Title page:

The end of the unique myocardial band: Part I. Anatomical considerations

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Abstract

The concept of the “unique myocardial band”, which proposes that the ventricular myocardial cone is arranged like skeletal muscle, provides an attractive framework for understanding hemodynamics. The original idea was developed by Francisco Torrent-Guasp. Using boiled hearts and blunt dissection, he created a single band of ventricular myocardium extending from the pulmonary trunk to the aortic root, with the band thus constructed encircling both ventricular cavities. Cooked hearts can, however, be dissected many ways. In this review, we show the band does not exist as an anatomical entity with defined borders. On the contrary, the ventricular cardiomyocytes are aggregated end-to-end, and by their branching produce an intricate meshwork. Across the thickness of the left ventricular wall, the chains of cardiomyocytes exhibit a gradually changing helical angle, with a circumferential zone formed in the middle. There is no abrupt change in helical angle, as could be expected if the wall was constructed of opposing limbs of a single wrapped band. Nor does the long axis of the cardiomyocytes consistently match with the long axis of the unique myocardial band. There are, furthermore, no connective tissue structures which could be considered to demarcate its purported boundaries. The unique myocardial band should be consistent with evolution, and while the ventricular wall of fishes and reptiles have one or several distinct layers, a single band is not found. In 1965, Lev and Simpkins cautioned that the ventricular muscle mass of a cooked heart can be dissected almost at the whim of the anatomist. We suggest the unique myocardial band should have ended there.

Key words: Helical ventricular myocardial band;Helical heart;Ventricular anatomy;Cardiac CT;Histology;Echocardiography;Embryology;Comparative anatomy

Introduction

An accurate description of the architectural arrangement of the cardiomyocytes making up the walls of the left ventricle is fundamental to the understanding of myocardial function. Ventricular mural anatomy has been extensively studied over the last 400 years, but debate continues regarding the precise pattern of the architectural arrangement of the cardiomyocytes aggregated together within the walls. Amongst various models, an intriguing concept was introduced by Torrent-Guasp.[1] He postulated the existence of a "unique myocardial band", or "helical ventricular myocardial band", which was wrapped in such a way as to produce a "helical heart".[2] The concept has since been developed by some so as to provide explanations for many aspects of surgical cardiac disease,[3-5] even being cited recently to explain the actions of cardioplegia.[6] None of these multiple publications, however, including the initial studies of Torrent-Guasp, have been validated by histological studies. In contrast, there is a wealth of anatomical evidence, including multiple histological investigations, which demonstrates the cardiomyocytes to be aggregated together to form a three-dimensional mesh. This arrangement is much more complex than the structure envisaged by proponents of the "unique myocardial band". Here we review the anatomy of the ventricular mass so as to demonstrates the multiple shortcomings of the concept of a unique myocardial band. In an accompanying paper, we review several lines of evidence from physiology which, like the present paper, do not lend support for the notion of the unique myocardial band.

The beginning of the "unique myocardial band"

Based on gross dissections, Torrent-Guasp proposed that the walls of the right and left ventricles exist as a continuous myocardial band, which extends from the root of the pulmonary trunk to the root of the aorta.[1] The muscular band thus sculpted from the ventricular mass was held to form two loops, which surround the cavities of both right and left ventricles. The first, or basal, loop commences at the pulmonary valve, and consists of the right ventricular free wall. It leads to the outer layer of the left ventricular free wall, and thence on to to the right ventricular side of the ventricular septum. The band then continues as the second, or apical, loop, which has a descending segment comprising of the inner left ventricular free wall, and an ascending segment. The latter segment then forms

the sub-epicardial component of the apex and the rightward component of the ventricular septum, terminating at the aortic root. The cardiomyocytes aggregated together within the band were held to be aligned along its long axis, so that the ascending and descending segments crossed in approximately perpendicular fashion within the septum. Cleavage planes, or sliding surfaces between the segments, were alleged to exist, thus allowing the parts of the band to move across one another. The purported physiological consequences of this arrangement were subsequently described in numerous publications, [5, 6] including an account of cardiac development.[7]

The dissection process used to create the "unique myocardial band”"

Torrent-Guasp developed his technique of dissection over a period of 25 years.[1, 3] The hearts were boiled for a prolonged period, softening the myocardium so as to permit subsequent dissection.[6] The anterior free wall of the right ventricle, along the anterior interventricular groove, was prised off the ventricular septum, using the thumb to cut through the cardiomyocyte aggregates and connective tissues. The pulmonary trunk was thus detached from the root of the aorta, with the blunt dissection extended to the apex of the right ventricle to open the right ventricular cavity. At the inferior limit of the right ventricular cavity, at the junction of the right ventricular free wall and ventricular septum, the blunt dissection was continued into the mid zone of the left ventricular wall, and on towards the root of the aorta, thus exposing the inner helical zone. The left fibrous trigone was cut, permitting creation of a plane in the middle of ventricular septum. The dissection was continued between the inner and outer helical zones, followed by cutting the right fibrous trigone and freeing the aorta. Unfolding the dissection thus created an allegedly unique myocardial band, extending from the pulmonary trunk to the aortic root. This concept of a continuous myocardial band, with attachments at the arterial roots, is attractive, since it permits direct comparison with skeletal muscles, whose myocyte aggregates do indeed run between points of origin and insertion formed by connective tissue or bony structures. Most skeletal muscles, however, are enclosed in fibrous sheaths, thus permitting their dissection along identifiable boundaries. As has been emphasized previously,[7] this is not the case for the ventricular myocardial cone.

Histological and anatomical perspectives

The essence of skeletal muscles is that the extent of each entity can readily be revealed by anatomic dissection. None of the histological studies of the myocardium of which we are aware, in contrast, has provided any evidence for an origin and insertion as described for the alleged unique myocardial band. [8, 9] Already in 1864, Pettigrew had emphasised that the myocardial mass was not arranged like skeletal muscle, instead describing the arrangement of cardiomyocytes within the ventricles as aggregated to form multiple interleaving sheets.[10] Nearly 40 years later, Krehl showed how some of the cardiomyocytes were aligned in circumferential fashion within the middle zone of the left ventricular walls.[11] These histological findings were subsequently confirmed by Feneis, [8] and by Greenbaum and colleagues.[12] Dissection of the left ventricle shows the gradual transition in the myocardial grain between the inner, middle and outer zones (Figure 1).[13] Sanchez-Quintana and associates were able to show the presence of the circumferential cardiomyocytes in human hearts using anatomical dissection (Figure 2).[14] LeGrice and his associates subsequently showed how the cardiomyocytes themselves were aggregated together in sheet-like configurations.[15] These aggregated entities, or lamellar units, however, do not extend across the ventricular wall, as was suggested by the diagrammatic depiction originally provided by LeGrice and his colleagues [15]. Instead, the aggregated cardiomyocytes throughout the ventricular walls are bound together both by their meshed branching, and by the endomysial component of the fibrous matrix, being separated by spaces containing loose perimysial tissue, arteries and veins.[16] This arrangement, validated by histology, is incompatible with the concept of the “unique myocardial band”. The intercellular spaces and myocytic branches are ubiquitous within the walls, failing to provide the boundaries needed to produce an anatomically discrete myocardial band.

Although providing no evidence to validate the notion of the unique myocardial band, the histological evidence does support the presence of helically arranged chains of aggregated cardiomyocytes. Indeed, a well-recognised study had long since demonstrated the progression of such helical angulations when traced through the thickness of the left ventricular walls.[17] The arrangement is that of a left-handed outer helix, with negative angulation relative to the ventricular equator, progressing through a region of zero

angulation at the midwall, and continuing as a right-handed helix, with positive angulation, towards the inner endocardial ventricular surface.[17] This gradual change in helical angulation exists in all the regions of the ventricular walls, including the ventricular septum.[17] In the initial study [17], all the cardiomyocytes, despite their change in helical angulation, were reported to be aligned in more-or-less tangential fashion when assessed relative to the epicardial ventricular surface. Subsequent histological investigations, which used circular knives to cut tissue blocks from the ventricular walls, thereby cancelling the effect of the helical angle on the orientation of the cardiomyocytes within the sections transferred to the microscope slides, revealed that significant numbers of cardiomyocytes deviated from the tangential plane.[18, 19] Investigations using pneumatic dissection of the ventricular walls [20] then showed how it was possible to disrupt the weaker perimysial component of the fibrous matrix. These manoeuvres confirmed that the cardiomyocytes were aggregated together to form an intricate three-dimensional meshwork. Histological findings, therefore, provide further evidence of a complex mural ventricular structure (Figure 3). None of these investigations has provided any evidence of an alignment of the cardiomyocytes that follows the course of the unique myocardial band. All of the studies, in contrast, have shown a relatively uniform pattern of aggregation throughout the ventricular circumference.[8] The only study of which we are aware to have produced the band by following the directions of Torrent-Guasp,[1] [2] and then sectioning it histologically, failed to find correlation between the long axes of the band and its contained cardiomyocytes.[21]

High resolution computer tomography

Recent advances in microcomputed tomography, using iodine enhancement of myocytic and vascular structures, have provided images of sufficient spatial resolution to reveal the alignment (Figure 4) and dimensions of the chains of individual cardiomyocytes (Figure 5), along with the pattern of the units produced in consequence of their aggregation within the endomysial weave of the supporting fibrous matrix.[16, 22, 23] ~~(Figure 5)~~. ~~They~~ The CT images (Figure 5) confirm the presence of the chevron-like configurations revealed histologically (Figure 3), which exist within the setting of a relatively smooth helical transmural arrangement (Figure ~~3,~~4 &~~,~~5). ~~They~~ These images fail to reveal the abrupt

changes in angulation at the midwall that would be expected were the ventricular cone based on the postulated wrapped myocardial band (Figure 4 & 5). Instead, they support the notion of the complex mural mesh, with units exhibiting both helical and transmural angles, complex heterogeneous morphologies, and multiple connections to adjacent units via myocytic chains ~~(Figure 4)~~.[16]

Embryological perspective

The ontogenetic development of the human heart is complicated. In a review that sought to correlate development with the notion of the helical heart, we were asked to envisage that "a simple and integrated triple figure-eight spiral band, with three S-shaped helixes and their apices may correlate the conventional embryologic development of the primitive heart (bulbus cordis, ventricle, and arterial outflow vessels)".[7] Much has been learned regarding cardiac development since the publication of this review. We now know that the original linear heart tube forms little more than the definitive left ventricle.[24] New material is added at the arterial pole from the heart-forming areas to form the right ventricle and the outflow tract. Similar new growth at the venous pole produces the atrial chambers and the veno-atrial connections.[25] In terms of development of the ventricular mass, initially the walls are made up predominantly of a meshwork of luminal trabeculations, with minimal formation of a compact layer. At the early stages of development, subsequent to looping of the heart tube, the atrial chambers connect to the developing left ventricle, while the outflow tract is supported above the developing right ventricle. Rightward expansion of the atrioventricular canal then brings the right atrial cavity into communication with the cavity of the right ventricle.[26] After this process, which occurs during the twelfth day of development in the mouse, the developing outflow tract, which is beginning its separation into the aortic and pulmonary roots, remains supported by the developing right ventricle, The left ventricle at this stage, therefore, connects to the developing aortic root through the embryonic interventricular communication. It is only subsequent to transfer of the aortic root to the left ventricle that there is closure of the interventricular communication. Even at this stage, which has occurred by the fourteenth day of murine development, there has been minimal growth of the compact layers of the ventricular walls. The rate of proliferation of the compact myocardium, and the compact component of the ventricular septum, is

known at this stage to exceed that of the trabeculated myocardium.[27, 28] Beginning at this stage, it is then possible to recognise the aggregation of the individual cardiomyocytes into units of various shapes and dimensions, with the units separated by perimysial spaces throughout the circumference of the walls. When assessed in long axis, many of the units show the sheet-like configuration emphasised by LeGrice and his colleagues, although none of the aggregated units extend in full transmural fashion (Figure 6A). When assessed relative to the short axis of the ventricular cone, the aggregates show an obvious circumferential arrangement in the middle component of the wall, with the parietal left ventricular aggregates extending into the ventricular septum (Figure 6B). The perimysial spaces are not positioned in such a way as to permit unwrapping of the alleged myocardial band. On the contrary, the overall arrangement of the walls is very much that of a complex three-dimensional mesh. Molecular identification of the compact wall and ventricular septum, besides being possible using proliferation markers, can also be made based on expression of *Hey2* and *N-myc*.[29] *CHF1*/*Hey2* plays a pivotal role in left ventricular maturation through suppression of ectopic atrial gene expression.[29, 30] Neither of these genes, nor indications of proliferation by *Brdu* incorporation or expression of *Ki-67* and *PCNA,*[25, 30, 31] give any indication of distinct bands in the compact wall compatible with the postulated helical heart. A recent developmental study, furthermore, suggested the anterior ventricular septum to be formed from a merger between the embryonic left ventricle and the outflow tract.[32] This arrangement provides no support for the opening of the ventricular wall in the manner of Torrent-Guasp.

Comparative anatomical perspective

It has been suggested that the unique myocardial band is compatible with the overall trends of evolution of the heart.[7] Mammals evolved from ectothermic (cold-blooded) vertebrates, but the orientation of cardiomyocytes in these species has received limited attention.[33, 34] We do know that, in some fishes and most amphibians, the compact wall may be so thin that the epicardium almost touches the ventricular lumen. In this setting, the compact wall consists of one layer only (Figure 7). In some highly active animals, like tuna fish, in contrast, the compact wall is well developed, and may consist of two or three layers. The number of layers generally appears to increase with the width of the compact wall.[35]

At least in fish, the cardiomyocytes of the distinct compact layers may be at almost right angles to each other.[10, 36, 37] and the different myocardial layers may be so distinct that they are easily separated[35, 38, 39] In fishes, nonetheless, we have never observed findings to support the concept of a myocardial band that connects the atrioventricular orifice with the conoventricular, or bulboventicular, orifice. Reptiles, which may be considered to represent the ancestral state of mammals and birds, have a variable number of compact layers, like in fishes, but generally there are 2 or 3 layers[37, 40-42] The innermost layer is the interface between the compact wall and the trabeculated, or spongy, interior wall. It is the thinnest of the compact layers when there is a sizable compact wall. [41, 42] The ventricular compact wall of many reptile species have two zones, distinguished by the orientation of the cardiomyocytes. The smooth progression of the helical angle within the depth of the ventricular walls (Figures 1,4,5), in contrast, is a feature of all mammalian species studied to date, regardless of their size, which suggests a common geometric environment for the cardiomyocyte. This is because the geometric interplay between the inner and outer surfaces of the left ventricle, with mural thickening, is an expression of the ratio of wall thickness to chamber size, and not their absolute dimensions.[13] The ventricular wall of ectothermic vertebrates may have substantial deviations from the architectural arrangement of two distinct layers. Many species, however, do have a bi-layered compact wall, but the two layers appear largely distinct, not unlike a Russian Matryoshka nesting doll (Figure 7). Unwinding such layers would produce an outer and an inner shell, not a single band. It follows that the “aberrant fibers” that are initially disrupted in the unwinding of Torrent-Guasp, are in fact an evolutionarily old part of the ventricle (Figure 7). We propose the “aberrant fibers” is a spurious concept and the disruption of such commonly found circumferential compact myocardium immediately invalidates the significance of unwinding of the heart.

Congenital heart disease perspective

There are multiple congenital lesions that point to the lack of credibility of a concept depending on the presence of a unique myocardial band extending from the pulmonary to the aortic roots, and encircling both ventricular cavities. In the first instance, it is difficult to envisage how such a concept would be compatible with the development of a heart having

double inlet to, and double outlet from, the right ventricle. In this setting, the left ventricle is no more than a hypoplastic apical component. It is equally difficult to envisage how the notion of a band extending from the pulmonary to the aortic roots would be compatible with the presence of a common arterial trunk. It is similarly difficult to explain hearts having either aortic or pulmonary atresia, not to mention the fact that, in Ebstein's malformation, the location of the alleged passage of the myocardial band from the right to the left ventricle inferiorly can be paper-thin due to atrialisation of the inlet component of the right ventricle. The presence of a myocardial band should have important implications for the development of congenital heart disease. We are unable to find any such evidence. Dissections performed in congenitally malformed hearts also confirm the presence of the cardiomyocytes aligned in circumferential fashion, a feature denied by some of the proponents of the band.[43] The circumferential cardiomyocytes, furthermore, were present in the hypertrophied walls of the right ventricle in a heart obtained from a patient with tetralogy of Fallot (Figure 8).

Current understanding of myocardial structure

The wealth of data available from the techniques and approaches discussed above shows that the myocardial walls are made up of cardiomyocytes aggregated together to produce a three-dimensional meshwork of interconnected units. The average orientation of cardiomyocytes show a gradual change in their helical angulation, with a middle component having approximately zero angulation relative to the ventricular equator. There are no gaps in the assembly of the units that would permit a dissector to begin to reveal the presence of a unique myocardial band. Nor are there planes of cleavage that would permit the tracing of such a band from the pulmonary trunk to the aortic root, particularly when note is taken that the outer wall of the left ventricle is held, by proponents of the band, to contribute to both its basal and apical loops. Lev and Simpkins had already emphasized, in 1965, that under the conditions employed by Torrent-Guasp, the ventricular muscle mass can be dissected almost at the whim of the anatomist.[44] We do not deny that, with skill and practise, it is possible to unravel the heart to produce a continuous myocardial band. Indeed, it is now possible to observe Torrent-Guasp producing the strip on an online video.[2] The important question is whether Torrent-Guasp is producing the band according

to his own pre-conceived notions, or on the basis of the accepted techniques for anatomic dissection. When analysing the arrangement of adjacent skeletal muscles, relatively uniform dissections are produced simply by delimiting the boundaries of the individual muscles, with the skeletal myocytes aggregated together within epimysial sheets. Such an approach is not possible when considering the ventricular cone, since the cardiomyocytes within the ventricular walls are aggregated together by the endomysial components of the fibrous matrix, and by their own branched connections via the intercalated discs. The aggregated units themselves are separated by perimysial spaces, with the overall walls enclosed between the epicardial and endocardial boundaries. There are no obvious planes of cleavage that permit delimitation of anatomically defined tracts or subunits within the walls. Observation of the approach taken by Torrent-Guasp reveals that his initial separation of the right ventricle tears away its parietal wall from the ventricular septum, disrupting what are described as “aberrant fibres” (Figure 3).[2] They are, of course, only aberrant according to the preconception of the band. In reality, these cardiomyocytes can be shown, by following the grain produced by the aggregated chains, to form a myocardial component common to both ventricles.[12, 14] Having reached the inferior interventricular groove, Torrent-Guasp then alleges to show loops of the band that encircle the left ventricle. The plane developed by Torrent-Guasp is within the aggregated cardiomyocytes that surround the cavity of the left ventricle in circumferential fashion. Such circular cardiomyocytes, denied by current proponents of the band, are well demonstrated by dissections made following the overall alignment of the aggregated units (Figure 1). Detailed anatomical analysis, therefore, using all available techniques, contradicts the hypothesis of the band.

Conclusions

There is extensive experimental evidence to show that the ventricular walls are made up of an intricate three-dimensional network of aggregated cardiomyocytes. Apart from the questionable blunt dissections performed by Torrent-Guasp, there are no direct or indirect observational data to support the concept of a compartmentalised ventricular myocardial band that extends from the pulmonary trunk to the aorta (see on-line supplement- Table). We submit that the notion of a unique myocardial band is anatomically spurious. Taken with our second review,[45] we conclude that the value of the band as an explanation of

ventricular structure, function and cardiac pathophysiology has come to an end.

Figures:

Figure 1. Macroscopic anatomy of the porcine heart

Blunt dissection of the heart shows the gradual transition of the helical angle of the inner, midwall and outer zones (black lines) compared with the long axis (red line). Figure kindly provided by Prof PP Lunkenheimer.

Figure 2. Macroscopic anatomy of the human heart

As seen in Panel A, the dissection of a human heart reveals that the cardiomyocytes of the superficial layer are common for both ventricles, descending obliquely on the sternocostal and diaphragmatic aspects to the apex, crossing the interventricular grooves. The course of the cardiomyocytes around the right ventricle is more circumferential than in the left ventricle. Panel B shows that the grain of the middle layers of both the right and left ventricle are orientated in a second direction.

Figure 3. Microscopic anatomy of the human heart

Cross-section of human heart at the equator stained using Masson's trichrome technique. The dashed arrow indicates the region where the dissection as performed by Torrent-Guasp damages cardiomyocytes whilst entering the right ventricle. The solid arrow shows the disruption required within the mid-zone of the circumferentially orientated cells. The presence of aggregated units is evident, forming chevron-like structures around most of the ventricular circumference.

Figure 4. Eigen analysis of the human heart using microcomputed tomography

Angle maps are viewed in short axis and colour bars indicate cardiomyocyte helical angulation. Note the cardiomyocytes with a helical angle close to zero (blue) encircling the entire circumference of the mid-ventricular wall.

Figure 5. Transmural tangential reconstructions using high resolution microcomputed tomography

Figure 5 shows cardiomyocyte aggregates in the subepicardial (1), outer (2-4), midwall (5-7), inner (8-9) and sub endocardial zones (10) from a rabbit heart. Similar transitions are seen around full circumference of the left ventricle. Note a gradual transition in angulation that is not compatible with a concept of the "unique myocardial band". Spatial resolution ~6µm.

Figure 6. Embryological findings

Figure 6A shows a hematoxylin-eosin staining cross-section in a human fetus of 20 weeks of development. Note the changing orientation from radial lamellae to circular orientation, with formation of chevrons. There is no evidence of the "edges" that would be required to support the notion that the walls are made up of a wrapped band, nor evidence of fibrous partitions separating the components of the alleged band. A short axis map of the helical orientation of the cardiomyocytes using DTMRI in a human heart at 24 weeks of gestation is shown (6B). Colour coding indicates helical angle, such that blue indicates circumferentially orientated cardiomyocytes.

Figure 7. Comparative anatomy.

Ventricular architecture in a frog and a snake illustrated by 10µm thick transverse sections stained with picro-sirius red. The (contracted) ventricle of the *Xenopus* frog exemplifies the highly trabeculated found in many fishes and amphibians. The arrows show three pathways were no myocardium was crossed and by which the extremely thin outer compact layer can be reached from the central lumen. Distinct layers to the compact wall is not recognized in such settings, and even if they were, the functional implications would be proportional the mass of the layers, that is miniscule. The ventricle of pythons has a high-pressure left

ventricle (LV) and a low-pressure right ventricle (RV) surrounded by two distinct layers of compact myocardium (This ventricle was fixed in diastole). Where the dashed arrow is placed (as in Figure 2), much of the compact wall is made up of approximately circumferential oriented myocardium. The presence of this myocardium suggests an old evolutionary origin to the so-called "aberrant fibers" that has to be disrupted initially in the Torrent-Guasp procedure. We propose "aberrant fibers" is a spurious concept and further propose the disruption of such commonly found circumferential compact myocardium immediately invalidates the significance of unwinding of the heart.

Figure 8. Ventricular architecture in tetralogy of Fallot.

The dissection reveals the macroscopic features in the setting of tetralogy of Fallot, showing a middle layer with a circumferential orientation in the right ventricle (arrow). The presence of circumferential cardiomyocytes in a direction perpendicular to the direction of the 'basal loop' is incompatible with the concept of a "unique myocardial band".

References

[1] Torrent-Guasp F. *Anatomia Funciónal del Corazón. La actividad ventricular diastólica y sistólica*. Madrid: Madrid, 1957.

[2] Buckberg GD. *The Helical Heart.* http://www.helicalheart.com/ (Accessed 04/02/17 date last accessed).

[3] Torrent-Guasp F, Kocica MJ, Corno AF, Komeda M, Carreras-Costa F, Flotats A *et al. Towards new understanding of the heart structure and function*. Eur J Cardiothorac Surg 2005;**27**:191-201.

[4] Buckberg GD, Hoffman JI, Coghlan HC, Nanda NC. *Ventricular structure-function relations in health and disease: Part I. The normal heart*. Eur J Cardiothorac Surg 2015;**47**:587-601.

[5] Buckberg GD, Hoffman JI, Coghlan HC, Nanda NC. *Ventricular structure-function relations in health and disease: part II. Clinical considerations*. Eur J Cardiothorac Surg 2015;**47**:778-87.

[6] Torrent-Guasp F, Ballester M, Buckberg GD, Carreras F, Flotats A, Carrio I *et al. Spatial orientation of the ventricular muscle band: physiologic contribution and surgical implications*. J Thorac Cardiovasc Surg 2001;**122**:389-92.

[7] Buckberg GD. *The Structure and Function of the Helical Heart and Its Buttress Wrapping. II. Interface Between Unfolded Myocardial Band and Evolution of Primitive Heart*. Semin Thorac Cardiovasc Surg 2001;**13**:320-32.

[8] Feneis H. *Das gefüge des herzmuskels bei systole und diastole*. Morphologisches Jahrbuch 1943;**89**:371-406.

[9] Hort W. *[Macroscopic and micrometric research on the myocardium of the left ventricle filled to varying degrees]*. Virchows Arch Pathol Anat Physiol Klin Med 1960;**333**:523-64.

[10] Pettigrew JB. *On the arrangement of the muscular fibres in the ventricles of the vertebrate heart, with physiological remarks*. Philosophical Transactions of the Royal Society of London 1864;**154**:445-500.

[11] Krehl L. *Kenntniss der Fallung und Entleerung des Herzens*. Abhandl Math Phys Kl Koniglichen Saechs Ges Wiss 29: 341 1891;**362**.
[12] Greenbaum RA, Ho SY, Gibson DG, Becker AE, Anderson RH. *Left ventricular fibre architecture in man*. Br Heart J 1981;**45**:248-63.
[13] Partridge JB, Smerup MH, Petersen SE, Niederer PF, Anderson RH. *Linking left ventricular function and mural architecture: what does the clinician need to know?* Heart 2014;**100**:1289-98.
[14] Sanchez-Quintana D, Garcia-Martinez V, Hurle JM. *Myocardial fiber architecture in the human heart. Anatomical demonstration of modifications in the normal pattern of ventricular fiber architecture in a malformed adult specimen*. Acta Anat (Basel) 1990;**138**:352-8.
[15] LeGrice IJ, Smaill BH, Chai LZ, Edgar SG, Gavin JB, Hunter PJ. *Laminar structure of the heart: ventricular myocyte arrangement and connective tissue architecture in the dog*. Am J Physiol 1995;**269**:H571-82.
[16] Stephenson RS, Agger P, Lunkenheimer PP, Zhao J, Smerup M, Niederer P *et al. The functional architecture of skeletal compared to cardiac musculature: Myocyte orientation, lamellar unit morphology, and the helical ventricular myocardial band*. Clin Anat 2016;**29**:316-32.
[17] Streeter DD, Jr., Spotnitz HM, Patel DP, Ross J, Jr., Sonnenblick EH. *Fiber orientation in the canine left ventricle during diastole and systole*. Circ Res 1969;**24**:339-47.
[18] Lunkenheimer PP, Redmann K, Westermann P, Rothaus K, Cryer CW, Niederer P *et al. The myocardium and its fibrous matrix working in concert as a spatially netted mesh: a critical review of the purported tertiary structure of the ventricular mass*. Eur J Cardiothorac Surg 2006;**29**:S41-S49.
[19] Lunkenheimer PP, Redmann K, Kling N, Jiang X, Rothaus K, Cryer CW *et al. Three-dimensional architecture of the left ventricular myocardium*. Anat Rec A Discov Mol Cell Evol Biol 2006;**288**:565-78.
[20] Lunkenheimer PP, Niederer P. *Hierarchy and inhomogeneity in the systematic structure of the mammalian myocardium: towards a comprehensive view of cardiodynamics*. Technol Health Care 2012;**20**:423-34.
[21] Anderson RH, Sanchez-Quintana D, Redmann K, Lunkenheimer PP. *How are the Myocytes Aggregated so as to Make up the Ventricular Mass?* Seminars in thoracic and cardiovascular surgery: Pediatric cardiac surgery annual 2007;**10**:76-86.
[22] Stephenson RS, Boyett MR, Hart G, Nikolaidou T, Cai X, Corno AF *et al. Contrast enhanced micro-computed tomography resolves the 3-dimensional morphology of the cardiac conduction system in mammalian hearts*. PLoS One 2012;**7**:e35299.
[23] Agger P, Stephenson RS, Dobrzynski H, Atkinson A, Iaizzo PA, Anderson RH *et al. Insights from echocardiography, magnetic resonance imaging, and microcomputed tomography relative to the mid-myocardial left ventricular echogenic zone*. Echocardiography 2016;**33**:1546-56.
[24] Kelly RG, Buckingham ME, Moorman AF. *Heart fields and cardiac morphogenesis*. Cold Spring Harb Perspect Med 2014;**4**:a015750.
[25] Sizarov A, Ya J, de Boer BA, Lamers WH, Christoffels VM, Moorman AF. *Formation of the building plan of the human heart: morphogenesis, growth, and differentiation*. Circulation 2011;**123**:1125-35.
[26] Jensen B, Moorman AF. Evolutionary aspects of cardiac development. *Congenital Heart Diseases: The Broken Heart*: Springer, 2016:109-17.
[27] Sedmera D, Reckova M, DeAlmeida A, Coppen SR, Kubalak SW, Gourdie RG *et al. Spatiotemporal pattern of commitment to slowed proliferation in the embryonic mouse heart indicates progressive differentiation of the cardiac conduction system*. Anat Rec A Discov Mol Cell Evol Biol 2003;**274**:773-7.
[28] de Boer BA, van den Berg G, de Boer PA, Moorman AF, Ruijter JM. *Growth of the developing mouse heart: an interactive qualitative and quantitative 3D atlas*. Dev Biol 2012;**368**:203-13.
[29] Koibuchi N, Chin MT. *CHF1/Hey2 plays a pivotal role in left ventricular maturation through suppression of ectopic atrial gene expression*. Circ Res 2007;**100**:850-55.

[30] Luxan G, Casanova JC, Martinez-Poveda B, Prados B, D'Amato G, MacGrogan D *et al. Mutations in the NOTCH pathway regulator MIB1 cause left ventricular noncompaction cardiomyopathy*. Nat Med 2013;**19**:193-201.
[31] Zebrowski DC, Becker R, Engel FB. *Towards regenerating the mammalian heart: challenges in evaluating experimentally induced adult mammalian cardiomyocyte proliferation*. Am J Physiol Heart Circ Physiol 2016;**310**:H1045-54.
[32] Poelmann RE, Gittenberger-de Groot AC, Vicente-Steijn R, Wisse LJ, Bartelings MM, Everts S *et al. Evolution and development of ventricular septation in the amniote heart*. PLoS One 2014;**9**:e106569.
[33] Sanchez-Quintana D, García-Martínez V, Climent V, Hurlé J. *Myocardial fiber and connective tissue architecture in the fish heart ventricle*. J Exp Zool 1996;**275**:112-24.
[34] Jensen B, Moorman AF, Wang T. *Structure and function of the hearts of lizards and snakes*. Biol Rev Camb Philos Soc 2014;**89**:302-36.
[35] Sanchez-Quintana D, Hurle JM. *Ventricular myocardial architecture in marine fishes*. Anat Rec 1987;**217**:263-73.
[36] Shaner RF. *On the Muscular Architecture of the Vertebrate Ventricle*. J Anat 1923;**58**:59-70.
[37] Bolk L, Göppert E, Kallius E, Lubosch W. *Handbuch der vergleichenden Anatomie der Wirbeltiere*. Urban & Schwarzenberg, 1933.
[38] Farrell A, Simonot D, Seymour R, Clark T. *A novel technique for estimating the compact myocardium in fishes reveals surprising results for an athletic air-breathing fish, the Pacific tarpon*. J Fish Biol 2007;**71**:389-98.
[39] Pieperhoff S, Bennett W, Farrell AP. *The intercellular organization of the two muscular systems in the adult salmonid heart, the compact and the spongy myocardium*. J Anat 2009;**215**:536-47.
[40] Kashyap H. *Muscular architecture of the ophidian ventricle*. J Herpetol 1975:93-102.
[41] Jensen B, Abe AS, Andrade DV, Nyengaard JR, Wang T. *The heart of the South American rattlesnake, Crotalus durissus*. J Morphol 2010;**271**:1066-77.
[42] Jensen B, Nyengaard JR, Pedersen M, Wang T. *Anatomy of the python heart*. Anat Sci Int 2010;**85**:194-203.
[43] Sanchez-Quintana D, Anderson RH, Ho SY. *Ventricular myoarchitecture in tetralogy of Fallot*. Heart 1996;**76**:280-6.
[44] Lev M, Simkins CS. *Architecture of the human ventricular myocardium; technic for study using a modification of the Mall-MacCallum method*. Lab Invest 1956;**5**:396-409.
[45] MacIver DH, Partridge J, Agger P, Stephenson RS, Boukens BJ, Omman C *et al. The end of the unique myocardial band. Part II Clinical and functional considerations* European Journal of Cardiothoracic Surgery 2018;**Submitted.**