to the atrioventricular node. The fulcrum and the atrioventricular node regulate and modulate the body's afferent information before converting it into the depolarization wave.

Conclusion: This work studies the fulcrum function and its anatomical relationships. The function provides support for the double helix that configures the anatomy of the heart, and also transmits signals, to the atrioventricular node and the autonomic nervous system. Each heartbeat is then a result of a reading of fluctuations in an external and internal environment, which enters through the autonomic system to the AV node, which is almost like a second brain at the base of the heart, in sync with the Fulcrum that generates rhythmic feedback with coupling and decoupling similar to a self-organizing process.

Keywords: Cardiac fulcrum, AV node, Self-organizing system

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Introduction

Francisco Torrent Guasp demonstrated in the 1960s that the heart was a single muscular band that coiled upon itself in a double helix formation [1]. Despite this work, the prevailing paradigm of a heart with a solid myocardium remained unchanged. Perhaps the main criticism was the lack of a fulcrum from which pulsatile movements could be generated. Jorge Trainini, one of his followers, later found this fulcrum in bovine and human hearts, an observation published in "Morphology" in 2020 [2,3]. This formation, termed the Cardiac Fulcrum, is composed of osteochondroid tissue in cattle and cartilaginous tissue in pigs and humans. What has been observed in this research is that when this continuous myocardium unfolds, all its anatomical relationships with the fulcrum and the atrioventricular node are destroyed. These nodes constitute an electromechanical unit where the muscular band inserts and where cardiac stimulation is regulated. Furthermore, we have studied the atrioventricular node in its relationship with the fulcrum, as well as its anatomy and histology (Figure 1). Purkinje cells, discovered in 1830, were also analyzed within this electromechanical relationship. Purkinje cells are considered conduction myocytes for the transport of the energy wave. The pathophysiological implications of these findings have also been evaluated in this article (Figure 1).

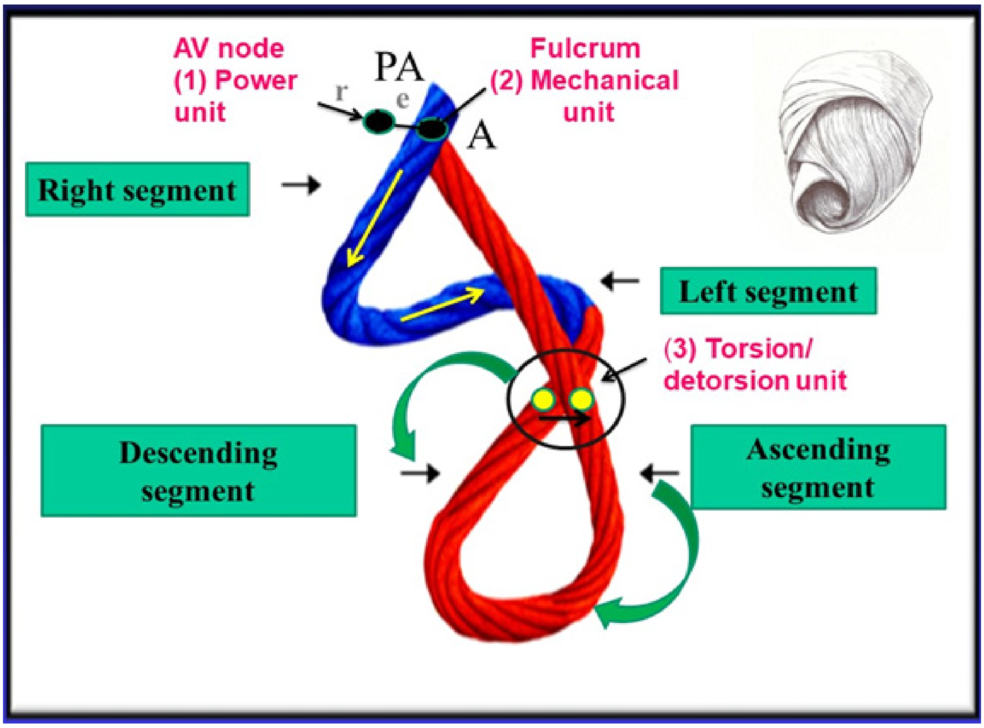

Figure 1: Helical myocardium in the cord model that simplifies the spatial structure. It shows the different segments that comprise it. In blue: basal loop. In red: apical loop. PA: pulmonary artery; A: Aorta; r: stimulus reception; e: stimulus emission. The three anatomical and functional units that allow integration between the AV node, the cardiac fulcrum, and myocardial torsion are detailed. The black circle details the site we have called band crossover. Given the different anisotropic orientations of the fibers, this area corresponds to the beginning of the helical opposite movement that produces myocardial torsion. The spatial arrangement of the continuous myocardium can be seen in the upper corner.

Material and Methods

The methods used in this research to explain the consisted of:

1) The use of 84 hearts from the morgue and slaughterhouses:

a) 57 two-year-old bovine hearts weighing between 1300 and 1900 g (average 1650 g);

b) 17 human hearts (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 300 g);

c) 10 porcine hearts (400 g);

2) Histological and histochemical analysis of the anatomical samples.

3) Immunostaining technique for neurofilaments [4].

Results

Topography of the cardiac fulcrum. The inevitable question arose from the beginning of the investigation. In order to twist, the muscular segments constituting the myocardial helicoid and forming the ventricular chambers should twist on a point of support in the same way as a skeletal muscle does on a firm insertion; is there any in the heart? If this support is real, how does the myocardium insert into this structure? This topic became an essential concern in our reflections. It was logical to speculate that its helical disposition and the remarkable physiological characteristics of the myocardium requires it to have a point of support in order to fulfill its function as an ejection (torsion) and suction (detorsion) pump.

The heart has a size equivalent to a human fist and an average weight of 270 grams; it propels a quantity of blood that ranges from 4 to 6 liters/minute at a speed of 200 cm/s. It also has a consumption of only 10 watts, works continuously for 80 years without maintenance and almost without noise, producing 100.000 beats per day. Its task is equivalent to extracting from a depth of 1 m 1 ton of water per day with a mechanical efficiency (work/energy ratio) of 50%, not attained by man-made machines, which reach 30%. Its efficiency allows 70% of the left ventricular content to be ejected with only 12% shortening of its contractile unit, the sarcomere.

This site of myocardial insertion, which we have called the cardiac fulcrum, is located in the vicinity of the tricuspid valve (right), the aorta (superior) and the pulmo-tricuspid cord (anterior) (Figure 2). In order to find it, it is necessary to move the pulmonary artery and the right segment to the left of the observer, baring the root of the aorta. This action reveals the fulcrum below the aorta and inferior to the right trigone, without any continuity with it, below the origin of the right coronary artery, detached from the aortic valve continuity, which rests on the upper surface of the fulcrum [5]. From this point, on the lateral wall of the aorta, its direction is towards the free wall of the right ventricle below the tricuspid valve (Figure 2).

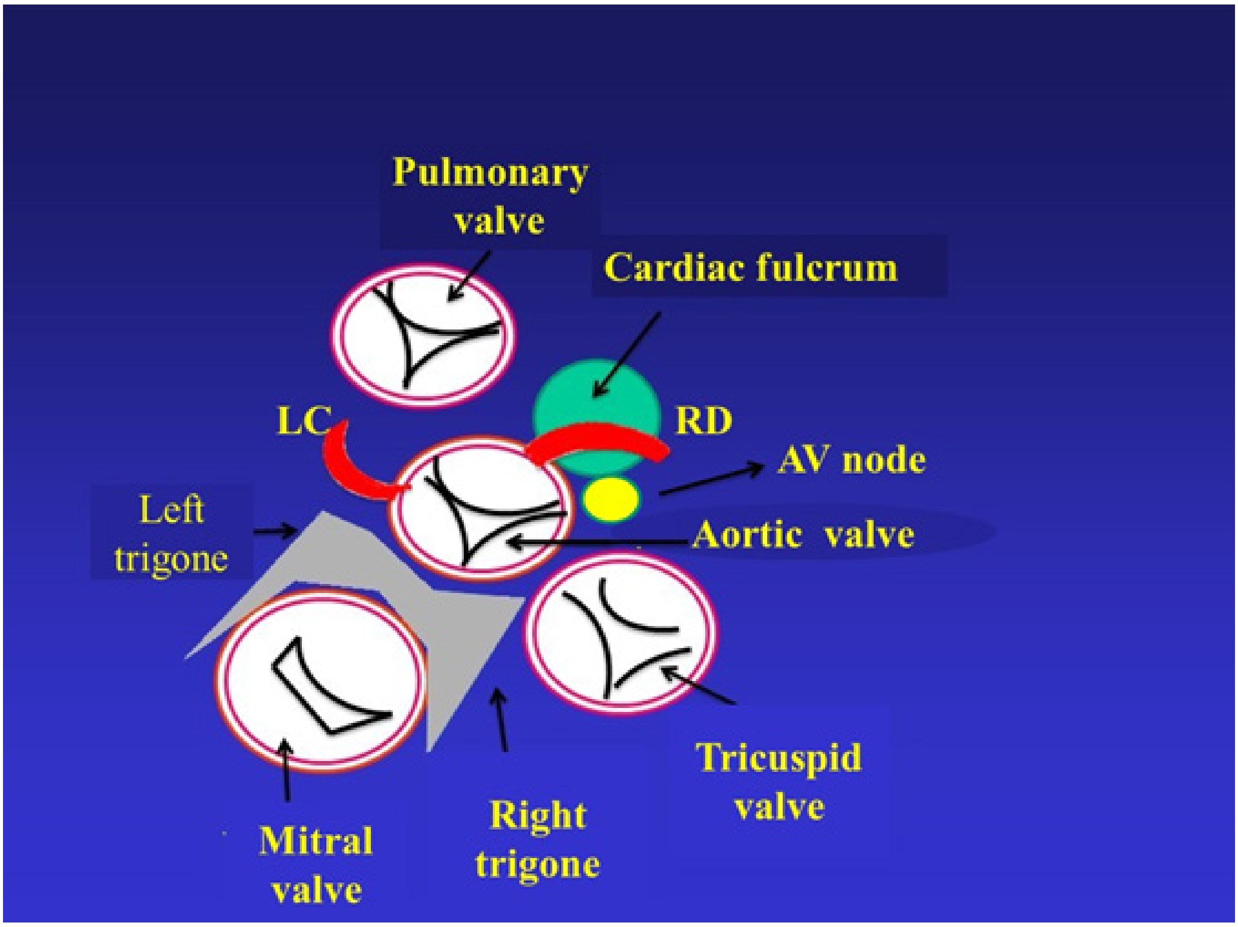

Figure 2: The location of the cardiac fulcrum is demonstrated. References: LCA: left coronary artery; RCA: right coronary artery. Note the atrioventricular (AV) node contiguous to the *cardiac fulcrum.*

The important fact of the fulcrum functionality comes from the macroscopic and microscopic observation that demonstrates the tethering of the myocardial fibers to this solid, consistent nucleus. Its conformation was corroborated by histology (Figure 3). This structure, origin and end of the continuous helical myocardium, was called Cardiac Fulcrum in a parallelism and homage to the designation of the point of support to exert a lever expressed by Archimedes of Syracuse (Greece, 288 BC-212 BC) with the words "Give me a point of support and I will lift the world", historical slogan that reached our days through Plutarch's text "Parallel Lives" and that corresponds to a letter sent by Archimedes to King Hieron of Syracuse [3].

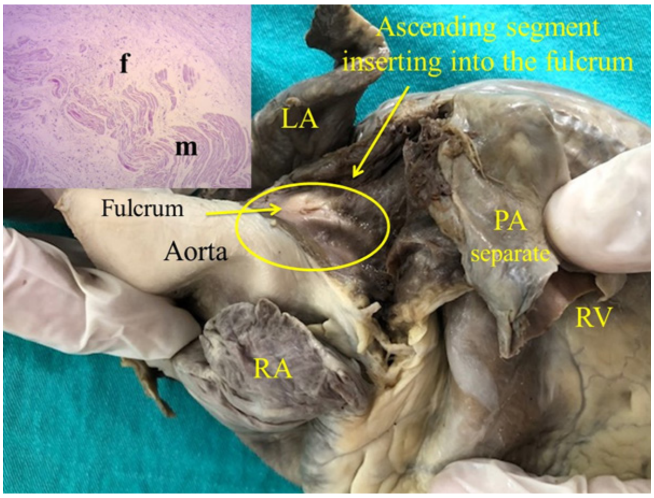

Figure 3: Adult human heart. The ascending segment is seen inserting into the *cardiac fulcrum*. References: LA: Left atrium; RA: Right atrium; PA: Pulmonary artery; RV: Right ventricle. The inserted image of the angle shows a microscopic view of the human fulcrum. Note the myocardial fibers (m) inserting into the tendinous fulcrum matrix (f).

It should be noted that in order to visualize the cardiac fulcrum in its anatomical situation and to establish its relationships, it is necessary to unfold the helical myocardium. (Figure 1) shows the location of the cardiac fulcrum in the cord model, supported by Torrent Guasp (1931-2005), which simplifies the understanding of the helical myocardium [6].

In bovids, its size, corroborated by dissection and imaging studies (computed tomography, magnetic resonance imaging, ultrasound), is approximately 37 mm long, 45 mm wide, and 15 mm thick, with a triangular shape (Figures 4-6). In humans, it has the same morphology, but its size is 50% that of the bovine fulcrum in each of its dimensions (Figure 7). In pigs, it also has the same shape (Figure 8).

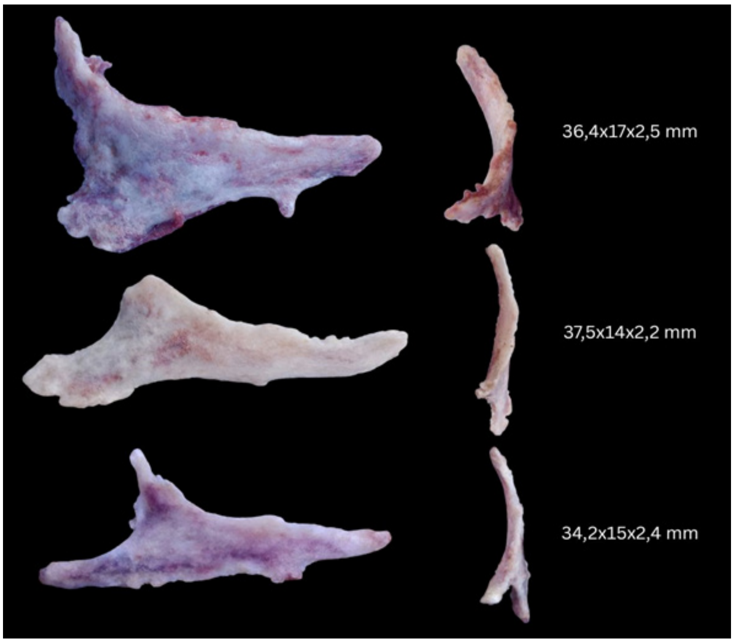

Figure 4: The size of the cardiac fulcrum obtained from bovine hearts is shown in its three dimensions.

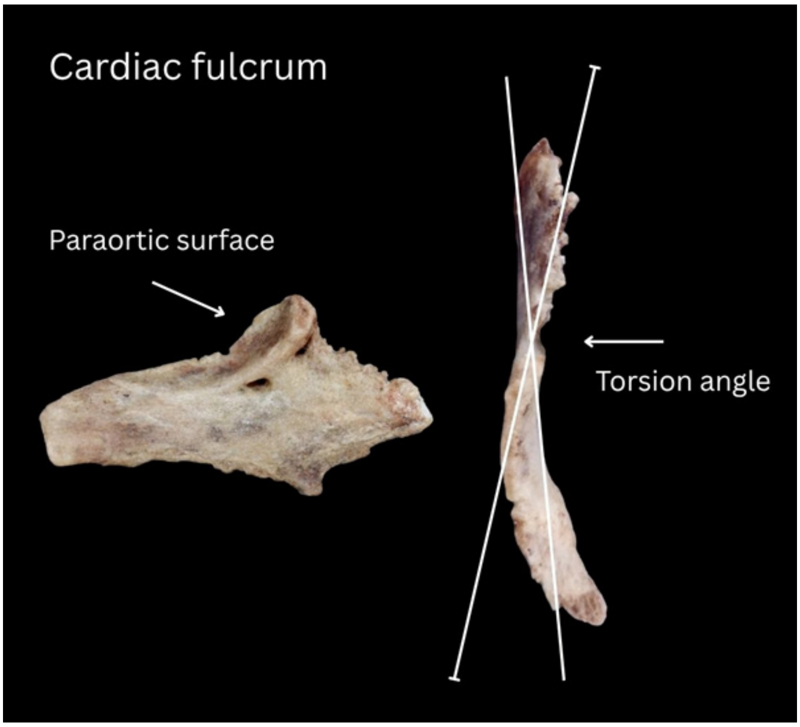

Figure 5: The para-aortic surface of the *fulcrum* contacting the aorta is seen on the left image. The right image shows the torsion angle shaped by cardiac movements (bovine heart).

Figure 6: *Cardiac fulcrum* of a bovine heart. Profile views.

Figure 7: *Cardiac fulcrum* of a dissected bovine (A) and adult human (57 years old) (B).

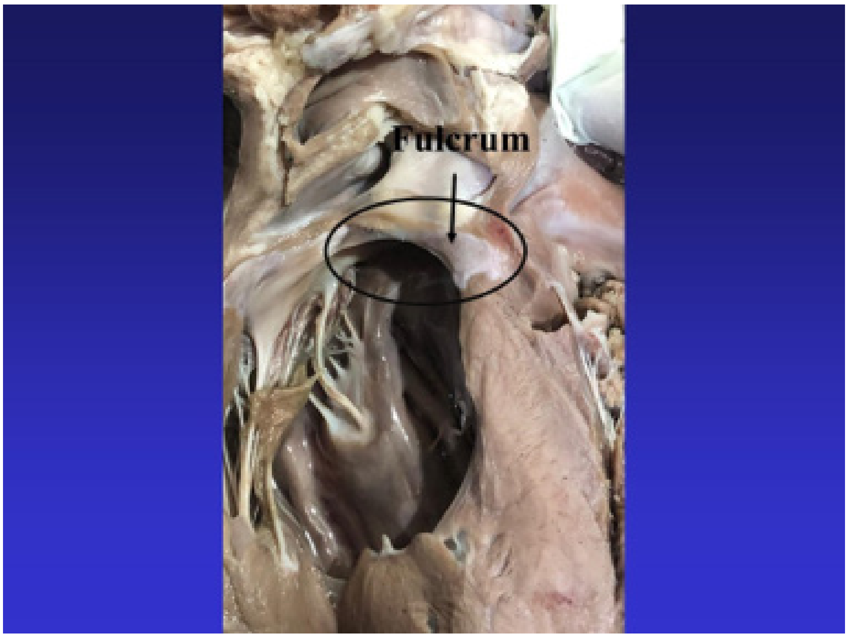

Figure 8: Cardiac fulcrum of a pig heart.

Its triangle-like shape has a bifid character at its right end (insertion of the right segment) and ends in a point at the opposite end (attachment of the ascending segment). (Figure 9) shows these details, as well as the articular surface with the aorta and its location in the heart.

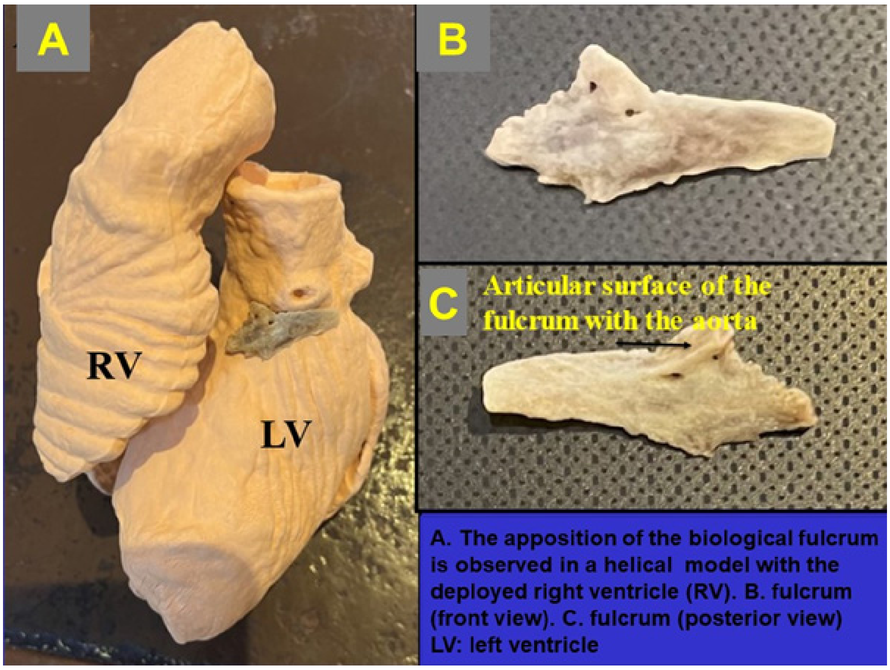

Figure 9: Bovine *cardiac fulcrum* located in its anatomical position in a silicone cardiac model (copy of a biological heart).

In this study, the anatomical and histological relationship between the cardiac fulcrum and the atrioventricular node in human, bovine, and porcine hearts was analyzed, as well as the possible functionality between the two structures. This situation will be analyzed in detail given its importance (Figure 10).

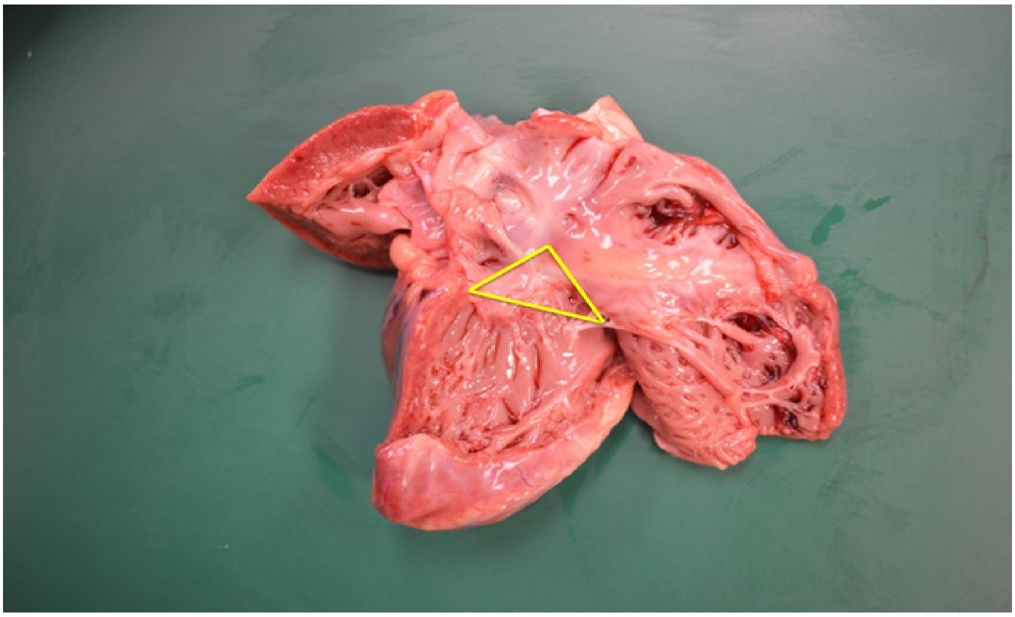

Figure 10: 4-year-old human heart: Macroscopy of Koch's triangle, delimited by the septal leaflet of the tricuspid valve, the tendon of Todaro and the coronary sinus. This triangle is a reference to find the AV node.

The single continuous helical myocardium was deployed according to the technique published in our works [3,7]. There is a fundamental concept at the beginning of the unfolding, since any attempt not to respect in the dissection the axes where the myocardium folds as a helicoid, produces a rupture of the cardiac mass. The conjunction between the beginning and end of the cardiac muscle at the cardiac fulcrum constitutes a meeting point between the right segment and the ascending segment, origin and end of the myocardium. Thus, both ends are located in the same place, the origin of the myocardial fibers being in a plane anterior to those of its termination. Samples were taken from the AV node and His bundle in Koch's triangle (Figure 10).

The fulcrum, being located in the atrioventricular junction at the insertion of the interventricular septum, below the aorta and pulmonary artery, is adjacent to the Aschoff-Tawara AV node, which is located to its right (Figure 11-14). The heart support, at its right end, reaches the tricuspid valve ring. The AV node is positioned at the atrioventricular junction, at the base of the muscular septum, below the origin of the great vessels. It is adjacent to the cardiac fulcrum, located between it and the implantation of the septal leaflet of the tricuspid valve. It constitutes a conglomerate of cells (specialized myocytes) that R.F. Rushmer defines as a spherical or bulbous end composed of bundles of fibers [8-10] to transmit electrical impulses to the myocardial mass. In its continuity, it is slightly transformed into the bundle of His, of short extension, sometimes even nonexistent. In humans it is approximately 5 mm long, 3 mm wide and 1 mm thick and is irrigated by a branch of the coronary arteries, generally from the right coronary artery in 90% of cases and from the circumflex artery in the remaining fraction [11].

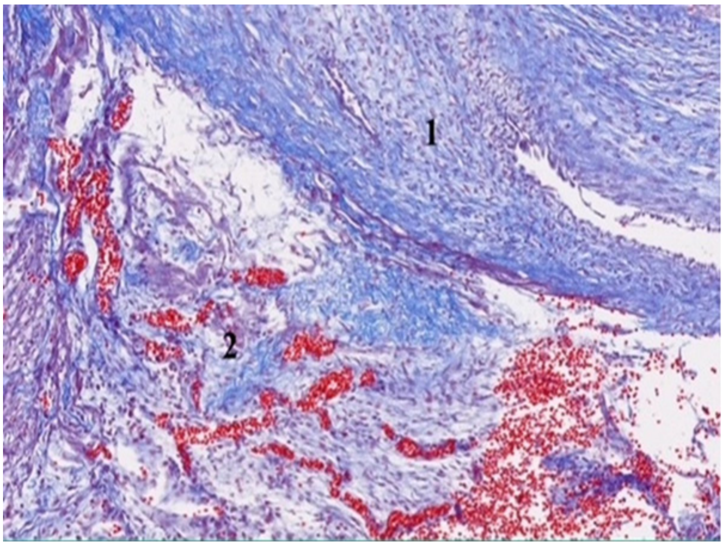

Figure 11: Human embryo heart showing the relationship between the AV node (2) and the cardiac fulcrum (1).

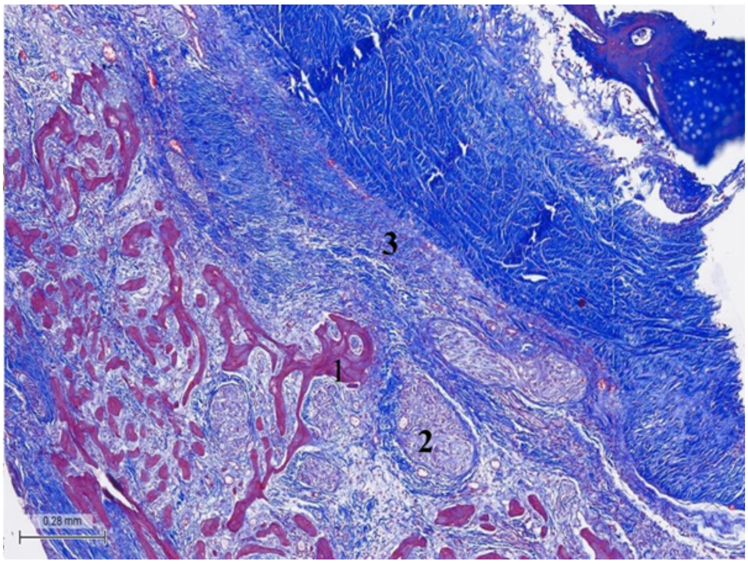

Figure 12: (Bovine heart). Masson's trichrome technique, 25x. Tangential section of the *fulcrum*, showing bony trabeculae of the *fulcrum* including plexuses with neurofilaments. 1: bone tissue. 2: terminal plexuses. 3: Fibroconnective tissue.

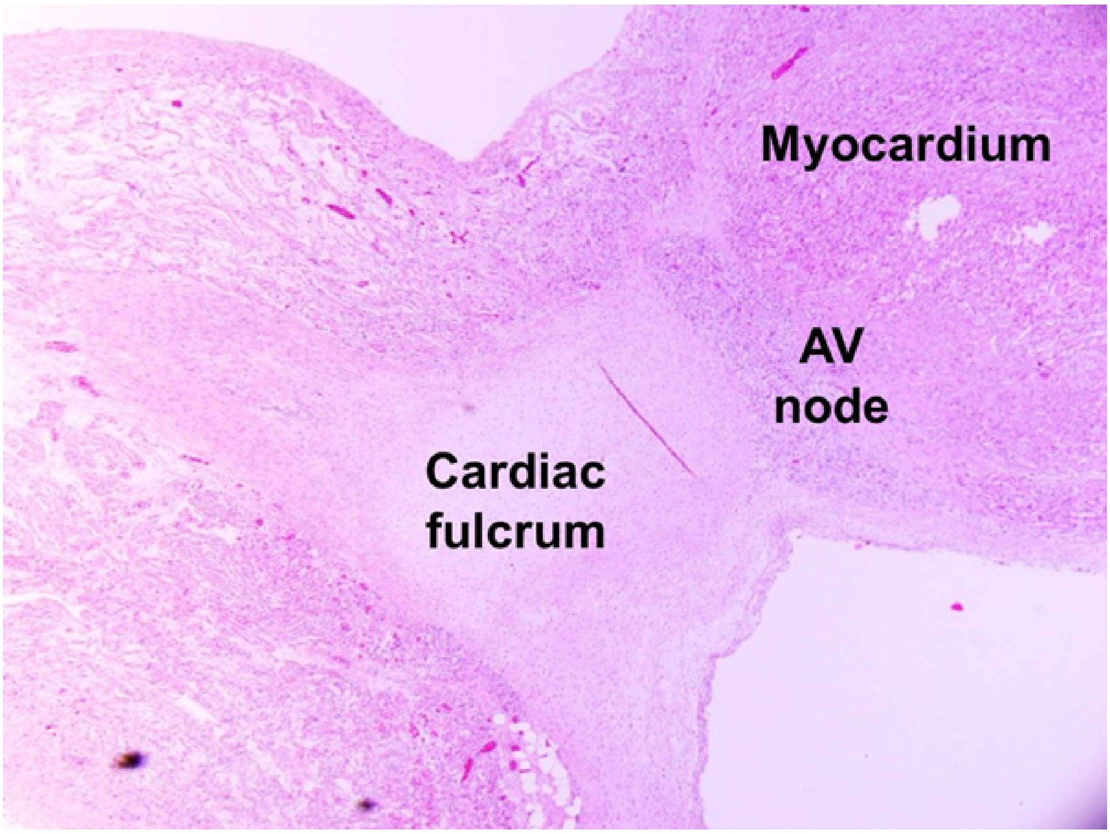

Figure 13: 36-day-old newborn human heart. Magnification 20x. The *cardiac fulcrum* of cartilaginous matrix is seen with the myocardium and adjacent AV node. AV: Aschoff-Tawara atrioventricular node.

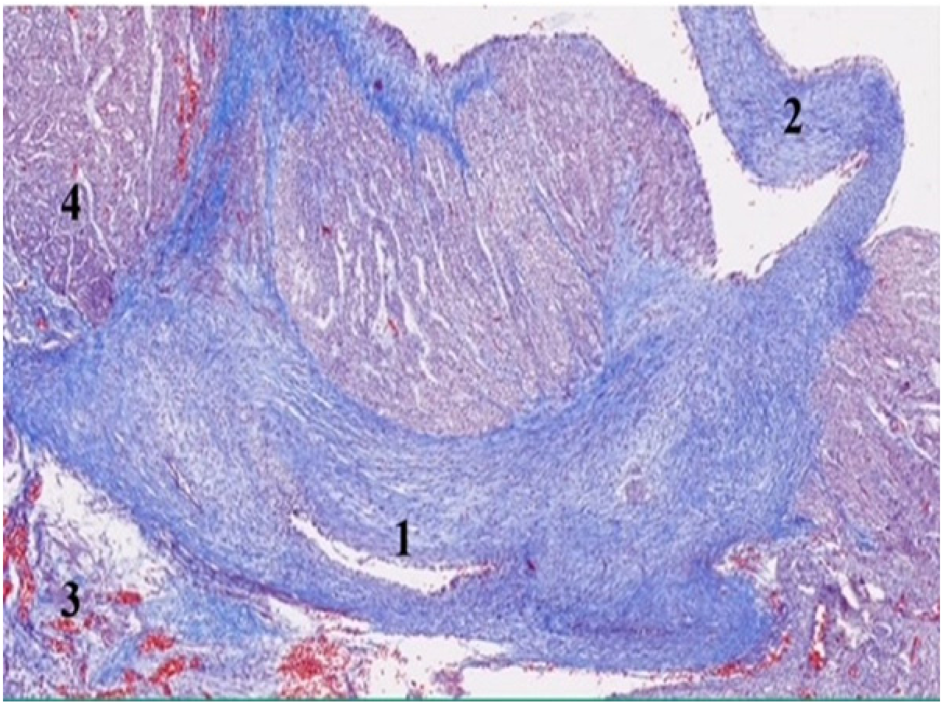

Figure 14: Human embryo heart (20 weeks) showing the relationships between the *cardiac fulcrum* (1), the tricuspid valve (2), the AV node (3) and ascending segment (4).

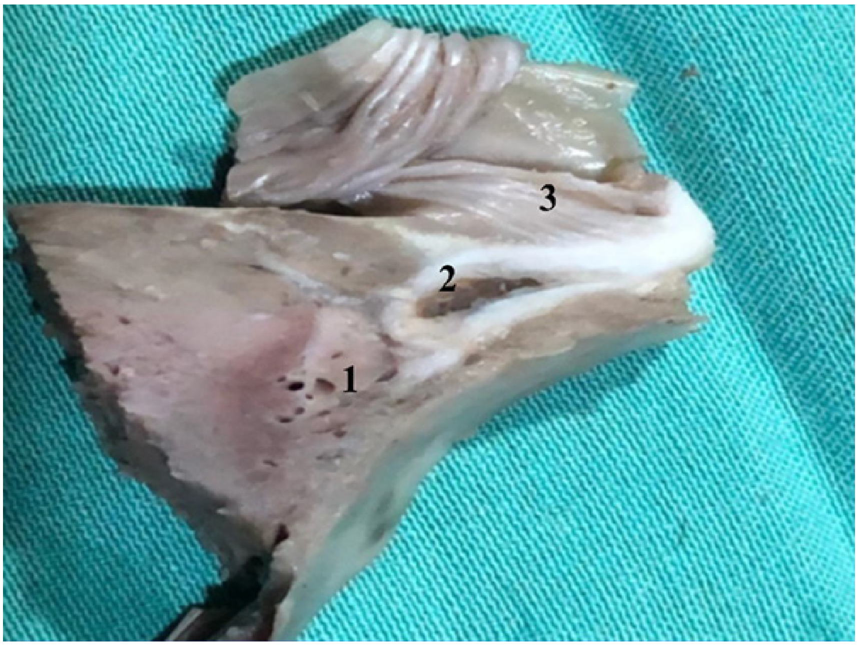

Figure 15: Bovid heart. A longitudinal section of the *cardiac fulcrum* is observed. Ref. 1: AV node; 2: fulcrum; 3: tricuspid valve.

Relationship of the cardiac fulcrum with the AV node. This analysis reveals, in both human and bovine hearts, an issue of importance for cardiac pacing therapeutics (Figure 15) [12]. In the histological study, the fulcrum was found to be adjacent to the AV node, forming a cellular conglomerate rich in neurofilament plexuses (Figures 16-18). This contiguity between the two structures is found in all specimens studied, both in bovine and human hearts. Central to the research finding is that neurofilaments are also found within the cardiac fulcrum, upon contact with the muscle fibers that insert into it. Fibroblasts and connective tissue are located in the thickness of the conduction system and between this and the working myocardium, acting as an insulation layer. It is also the connective tissue that constitutes the fibrous ring and the central fibrocartilaginous portion of the fulcrum, thus electrically isolating the atrial and ventricular chambers (Figures 19-22).

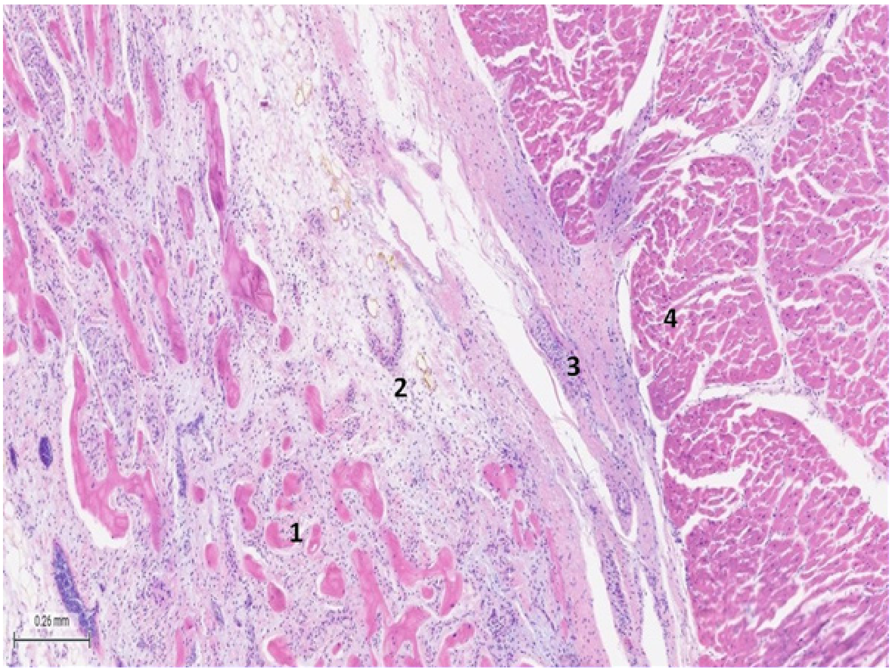

Figure 16: (Bovine heart). H&E (x25). Plexuses are seen associated with fibrochondroid trabeculae and the myocardium. 1: osseous trabeculae. 2: plexuses. 3: fibroconnective tissue. 4: myocardium.

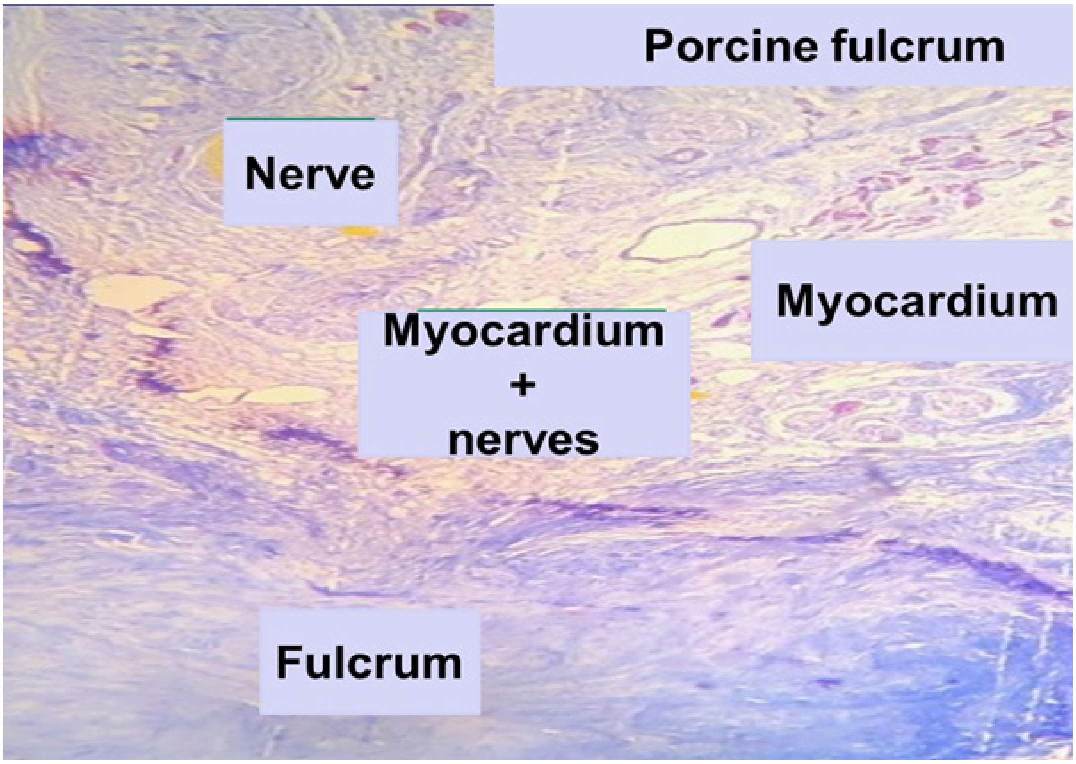

Figure 17: Porcine fulcrum (x20)

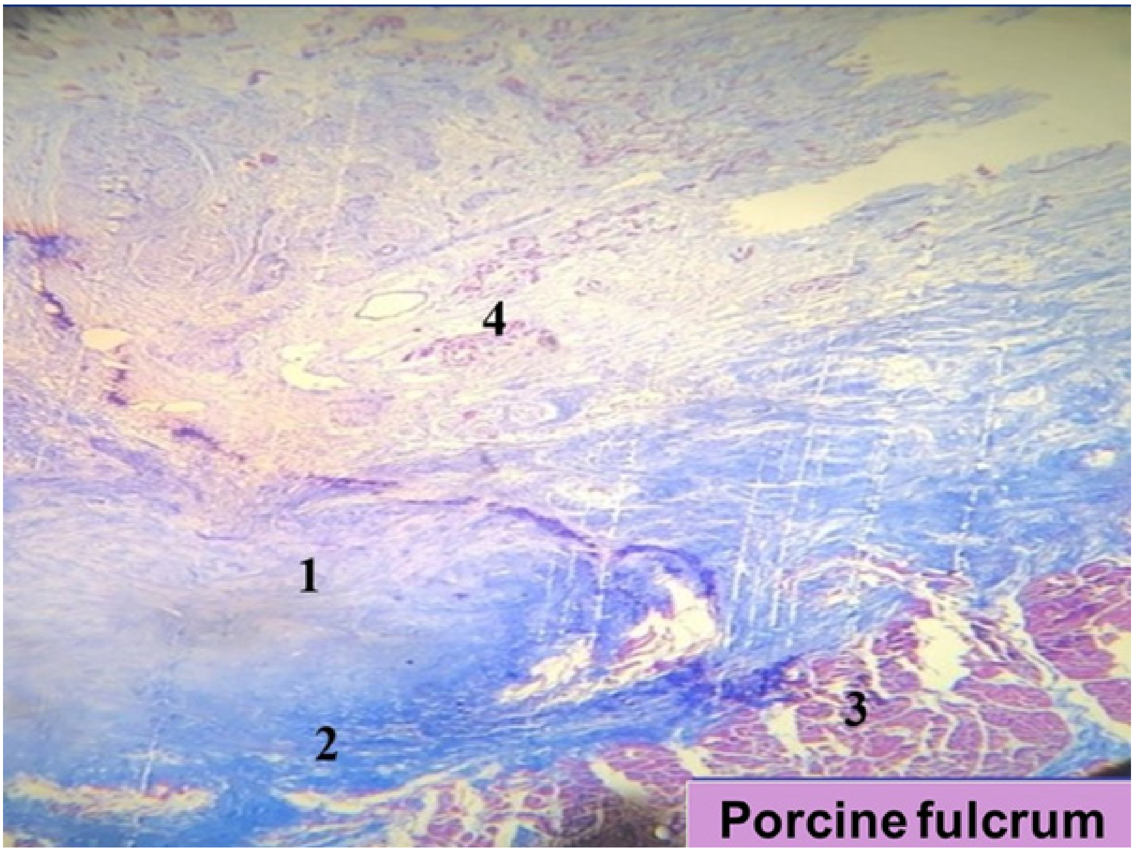

Figure 18: Porcine fulcrum 25x, Masson's staining. 1: Porcine cartilaginous fulcrum. 2: perifulcrum fibrous tissue. 3: septum. 4: intermingled cardiomyocytes of conduction nerves and ganglions can be seen reaching the *fulcrum*.

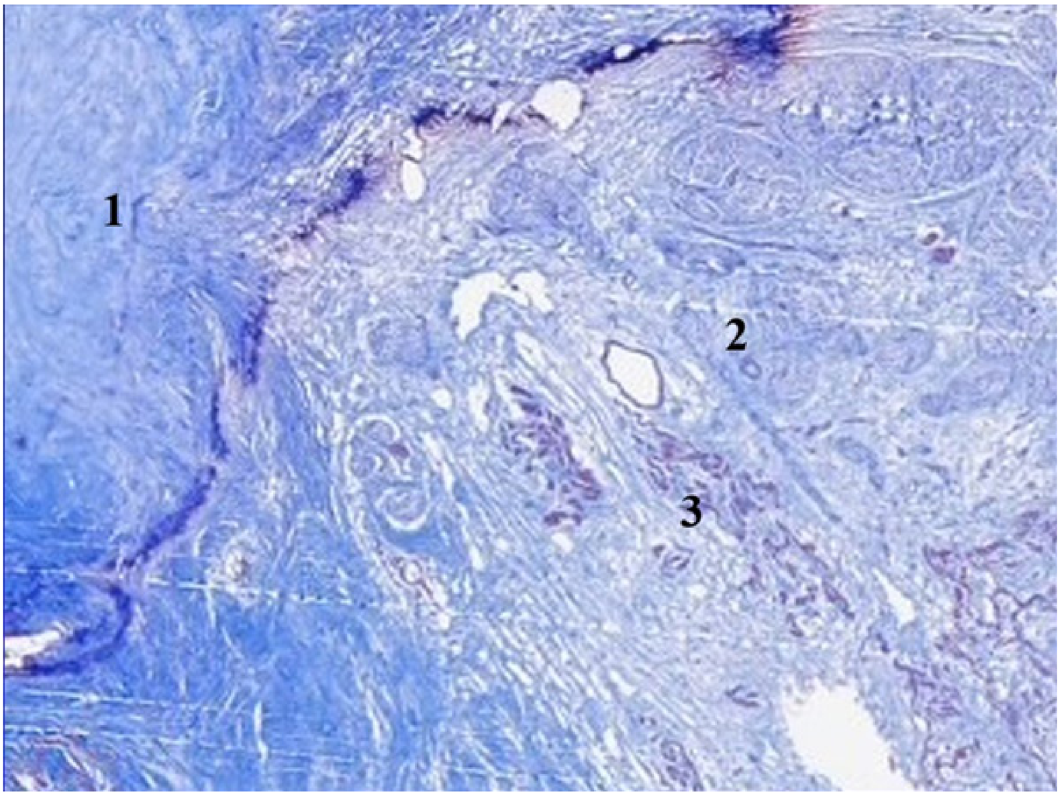

Figure 19: Porcine heart. Relationship of the *fulcrum* with the AV node. 1: *fulcrum*; 2: AV node; 3: cardiomyocytes (Purkinje cells) within the AV node.

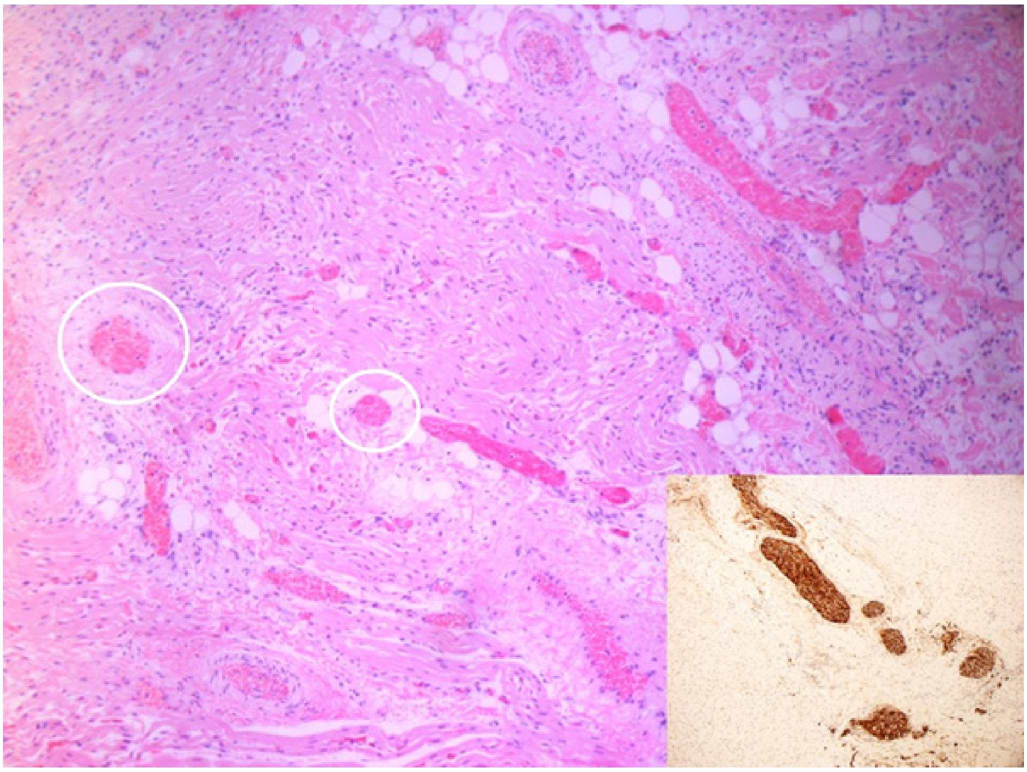

Figure 20: 27-week-old infant heart. Nerve trunk hypertrophy is seen in the *cardiac fulcrum* (white circles) adjacent to the AV node. HEx200. Inset shows thickened nerve trunk in the *cardiac fulcrum* confirmed by immunohistochemistry for S-100.

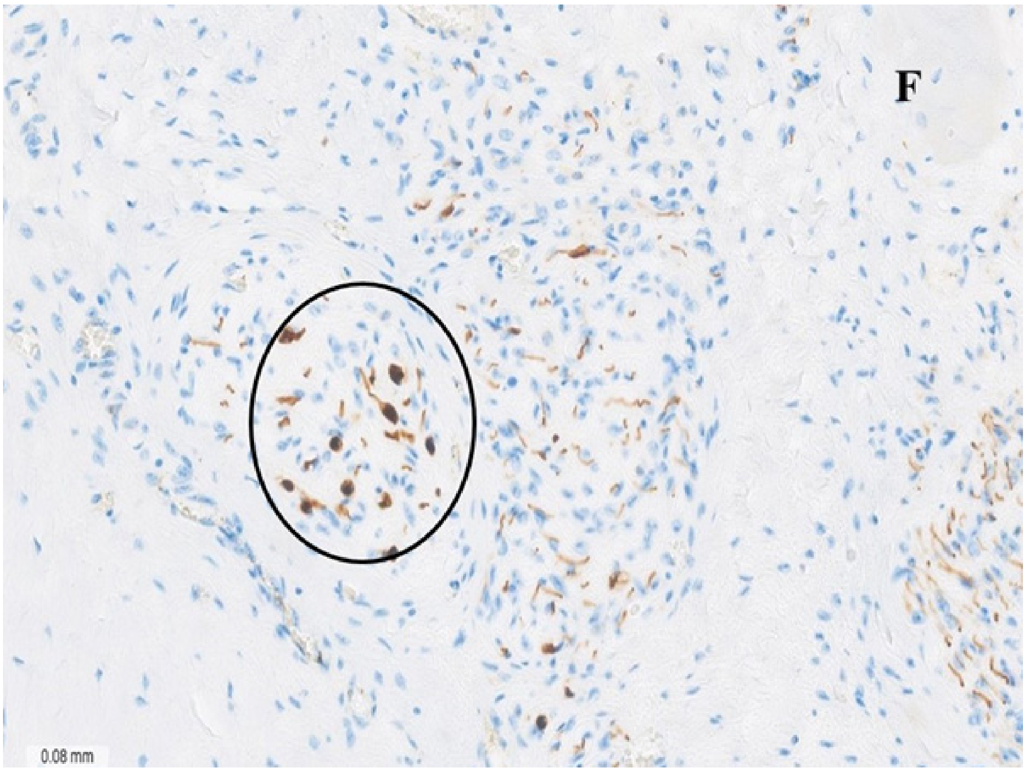

Figure 21: Bovine heart. Immunolabeling technique for neurofilaments (50x). Axons and ganglion cells are observed in the area marked by the circle. Chondroid tissue in the upper right region corresponding to the cardiac fulcrum (F).

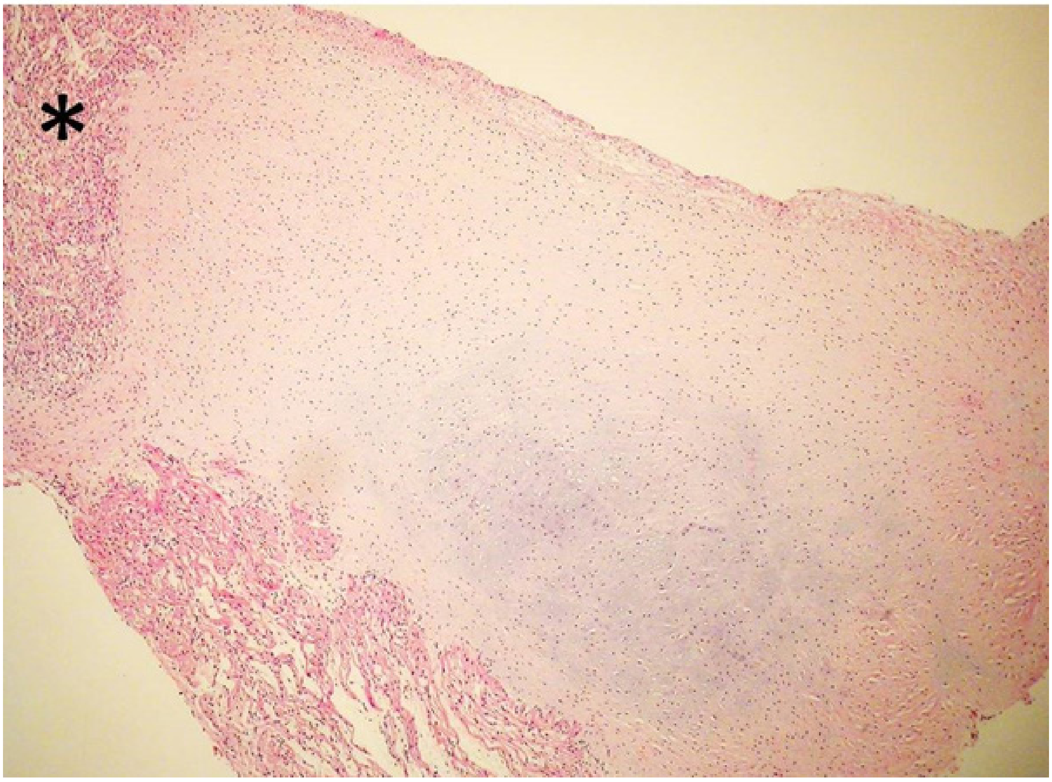

Figure 22: Cross-section of the cartilaginous *cardiac fulcrum* adjacent to the atrioventricular region (AV node marked with an asterisk). H&E x10.

The AV node has a compact portion and a marginal portion of transitional cells [9]. The transition zone is located between the wall of the right atrium and the AV node, acting as its "external" layer. The "compact" component has a semi-oval shape. The cells of the compact part of the node are smaller and tapered than the transitional cells. The latter are distributed parallel to each other and are surrounded by a greater amount of connective tissue. They are attributed the function of transmitting electrical information.

The spatial helical arrangement of the myocardium forces the muscle to overlap segments in its spatial conformation. This anatomical situation has a profound correspondence with myocardial movements and with the stimulation that runs through its segments, according to the electrophysiological studies we have performed [13-24]. The interpretation of the anatomical relationships between the cardiac fulcrum and the AV node implies the complementarity of the anatomy with the physiology of the continuous helical myocardium, since their contiguity is found at the site where stimulation begins and ends, with the production of the mechanical action of torsion and detorsion in the systolic and suction phases of the ventricles.

The cardiac fulcrum, support and insertion of the myocardium to exercise a lever function in its movements, is adjacent to the Aschoff-Tawara AV node. Thus, it constitutes an electromechanical unit located at the beginning and end of the continuous and helical myocardium, that is, at the fulcrum. This anatomical and functional arrangement of the myocardium is supported by a rich plexus of specialized filaments located inside the cardiac fulcrum that interact with the mechanical working cardiomyocytes [25].

This interpretation of the research findings in human, bovine and porcine hearts inevitably lead to therapeutic action [26]. What is the explanation in our experience for the better synchrony of pacemakers with the catheter placed in the vicinity of this electromechanical unit? [3]. The AV node is on the base of the muscular septum at the base of implantation of the septal leaflet of the tricuspid valve, in the site of insertion of the interventricular septum with the aorta and the pulmonary artery. In this aspect, the adjacency between the cardiac fulcrum and the beginning of the continuous myocardium in its helical trajectory, in relation to the AV node, demonstrated that stimulation in the right ventricular outflow tract was more effective. In this experience on pacemakers implanted in different points of the right ventricle (apex, para-Hisian, outflow tract), using standard active fixation catheters, the right ventricular outflow tract achieved better electrical synchrony in the left ventricle [3,27,28]. The ideal region for pacemaker pacing catheter placement would be high in the right ventricular outflow tract, below the pulmonary valve, and preferably on the septum, but not in the free wall.

Function leads the myocardium to have a point of support like any skeletal muscle both at its origin and at its end. If it did not have this spatial helical anatomical conformation, did not have an insertion at its ends located at the cardiac base and did not remain free at the apex, that is, pendular in the thorax; and furthermore, if it did not present a stimulation that allows its torsion and detorsion, it would not be able to fulfill its extraordinary muscular power.

The adjacency of the cardiac fulcrum to the AV node, surrounded by a rich plexus of neurofilaments (Figures 23, 24), puts us in the anatomical consideration of an electromechanical unit in which stimulation energy and muscular mechanics participate [29]. The effectiveness achieved with the placement of the pacing catheter in the vicinity of the right ventricular outflow tract validates the findings of this investigation.

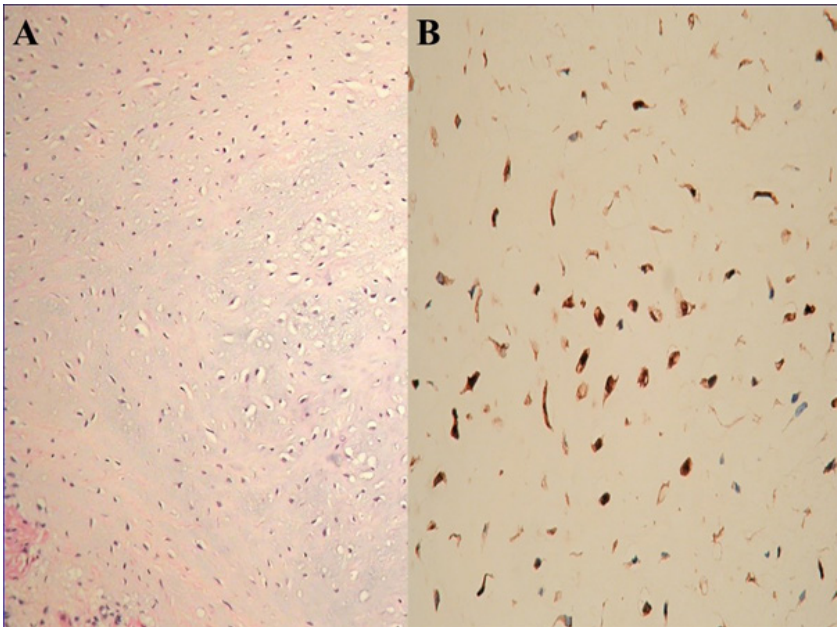

Figure 23: A 3-day-old premature neonate born at 27 weeks. Histological examination shows neurofilaments in the fulcrum adjacent to the atrioventricular node in A (A&E x 100). This finding is confirmed in B at higher magnification (H&E x 200) (immunohistochemistry with S-100).

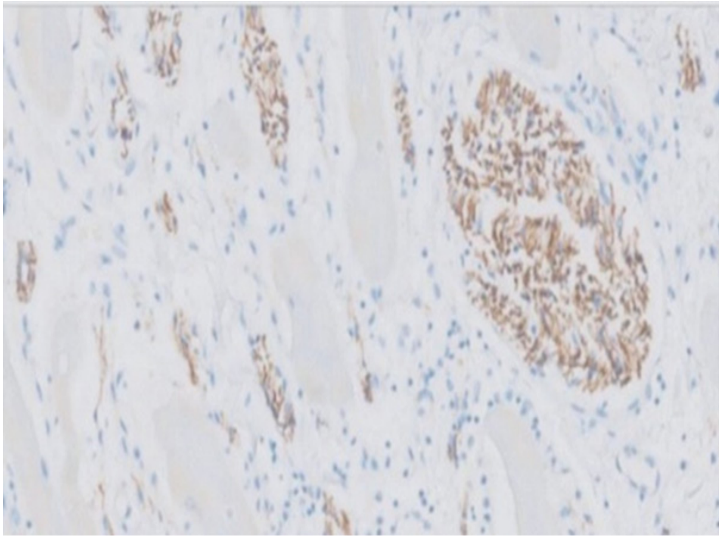

Figure 24: Porcine heart. Fulcrum-conduction cardiomyocytes at the fulcrum with nerve plexuses. Neurofilament stain (10x).

The interpretation we have is that the cardiac fulcrum of cartilaginous-osseous characteristic is a vestigial organ characteristic of the evolution of mammals. A vestigial structure should be understood as the retention during the process of evolution of genetically determined attributes that have lost part or all of their ancestral function in a given species [30]. Due to this fact we find it in the initial process of human gestation, but then its osteo-cartilaginous histology disappears, remaining as a tendinous matrix sufficient to achieve the insertion of the myocardium in order to comply with a muscular power far below that of larger mammals.

It should be remembered that in bovines the fulcrum is bony in nature. (Figure 25) shows a histological section of the fulcrum and its relationships in a porcine heart.

Innervation and Microvasculature. (Figure 26) details the concept of interrelated components between the AV node and the cardiac fulcrum.

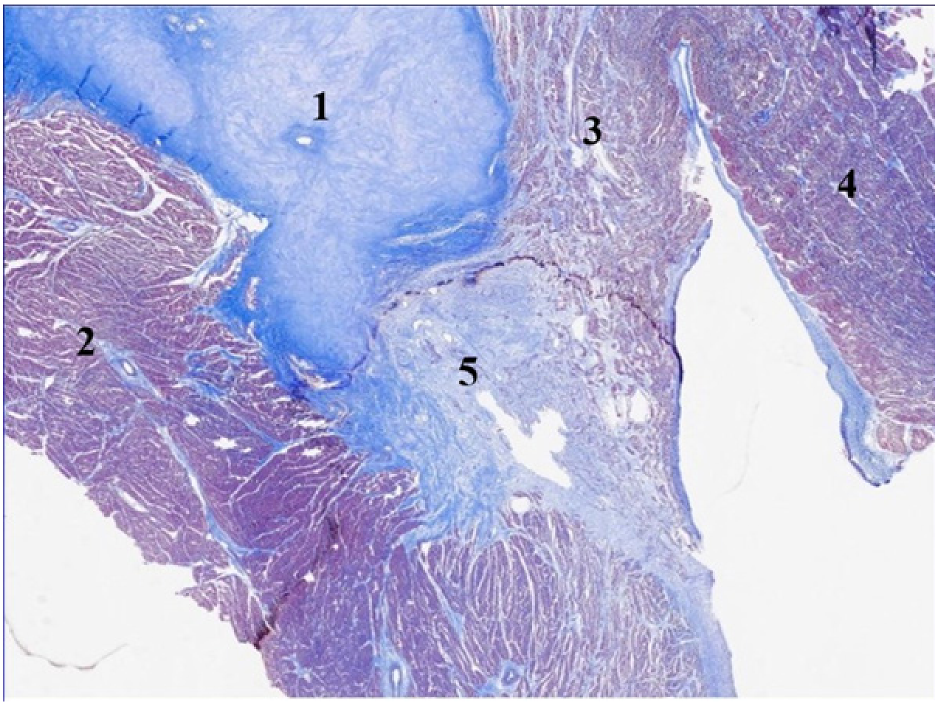

Figure 25: Porcine heart. Relationships of the *fulcrum*. 1: fulcrum; 2: ascending segment inserting into the left end of the fulcrum; 3: right loop segment; 4: interatrial septum; 5: AV node (cardiomyocytes of the right segment intermingle with the neurofilaments).

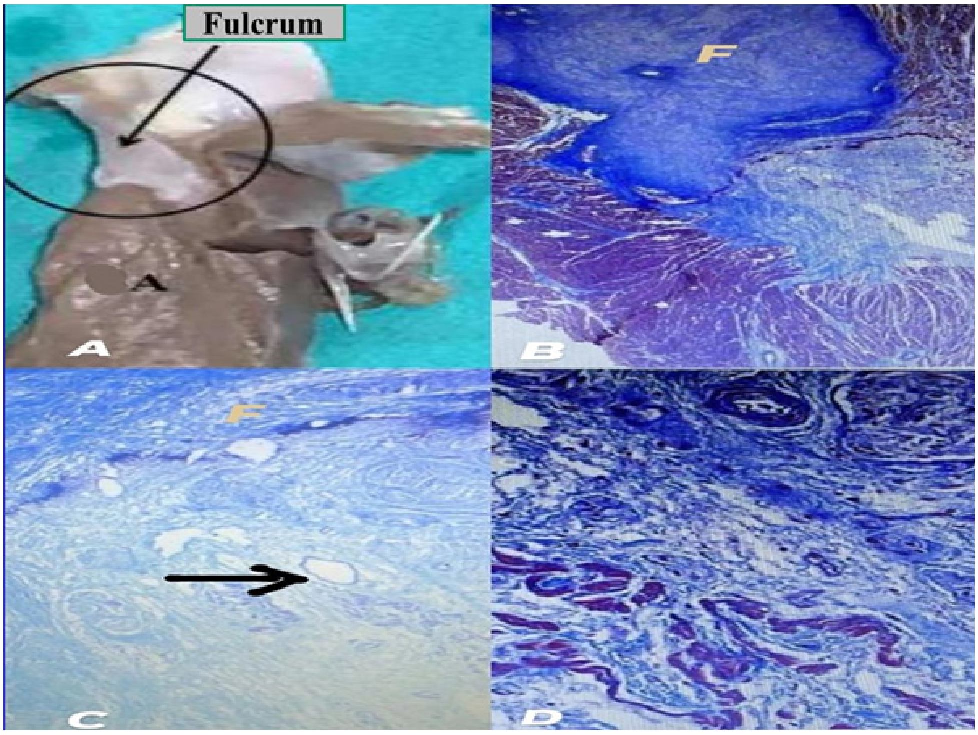

Figure 26: A: Fulcrum section (porcine heart). B: Histological section (without magnification) showing the terminal tongue of the right loop fraying and penetrating the atrioventricular node. The ascending loop is also observed fraying and entering the node. The atrioventricular node is in intimate contact with the left arch of the fulcrum (f), while the right arch shows insertion of ascending-loop cardiomyocytes. The interatrial groove and the floor of the left atrium are also visible. C. Atrioventricular node. Arrow points to vessels and Purkinje cells. D. Higher magnification (20×) showing Purkinje fibers in relation to nerve fascicles and ganglionic structures.

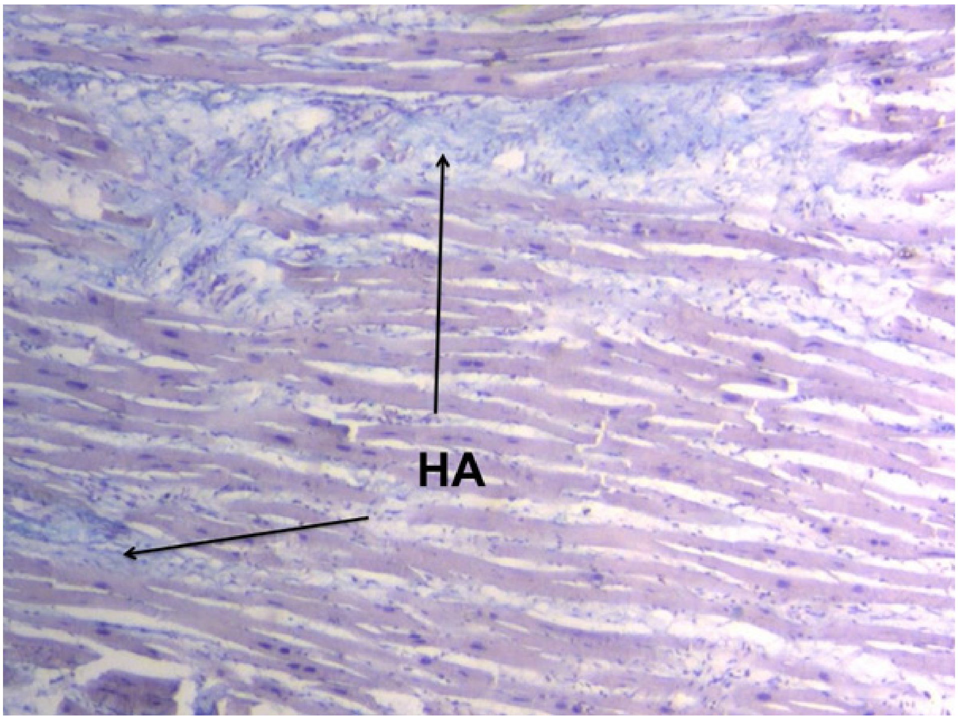

Figure 27: Interstitium between cardiomyocytes showing hyaluronic acid (HA) stained light blue with Alcian blue (15x) (adult human heart).

Discussion

We investigated the fulcrum and its relationship to cardiac innervation, respecting all anatomical relationships. These, are naturally altered during the unfolding of the heart, a fundamental aspect for understanding that the heart is a single muscular band arranged in a double helix. Furthermore, the study of the fulcrum revealed a rich innervation originating from the autonomic nervous system. Bovine, porcine, adult human, and human embryonic hearts were studied. Generally speaking, the fulcrum has two poles, left and right, and an intermediate arm approximately 3 cm long, depending on the species studied. The right pole inserts into the velamentous portion of the tricuspid valve, while its counterpart, the left pole, is in close contact with the atrioventricular node, as well as with the insertion of the ascending segment of the left ventricle.

In cattle, the fulcrum has a central zone composed of osteochondroid tissue. The right pole is hook-shaped, inserting into the tricuspid valve. The bovine fulcrum runs along the floor of the left atrium in its middle section. A muscular band is observed between the fulcrum and the floor of the left atrium. These relationships suggest two distinct functions: mechanical and electrical. Its central zone is approximately 3 cm long, acting as a lever arm.

Furthermore, we found a rich innervation that follows the blood vessels. This innervation belongs to the autonomic nervous system and reaches the heart through the adventitial layer of the superior and inferior vena cava and the coronary vessels; and the AV node via a loose connective tissue corridor bordering the adjacent surface between the ventricular septum and the AV node [31,32]. Therefore, all stimuli from the central nervous system are incorporated via the superior vena cava, while all stimuli from the gastrointestinal and urogenital systems are incorporated via the inferior vena cava. There is thus a somatic connection through the autonomic nervous system centered on the heart. We have observed that this innervation follows the course of the vessels and terminates in the atrioventricular node. Moreover, this node is in close contact with the fulcrum and is therefore affected by the pulsatile movement transmitted by its arm. Consequently, a pulsatile tilting motion is then transmitted to the fulcrum, which regulates and modulates the stimuli of the atrioventricular node.

It is worth now examining the histology of the atrioventricular node. The histology of the atrioventricular node shows a type of cell called Purkinje cells. They have a greater width, less transverse striation, and pronounced scalloping. These cells are arranged within a network of autonomic ganglia and nerve bundles that comprise the majority of the node. The distinct staining properties of these cells, as well as their marked scalloping, suggest an influence of the surrounding ganglion environment on their morphology. Furthermore, cardiac contractions and relaxations squeeze the hyaluronic acid-rich Thebesius-Langer vessels within the cardiomyocyte interstices, which act as a lubricant during the sequential movements of the myocardium (Figure 27).

In conclusion, the Fulcrum-Atrioventricular Node (AVN) complex acts as the unit of electromechanical self-organization of the cardiac system. The Fulcrum is not merely an inert anchoring point; Having a central section that acts as a lever and a pole in contact with the AV node, it transforms the mechanical movement of the heart (the contraction and torsion of the muscular band) into a signal that the fulcrum transforms into a pulsatile tilting movement. This suggests that the heart does not simply beat “blindly,” but rather that the fulcrum allows the AV node to “feel” the mechanical tension.

Conclusions

This work studies the fulcrum and its anatomical relationships. The final conclusion is that the fulcrum has a dual function. First, it provides support for the double helix that configures the anatomy of the heart, and second, it transmits signals, integrating with the atrioventricular node and the autonomic nervous system. Each heartbeat is then a result of a reading of fluctuations in an external and internal environment, which enters through the autonomic system to the AV node, which is almost like a second brain at the base of the heart, in sync with the Fulcrum that generates rhythmic feedback with coupling and decoupling similar to a self-organizing process.

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Conflict of Interest

None.

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