THE HELICAL VENTRICULAR MYOCARDIAL BAND OF TORRENT-GUASP

GLOBAL, THREE-DIMENSIONAL, FUNCTIONAL ARCHITECTURE OF THE VENTRICULAR MYOCARDIUM

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Anatome and Anatomia: *the words signify as much as a dissection. But being taken for an art and applied to a certain object, they signify an artificia dissection of that object in such manner as may most conduce to the perfect knowledge of the same and all its parts... Now this artificial dissection implies not the manual dissection only, but in especial manner the mental. For though the manual dissection be first in regard it leads us to the mental, yet the mental is that which mainly denominates the artist an Anatomist, and hath use in living as well as dead bodies; and nobody desires the manual dissectior of dead bodies but in order to the living, that so by mental assignation of the parts he may give an account of them in the living as well as the dead... The end of artificial dissection is not to mangle and cut the object it takes in hand rudely into shreds, but to gain the perfect knowledge of the same and all its parts thereby[1].*

Francis Glisson - English physician and anatomist.
(Glisson drew up this definition to introduce a series of public anatomies he gave in 1641 at the College of Physicians of London.)

Summary

We are currently witnessing the advent of a new diagnostic tools and therapies for heart diseases, but, without serious scientific consensus on fundamental questions about normal and diseased heart structure and function. During the last decade, three successive, international, multidisciplinary symposia were organized in order to set up fundamental research principles, which would allow us to make a significan step forward in understanding heart structure and function.

Helical ventricular myocardial band of Torrent-Guasp is the revolutionary new concept in understanding global, three-dimensional, functional architecture of the ventricular myocardium. This concept defines the principal, cumulative vectors, integrating the tissue architecture (i.e. form) and net forces developed (i.e. function) within the ventricular mass.

Here we expose the compendium of Torrent-Guasp's half-century long functional anatomical investigations in a light of ongoing efforts to define the integrative approach, which would lead to new understanding of the ventricular form and function by linking across multiple scales of biological organization, as defined in ongoing Physiome Project. Helical ventricular myocardial band of Torrent-Guasp may also, hopefully, allow overcoming some difficulties encountered in contemporary efforts to create a comprehensive mathematical model of the heart.

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1. Introduction

Ever since Danish anatomist, Nicolaus Steno (Niels Stensen, 1638-1686), settled the muscular nature of the heart, by vivisecting cold-blooded animals in 1663[2], the architecture of the ventricular myocardium became a fascination for the generations of investigators. Apart from many other features, almost all historical predecessors in a field (Figure 1), from Richard Lower (1631-1691) onward, have recognized helical, transmural, overlapping pattern of the ventricular myocardial fibers[3-22]. Unresolved problem was to reveal unique rule-based assignment which, as Franklin Paine Mall (1862-1917) urged, *"may be applied equally well to all the ventricular myocardia fibers, showing them joined together in a coherent, common general architectural plan."*[21] This task was considered as the ultimate missing link between the ventricular form and function. But, since it was *"easy to observe and difficult to comprehend"*, as claimed James Bell Pettigrew (1834-1908), the global arrangement of ventricular myocardial fibers remained the *"Gordian Knot"* of heart anatomy for almost five centuries[22].



Figure 1 – Illustrated historical timetable of the mayor contributions in understanding the ventricular myocardial architecture.

Indeed, ventricular myocardium has proven remarkably resistant to macroscopic analyses of functional anatomy. Pronounced and practically indefinite global and local structural anisotropy of its fibers and other ventricular wall constituents, produces electrical and mechanical properties that are nonlinear, anisotropic, time varying, and spatially inhomogeneous[4-13, 23,24].



Figure 2 – Francisco (Paco) Torrent-Guasp (1931-2005), the "father" of the HVMB concept.

Spanish scientist, ***Francisco (Paco) Torrent-Guasp (1931-2005)*** (Figure 2), unlike Alexander the Great, has invested half century of his life in painstaking and meticulous research, before he was able to dissect the heart in a manner advocated by Glisson (in the preamble of this article) and unravel this "Gordian Knot" [see Appendix 1: Francisco Torrent-Guasp's bibliography]. Helical ventricular myocardial band (HVMB) of Torrent-Guasp - ***"Torrent-Guasp's Heart"*** - is revolutionary new concept, which provides important and firm ground for reconciliation of some exceeded concepts in cardiovascular medicine. Developed "on the giant's shoulders", this concept is dazzling with unique intrinsic ingenuity (so specific for the great minds), appearing "exceedingly simple in principle but wonderfully complicated in detail"[22].

We live in the era of substantial progress in understanding myocardial structure and function at the genetic, molecular and microscopic levels (Figure 3). This rapid accumulation of knowledge has imposed a paradigm shift, necessitating integration and linking across multiple scales of biological organization - from proteins to cells, tissues, organs and organ systems - in order to understand a complexity of interactions between form and function, generating a specific behavior (normal or abnormal) in the biological system[23-26]. Accordingly the global three-dimensional model of the ventricular myocardial mass, as HVMB rightfully tends to be, has to provide not only common architectural plan of the ventricular myocardial fibers, but also to explain and test its integrative capacity with all other levels of biological organization, unifying ventricular form and function as described in ongoing "Physiome project"[25,26].

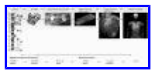


Figure 3 – Linking molecular and cellular events with physiological function must deal with wide ranges of length scales and timescales. Levels of biological organization from genes to proteins, cells, tissues, organs and finally the whole organism. The range of spatial scales - from 1 nm for proteins to 1 m for the whole body - requires a hierarchy of models. Different types of model are appropriate to each level, and relationships must be established between models at one level and the more detailed, but spatially or temporally limited, models at the level below. *(Modified and reproduced with kind permission from Peter J. Hunter, The University of Auckland, Bioengineering Institute, Ref. 25).*

Here we expose the anatomical background of HVMB concept, along with attempt to elucidate and clarify certain aspects, which were identified, so far, as points of mayor misunderstandings and disagreements[8,13,18,19,27,28]. Previous detailed anatomical descriptions of the HVMB could be found elsewhere[3,4,6,7,14,16,17, Appendix1] in the literature and online.

2. Helical Ventricular Myocardial Band of Torrent-Guasp – Anatomical Compendium

"Follow the argument, wherever it leads."
The Apology of Socrates. Plato (427 BC – 327 BC).

Trying to reach the endocardial surface or even to enter the ventricular cavity from any, arbitrary chosen, ventricular free-wall epicardial point, the path which offers the least resistance coincide with the natural, helical, overlapping course of the myocardial fibers (Figure 4).



Figure 4 – Transversal section through the ventricular mass (bovine heart) – anterior (left) and upper (right) view. Asterisks (black) indicate the site of arbitrary linear sharp intrusion into the ventricular mass. Arrowhead (black) indicates the natural, helical, overlapping course of the myocardial fibers during their epi- to endocardial transition. RV – right ventricle; LV – left ventricle; apm – anterior papillary muscle; ppm – posterior papillary muscle.

At this point, it is important to emphasize that, since there is no any "natural entrance" into the ventricular wall, a controlled incision (or blunt disruption) of the subepicardial fibers is the inevitable "first step" in this experiment. This fact depicts that intact ventricles are naturally well coupled, both anatomically and functionally, so that *"two hearts can beat as one"*[29]. Another important fact is to realize that random "cleavage plan", produced in this manner, does not disjoin and expose any distinctive anatomical structures (i.e. muscle bundles delimited by highly organized fibrous tissue or fascial sheaths, comparable to skeletal musculature), as some researches persistently want to believe [8,13,18,19]. Instead, as we repeated many times before[3,4,6,7,14,16,17], it is initiated by intentional blunt "intrusion" into the ventricular mass and subsequently guided by the *"principal fiber direction at given point, to accommodate factual difficulties arising from highly complex and anisotropic myocardial architectural design"*[6]. Therefore, methodologically, Torrent-Guasp's blunt anatomical dissections following predominant fiber direction, are revealing their unique functional (i.e. vectorial) and not any eclectic (i.e. discrete) anatomical personality within ventricular mass. Adopting this reproducible statistical criterion, it was not difficult to understand and prove that myocardial fiber fields have a very consistent and comparable organization between normal hearts of the same species[3,4,7,14,16,17].

To avoid any semantic confusion, a certain terms from classical myocardial histology, in a sense they will be used in this paper, have to be clearly defined. Ventricular mass is heterogeneous structure consisting of cardiac myocytes, connective tissue elements, blood vessels nerves and interstitial fluid. First, it is important to emphasize that ventricular myocardium does not fulfill biological criteria to be designated as "true syncytium". Instead, being composed of individual, morphologically discrete, but functionally very-well-coupled cells, it should be considered as "functional syncytium". This annotation might be useful for those who apply mathematics in biological systems, since it depicts that stochastic nature of myocardial form and function on microscopic level, becomes averaged and appears consistent with a continuous medium on macroscopic level[30]. Individual ventricular "working" myocyte is elongated, branched, cylindrical cell with lengths that range from 50 to 150μm and diameters ranging from 10 to 20μm. Branching outer cell contours resembles the *"step-like facades of skyscrapers; the plateau of each step being occupied by an intercalated disc"*[31]. Each ventricular myocardial cell is coupled by average of 11 neighbors, with 47% of the connections being of side-to-side (i.e. transverse) type and 53% of end-to-end (i.e. longitudinal) type[30-33]. The branching angle is usually acute so that tightly coupled adjacent cells run almost parallel with one another. Complex hierarchy of connective tissue (i.e. endomysium, perimysium and epimysium) provides a "sponge-like" scaffold for complex hierarchy of myocardial cells, blood vessels and nerves. Thus, the groups of three or more myocytes, surrounded by the perimysium could be distinguished as "myocardial fibers" and predominant local direction of their longitudinal axes defines the "principal fiber direction"[8,19,34-37]. These fibers as well as their directions are clearly visible during the macroscopic analyses of the intact ventricles (after removal of fat tissue and epicardium). The Auckland group has demonstrated a higher, laminar level of the ventricular myocardial organization, providing additional evidence that the ventricular myocardium *"should not be viewed as a uniformly continuous structure"*[9,26,38,39].

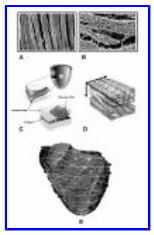


Figure 5 – The Auckland "laminar sheet" model of the ventricular mass microstructure. A) Micrograph of tangential surface of specimen showing layered organization of myocytes, branching of layers (arrow), and collagen fibers between adjacent sheets. Scale bar, 100 mm. B) Micrograph of transverse surface of specimen. Perimysial connective tissue weave surrounding myocardial sheets is evident and covers surface capillaries - C. Scale bar, 025 mm. C) Schematic of cardiac microstructure. Tissue block contains layers of tightly coupled

myocytes – laminar sheets. The cardiac myocytes (fibers) are tightly coupled within the same, but sparsely coupled between the adjacent laminas. The planes of the laminas could be defined locally by the longitudinal axis of comprising myocardial fibers and by their spiral, branching transmural direction on the ventricular mass level. D) Orientations of the principal muscle fiber axes (i.e. tissue vectors) are indicated. E) Rectangular tubes track along the fiber direction with the major flat dimension lying in the sheet plane. *(A-D: Modified and reproduced with kind permission from Ref. 8, © The American Physiological Society, 1995; E: reproduced with kind permission from Ian LeGrice and Peter J. Hunter, The University of Auckland, Bioengineering Institute).*

They have clearly shown that muscular fibers are arranged into distinct myocardial laminas, four to six myocytes thick, separated from adjacent laminas by the extra cellular collagen network (Figure 5A,B,C). The cardiac myocytes (fibers) are tightly coupled within the same, but sparsely coupled between the adjacent laminas. The planes of the laminas could be defined locally by the longitudinal axis of comprising myocardial fibers and by their spiral, branching transmural direction on the ventricular mass level (Figure 5C,D,E)[9,26,38,39].

As observed by predecessors[5] and quantitatively demonstrated by Streeter in his histological sections through the ventricular free wall [6], myocardial fibers change their directions gradually from endocardium to epicardium. Subepicardial fibers are becoming subendocardial ones, after helical overlapping around the natural orifices. Figure 6 demonstrates four fundamental anatomical facts, easily recognizable by pure inspection of the intact ventricles. Some of the most superficial fibers are removed, by gentle peeling-off along their principal direction, to make these facts even more obvious.



Figure 6 – Upper tray: Helical overlapping path of subepicardial fibers at basal (A) and apical (B) regions of the bovine ventricles. The epicardium and some of the most superficial fibers are removed, by gentle peeling-off along their principal direction. Lower tray: 2D helical rope-model mimicking the fiber path at the ventricular base (A) and apex (B).

The first fact to observe is that the apex of the heart belongs to the left ventricle (LV). Apical LV orifice (easily palpable during cardiac surgery) is normally very small and virtual one, covered with endo- and epicardium only. It may become a clinical and surgical problem in ischemic and dilated ventricles, when its size increases due to spherical remodeling[14]. Apical orifice becomes more obvious after additional removal of apical superficial fibers (Figure 6B). The continuity of subepicardial and subendocardial fibers, after helical overlapping around a central tunnel, is evident and was recognized since 17th century, when Lower designated it as *"vortex cordis"*[20].

The second fact is that the orifice at LV base (i.e. the mitral orifice) also demonstrates helical overlapping path during the continuous outside-inside transition of the LV free-wall myocardial fibers. To make this more obvious, an alternate group of fibers (Figure 6A) was removed to expose the grooves defined by the intact adjacent fibers. It is interesting to note that the majority of fibers are passing without any insertion to "the mitral fibrous annulus", which practically does not exist in the posterior leaflet area, or is presented as discontinuous tiny fibrous structure.

The third fact appears after dissecting the alternate groups of fibers belonging to the linear apical border of the right ventricular (RV) free wall. The crescent orifice which consequently appears also shows helical overlapping path of the subepicardial fibers during their continuous transition to the subendocardial ones (Figure 6B).

Finally, the fourth fact reveals the RV free-wall myocardial fiber arrangement around the orifice at RV base (i.e. tricuspid orifice). Again, helical overlapping and continuous epi- to endocardial transition could be easily observed (Figure 6A).

Previously described anatomical facts are mainly depicting similarities, but there is also significant difference between the basal and the apical regions. The fibers belonging to these distinctive regions, in their helical course from the epicardium to the endocardium, run in the opposite sense (Figure 7).



Figure 7 –The opposite directions (arrows) of helical overlapping fiber courses at the LV (A) and RV (B) basal and apical portions (bovine heart), with helical rope-model depicting this difference.

An elegant way to demonstrate not only this - but also many other relationships within the complex architecture of the ventricular myocardium - was "apparently hidden" in a simple rope. The helical rope model, at this stage (Figures 6 and 7), could only depict cross-sectional, two-dimensional relationships. A brisk global view on the rope model also demonstrates the anatomical reasons for different thickness of the LV and RV free walls. The LV free wall, being made up of two loops, is thicker than the RV free wall, constituted by only one loop. Another interesting similarity with ventricular myocardium is the complex hierarchy of helical structures *("spirals within spiral")* at different length scales within the rope[14,20]. Finally, this model allows comprehending how does the continuum mechanics could be efficiently applied on discreteness[40]. The mayor weakness of this model is the absence of visible branching connections between large rope bundles, although they might be realistically assumed to exist between smaller filaments (i.e. myocardial fiber analogues) comprising the individual large bundle.

The aforementioned four anatomical facts together with comparisons with the rope model were suggesting a possible secondary, "helical rope-like" structure of the ventricular myocardium. A hypothesis that the ventricular myocardium could be viewed as muscular band (i.e. stretched-out rope), twisted and curled in two helical loops, was inspired by phylogenic and ontogenetic similarities between heart and blood vessels. Undoubtedly, either in phylogeny and ontogeny, either as the final product or as the intermediate form during embryogenesis, the heart appears as pulsatile, linear or looped tubular organ (i.e. modified blood vessel), interposed between inflow and outflow blood vessels. The looping and overlapping of the heart tube with atrio-ventricular separation and septation at macroscopic level, as well as complex events resulting in filling up the cardiac jelly with different cells at microscopic level (i.e. trabeculation, compaction, interstitial, coronary and conduction system development), generates specific differences in preferential three-dimensional myocyte orientation within developing ventricular mass. These morphological adjustments, occurring at different time and length scales during the cardiogenesis, are controlled both genetically and epigenetically. The final pattern, as the result of these rearrangements (i.e. the form), has to provide a smooth and coordinated coupling of electrical activation, contraction and directional blood flow (i.e. the function) through the ventricles into pulmonary and systemic circulation[41-50].

If the heart is modified blood vessel, than their similarity should be the greatest in the earliest cardiogenesis. In addition, the heart should be serially connected with true, inflow and outflow blood vessels, in order to maintain the blood flow and prevent its leakage outside developing cavities. All these facts are clearly recognizable during the earliest phases of normal cardiogenesis (i.e. the heart tube stadium) [41-43]. The heart tube as linear, segmented, hollow secondary structure, inevitably has its finite macroscopic (i.e. length, width,

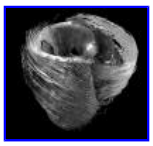
diameters, thickness, etc) and microscopic characteristics (i.e. cellular and interstitial composition, arrangement).

It seems quite logical to expect, that we could easily trace this secondary structure (i.e. the heart tube) within the final, three-dimensional architectural design of the mature organ, particularly because of blood flow and leakage-proof prerequisites. In a reality, it is not so difficult to follow the external transformations of the heart tube during its transition from linear to three-dimensional (tertiary) structure[41-43,46-50]. But, due to complex macroscopic and microscopic changes occurring inside the tertiary structure of developing ventricles, it is not realistic to expect that secondary structure would be accessible in a form of hollow tube, but rather, as we noted above, in a form of continuous muscular band. This band, of course, is not only composed of myocytes, but also of interstitial connective tissue and other non-muscular elements. Likewise, this muscular band does not present any distinctive embryological or anatomical entity, but reflects the unraveled helical path of muscular fibers encircling ventricular cavities. After atrial insulation, this path arranges to fit with spirally septated truncus arteriosus, allowing development and appropriate positioning of the pulmonary artery and the aorta in respect to the ventricular chambers. Thus, the great arteries indicate the beginning and the end of the underlying ventricular secondary structure[14,24].



Figure 8 – Successive dissection stages, unraveling the ventricular mass (bovine heart) into HVMB of Torrent-Guasp. Detailed description of particular stages may be found in paragraphs describing the dissection technique (see also Video 2).

Figure 8 depicts successive steps of dissection technique applied in unraveling the ventricular mass into HVMB. After the separation of the pulmonary artery and the aorta (Figure 8/1,2), some superficial fibers (i.e. aberrant fibers) bridging the anterior interventricular sulcus, are incised in order to move aside the right ventricular (RV) free wall (Figure 8/3-7). By doing so, we arrive to the posterior linear border of the RV cavity, which is represented by the linear bottom of the dihedral angle constituted by the RV free wall and the interventricular septum (Figure 8/8). The posterior linear border of the RV cavity has special importance, since it points out the only possible trajectory, which would allow further dissection of the HVMB. The beginning of this trajectory is exposed by pushing laterally RV free wall (Figure 8/9). Following the predominant fiber direction, we can easily see that this path encircles the LV, up to the root of the aorta (Figure 8/10-14, Video 1).



Video 1 - Heart fiber DT-MRI. (1.45Mb - wmv) *(By courtesy of Leonid Zhukov, Department of Computer Science, California Institute of Technology).*

By cutting their anchorage with the left fibrous trigon (Figure 8/15,16), we have finished the dissection of the HVMB basal loop. At this point, it is important to notice that some fibers (i.e. belonging to the descendent segment) are sinking into the LV (Figure 8/12,13), making the central fold of the HVMB. Trajectory of these fibers, while coming down towards the LV posterior wall, is pointing out an important cleavage plan at level of the interventricular septum (Figure 8/13-15). Namely, at the septal level, these fibers are crossing the ascendant segment fibers in a 90-degree angle. At this point, we are able to see this septal crossing from the LV side.

To continue with dissection, we should come back, to the site of the previous posterior linear border of the RV cavity (Figure 8/17). By pure inspection from the RV side, we can clearly distinguish two muscular strata. The deeper belongs to previously described descendent segment and the more superficial belongs to the ascendant segment. A right-angle crossing of these fibers, as described before, is now also visible from the RV side (Figure 28). The cleavage plan between these two strata (Figure 8/18), is the same one we described above, entering it from the LV side (Figure 8/13-15,20-21). The top of the line (i.e. previous posterior linear border of the RV), defined by these two strata, ends on the aortic root at the point of it's attachment to the right fibrous trigone. To separate described strata, going in between the vertical (more superficial, ascendent segment) and the horizontal (deeper, descendent segment) fibres, the first thing that we should do is to cut-off their anchorage to the right fibrous trigone (Figure 8/18,19). Now we are able to proceed with the most delicate part of the dissection, denominated as "dismounting of the aorta".

Prior to any further description of the dissection method, it is important to emphasize one fact. The only firm aortic attachments to the LV are the fibrous trigones, upon which the aorta leans over the LV outflow tract. Apart from that, the aortic annulus, belonging to the right coronary cusp, provides the additional, weak anchorage of the aorta to the septal portion of the LV. Thus, by cutting-off these firm and weak attachments, it becomes possible to dismount the aorta from the LV (Figure 8/15,19-21). By doing so, we are able to join two parts of the septal cleavage plan (Figure 8/20). In this manner, progressing along the predominant fiber path, we are able to detach the aorta with fibers belonging to the ascendant segment from the rest of the LV mass (Figure 8/21,22). Following the same cleavage plan along the predominant helical fiber path (Figure 8/22), we are entering the LV cavity, with fingertips appearing behind the anterior papillary muscle, at the level of previously mentioned central fold of the HVMB (Figure 8/23). If we proceed until we become able to close the fist, our fingertips would appear between anterior and posterior papillary muscle, the former being completely encircled by the hand.

Finally, we came to the most exciting part of the dissection, when the HVMB is ready to be stretched-out (Figure 8/24). Simple 90-degree rotation around the apex unravels the apical loop segments (Figure 8/25). Additional 180-degree rotation around the central fold unravels the basal and the apical loops of the HVMB (Figure 8/26). The HVMB of Torrent-Guasp now appears in its full extent and beauty, with pulmonary artery at one and the aorta at the opposite side (Figure 8/27). Figure 9 depicts the most important phases of the dissection procedure (see also Video 2).



Video 2 - Unraveling of the HVMB. (842Kb - rm). Francisco Torrent-Guasp, Denia, 2004.

The elegance and astounding simplicity of this dissection is reflected in the capacity to easily reverse these unraveling steps, with ready re-establishment of the well-known three-dimensional ventricular architecture that existed prior to beginning of dissection (Figure 9, Video 1).



Figure 9 – The most important phases of the dissection procedure (bovine heart). Bottom: Torrent-Guasp's home-laboratory, where the HVMB concept was borne and where lots of people were able to learn Torrent-Guasp's dissections from the very source *(photo by M.J.Kocica, 2002)*.

The HVMB is divided in two loops, each of them comprising of two segments (Figure 10D). The central 180-degree fold of the HVME defines two loops: the basal loop (from the root of the pulmonary artery to the beginning of the central fold - i.e. to the anterior papillary muscle) and the apical loop (from the beginning of the central fold to the root of the aorta) (Figure 10B,D). Each of these two loops could be further divided in two segments.

The posterior interventricular sulcus, which coincides topographically with the posterior linear border of the RV cavity, divides the basa loop into two segments: the right segment - coinciding with the RV free wall; and the left segment - coinciding with the LV free wall (Figure 10B,D). It is interesting to notice here, that the right segment also defines the outer (non-septal) border of the tricuspid orifice and the left segment defines the outer (non-septal) border of the mitral orifice. These borders are common targets in AV surgical annuloplastic procedures.

The apical loop could be also divided in two segments. After the 180-degree twist (at the central fold of the HVMB), the descendant fibres of the apical loop, make a 90-degree turn around the apex becoming the ascendant fibers (Figure 10B,D). Posterior papillary muscle (belonging to the descendant segment), demarcates the border between the descendent and the ascendent segments of the HVMB apical loop (Figure 10A,B,D).

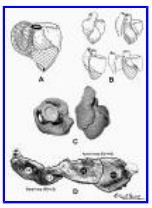


Figure 10 – A) The last drawing made by Torrent-Guasp, illustrating a complex three-dimensional fiber architecture of the ventricular mass; B) Schematic presentation of the silicone-rubber mould of the HVMB (anterior and left-oblique view); C) Torrent-Guasp's© silicone-rubber mould of the HVMB; D) Segmental anatomy of the HVMB: RS – right segment; LS – left segment; DS – descendent segment; AS – ascendant segment.

The result of anatomical studies, giving rise to the HVMB concept, provided that simple schema (Figure 10A,B), that *"applies equally well to all the ventricular myocardial fibres, showing them joined together in a coherent common general architectural plan"*[21]. With completion of the HVMB concept, we were able to give appropriate third dimension to previously described helical rope-model (Figures 6,7,11C). In addition, to make some three-dimensional relations more understandable, apart from the helical rope-model, we have developed a silicon-rubber model and the paper-strip model of the HVMB.

The first silicone-rubber mould of the HVMB (Figure 10C) was produced in the early 1990's, from the matrices that Torrent-Guasp made using the unraveled bovine hearts. Made of special elastic material, this model clearly reproduces all morphological features of the HVME with high fidelity. So far, we have distributed free-of-charge more than 1000 copies of the HVMB model worldwide.

A paper-strip model (Figure 11B,C) is also very interesting because it is widely accessible and it allows to comprehend a triple helices comprising the ventricular mass. In addition, this model depicts that global, three-dimensional ventricular architecture could be regarded as geometrically non-orientable surface, similar to triple-twisted Möbius strip (Figure 11A,B,C)[51]. A Möbius strip is a one-sided surface that is constructed from a three-dimensional rectangle. Twisting this rectangle (i.e. the paper-strip) for 180-degrees (one or more times) and attaching the ends to one another seems to eliminate one dimension of three-dimensional space. This is possible only in the curved space-time continuum revealed by Einstein. This purely geometrical analogy might be interesting in researches dealing with ventricular electrical and mechanical physiology.

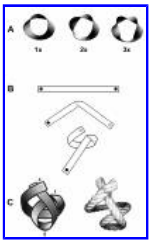


Figure 11 – Paper-strip model of the HVMB. A) single-, double- and triple-twisted Möbius strip[50]; B) Central fold of the HVMB demonstrated with paper-strip (black dot – visible side; gray dot – invisible side of the strip); C) Paper-strip and helical-rope models of the HVMB with annotated sites of three principal spirals within a complex helicoid: 1 – central fold, 2 – apical loop, 3 – great arteries (i.e. "truncus arteriosus" spiral septation).

3. Controversies

"Nature is simple, but scientists are complicated"
Francisco Torrent-Guasp

Although the basic anatomical investigations were completed by 1972, the first integral anatomical description of HVMB was published in 1980[7]. The background of this concept was more than 1000 meticulously prepared general or special (finite segments) dissections of the hearts, belonging to different species. Since then, some basic principles and advances in understanding of HVMB form and function derived from Torrent-Guasp's continuous efforts to refine this concept, as well as from different studies done by others, were published in numerous papers[3,4,6,7,10,11,14,16,17,52-57]. Moreover, during the last decade, three successive, international, multidisciplinary

symposia (Alicante 1995; Bethesda 2002 and Liverpool 2005) were organized with common task - to set up fundamental research principles, which would allow us to make a significant step forward in understanding heart structure and function[23]. The introduction of a new HVMB concept invariably introduces departures from currently accepted understandings and some of these issues will be addressed below.

3.1. Skeletal vs. vascular musculature analogy?

Conceptually, the two contemporary and opposing schools about macroscopic structure of the ventricular myocardium are designated as "HVMB" and "Syncytial Mesh" strongholds, but they share substantial common ground[8,13,18,19]. Neither concept questions the infinite anisotropy of the ventricular myocardium at microscopic level, whereby each myocyte is connected by intercalated discs and anchored to its neighbors by struts and weaves of supporting fibro-collagenous matrix (i.e. functional syncytial mesh, resembling modified vascular musculature[19]. Moreover, with the seminal work of Streeter[6] and subsequent reports on "laminar sheet" organization of the myocardial fibers and surrounding matrix by Auckland group[9], "functional syncytium mesh" (FSM) concept becomes the essential histological prerequisite for proper understanding of local, (but still) microscopic anisotropy within arbitrary chosen tissue-blocks (i.e. finite elements of the ventricular mass)[19].

However, can we resolve the problem of global, macroscopic myocardial anisotropy, applying purely (two- or even three-dimensional) histological analogy? Alternatively, can we simply apply a higher, "tissue-block logic", on the entire ventricular mass? The heart is simply *"greater than the sum of its constitutive parts"*[64]. Evidently, in spite of considerable efforts[26,38,59], not any of these structural approaches alone could provide global three-dimensional model, which could fully explain cardiac function and its efficiency from the point of view of vectors of forces, generated during dynamic interaction between the elastic and contractile elements.

The ultimate net result of the complicated myocardial fiber arrangement is to translate uniaxial sarcomere shortening into three-dimensional deformation of the ventricular cavity[60-62]. It is well known fact that myocardial architecture creates multiple inhomogeneities of electrical and mechanical loads at the cellular level, that cause cardiac function to be "stochastic in nature". At a macroscopic level however, these stochastic events become averaged and appear consistent with a continuous medium[30,60-65]. As we emphasized earlier, Torrent-Guasp's blunt anatomical dissections, following predominant fiber direction, shall reveal unique functional (i.e. vectorial) but not any eclectic (i.e. discrete) anatomical planes within ventricular mass. This arrangement defines a the global, rule-based assignment that exists, along which the majority of fibers lie in the optimal direction, permitting them to orderly perform their function as a continuous medium.

Therefore, while the term "myocardial fibers" reflects *"a convenient description rather than anatomical entity"*[8,19,35], this concept is interpreted to reflect the meaningful reason for structural hierarchy that performs function.. Our insisting on "functional" instead of "anatomical" personality of the ventricular fibers is based upon a "principal fiber direction", a term that implies that no search is made for discrete "bundle-like" anatomical entity because "principal fiber direction" definitively does not comply with this concept. Nor is there denial that there is anatomical existence and functional significance of the "non-principal" three-dimensional components (containing both myocardial and interstitial elements) that are destroyed within ventricular mass as "principal fiber direction" is developed.

Commonly used argument in erroneous comparisons of the HVMB with skeletal muscle model was its *"discrete origin, at the aortic outflow, and an insertion at the subpulmonary infundibulum"*[19]. Moreover, denying any fibrous insertions of the ventricular myocardial fibers FSM proponents[18,19] are opposing some classical anatomical observations[34]. This anatomical language enhances a false similarity of the HVMB and skeletal muscle (e.g. biceps brachii). Under no circumstances is the attachment of the entire ventricular mass, which extends from the pulmonary artery on the one side and to the aorta on the other, considered to perform its "skeletal-muscle-like-contraction".

3.2. The intervetricular grooves

Glisson compared, in 1641, the difference between "mangling" and "mental" dissections and lauded the mental capacity[1]. This concept was followed because there was not a place where we *"systematically destroy the continuum of the bordering fibers"*[18,19,28] without recognizing their existence and significance, while the predominant fiber orientation was defined. However, "predominant" does not mean "exclusive", so that certain areas within ventricular myocardial mass exhibit prominent fiber disarray (e.g. along the boundaries of the interventricular septum adjacent to the LV and RV free walls). However, specialized dissections showed that certain order in fiber arrangement exists even in these regions.

Thus, at early stages of HVMB dissection, we cut of the "aberrant fibers", that belong to the ascendant segment and traversing the anterior interventricular sulcus, end on the RV free wall and supraventricular crest (Figure 12).

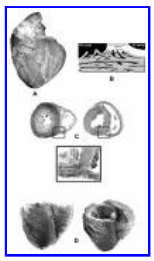


Figure 12 – Fiber disarray in the anterior and the posterior interventricular grooves. A) – Aberrant fibers (two-headed arrow lines) of the ascendant segment bridging the anterior interventricular sulcus (bovine heart). Single-headed arrow lines depict the opposite directions and independent intra-septal sinking of the anterior recurrent fibers (right) and the rest of the ascendant segment fibers (left). PA – pulmonary artery; Ao – aorta; LMCA – left main coronary artery. B) Cartoon depicting anterior interventricular fiber disarray. C) Histological and diffusion tensor MRI glyph-based visualization of the posterior interventricular fiber disarray. D) Reconstruction of the posterior interventricular fibers using moving least squares fiber tracing algorithm. (see also Video 1). *(C,D: Modified and reproduced with kind permission from Leonid Zhukov, Department of Computer Science, California Institute of Technology).*

The term "aberrant" is to define a smaller part of the LV ascendant segment fibers that significantly depart from the predominant direction of other fibers comprising this segment, but this term is not used to downgrade their importance. These fibers bridge the sulcus that separates two ventricles and may ensure their coordinated and synchronized function[29]. These fibers have clinical significance because they pass over the left anterior descending artery (LAD) to create an intramyocardial LAD vessel. Nevertheless, their division is essential at the beginning of the HVMB dissection to enter the cleavage plan separating two ventricles, defined by the predominant orientation of the LV ascendant segment fibers and RV anterior recurrent fibers (Figures 12A,B, 13C). After this interruption, it becomes clear that the majority of ascendant segment fibers actually sink towards anterior interventricular septum. The situation at the posterior interventricular sulcus is quite different. The majority of proprietary RV free wall fibers are passing over the posterior interventricular sulcus to the posterior free wall of the LV, while their smaller part (i.e. posterior recurrent fibers) departs and sinks towards the posterior interventricular septum (Figures 12C,D, 13C). Thus, in order to enter the cleavage plan which completes the dissection of the HVMB basal loop, we intentionally cut through this tiny layer of the posterior recurrent fibers in the posterior linear border of the RV (Figures 8/7-9, 12C,D, 13C, 14C).

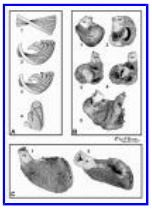


Figure 13 – HVMB concept of the right ventricular architectural design. A) "Japanese-fan" model of the right ventricle. B) Special dissections of the right ventricle (bovine heart) depicting the fiber architecture correspondent with "Japanese-fan" model. Two-headed arrow line (white) depicts the aberrant fibers bridging the anterior interventricular sulcus. PA – pulmonary artery; LAD – left anterior descending (artery); RCA – right coronary artery. C) The right ventricle separated from the rest of the ventricular mass (septal and superior view). Black asterisk indicates the site of sharp incision over the proprietary right ventricular free wall fibers, passing in greater extent over the posterior interventricular sulcus to the posterior free wall of the left ventricle (see the explanation in the text). arf – anterior recurrent fibers; prf – posterior recurrent fibers; SVB (SVC) – supra-ventricular bridge (crest).

3.3. The interventricular septum

The interventricular septum displays fiber disarray at the boundaries of LV and RV free walls, and contains an intriguing structure that may be freshly examined by the HVMB dissection. These dissections contradict the concept that the interventricular septum belongs to the LV since both ventricles participate in its formation and the ascending and descending segments provide the origin and significance of septa fiber crossing, as well as define the origin of the echocardiographic "bright line" that separates the septum into left and right side. We suspect the overlap of the crossing of descending and ascending segments creates this "bright line", a necessary border during the dissection. This is a connective tissue true space between ascending and descending segments and this belief may contradict the major assumption that this dissection *"might have disrupted the syncytial arrangement of the myofibres by creating a cleavage in the septum causing an artificially bilayered structure"*[66].

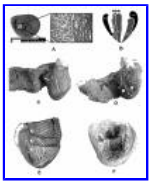


Figure 14 – Interventricular septum. A) Histological evidence (human heart) of septal fiber crossing illustrating the sharp border between two different principal fibers directions. B) Cartoon of the cleavage plans produced by following principal fiber direction (longitudinal section) depicting the fibers participating in septal formation. 1 – (rf) recurrent fibers (anterior and posterior); 2 – (AS) ascendant segment fibers; 3 – (DS) descendant segment fibers; RS – right segment; LS – left segment; DS/AS – descendent to ascendant segment transition. C) Septal disarray (crossing) demonstrated at the level of the posterior linear border of the right ventricle (white asterisks). D) Septal crossing at the level of the anterior interventricular sulcus. Dotted area depicts the zone of careful fiber pealing-off (no cleavage plans produced) until the first septal branch (S1) of the left anterior descending artery (LAD) appeared between 1 and 2 (numbers correspond with legend B). E) Special dissection of the interventricular septum (bovine heart) with arrows showing three principal fiber directions (numbers correspond with legend B). F) Reconstruction of the septal fibers using moving least squares fiber tracing algorithm emphasizing anterior and posterior recurrent fibers of the right ventricle (rectangle). *(A: By the courtesy of Francesc Carreras-Costa and Patho-histological department, Hospital Sant Pau, Barcelona, Spain; F: Modified and reproduced with kind permission from Leonid Zhukov, Department of Computer Science, California Institute of Technology).*

Simple histological evidence of septal fiber crossing (Figure 14A) illustrates the sharp border between two different principal fibers directions, which is not artifact but the reality. This histological fact was verified (Figure 14C,D) at the level of posterior linear border of the RV and anterior interventricular sulcus by careful fiber pealing-off, without producing any cleavage plan. Special dissections (of the RV and the interventricular septum), allowed us to conclude that both ventricles participate in the formation of the interventricular septum. The RV contributes with its anterior and posterior recurrent fibers (Figures 13A,C, 14B,C,E,F, 15). These tiny, superficial fibers (looking from the RV side) have almost vertical direction (Figure 14B,D,E,F). Recurrent fibers are laying over the ascendant segment fibers, which (after sinking into the anterior interventricular sulcus, as seen in Figure 12A) run slightly obliquely and upward, towards the root of the aorta (Figures14B,C,D,E,F, 15). The first septal branch (Figure 14D) of the left anterior descending artery (which is to be preserved in Ross operation) runs exactly between these septal layers with slightly different fiber orientations (the site of the first septal branch entrance is evident in Figure 12A,B).

Finally, the third principal fiber direction within the interventricular septum belongs to the descendant segment (Figures 14B,D,E,F, 15). The orientation of these fibers is pronouncedly different in respect to the adjacent, ascendant segment fibers. This fact is the anatomical substrate for the 90-degree septal fiber crossing (Figure 14A). The functional significance of this septal fiber organization has to be examined.



Figure 15 – Cartoon (A) and the anatomical specimen (B, bovine heart) illustrating the right and the left ventricular fiber architecture, as relevant for proper understanding of their relations at the anterior interventricular sulcus and the septum. DS – descendent segment; AS – ascendant segment; af – aberrant fibers; rf – recurrent fibers; PA – pulmonary artery; Ao – aorta.

3.4. Central fold of the HVMB

The HMVB dissection concurs with FSM concept proponents, regarding the ubiquitous existence of *"multiple side-branching within ventricular mass"* (including so called *"obliquely intruding elements"*) on the microscopic level[18,19] and also agree that *"cardiac muscle fibers are systematically aligned"* on the macroscopic level[36]. The central fold of the HVMB is probably the most obvious reason to study cardiac structure and function through additive synergism instead of competitive antagonism.

The central fold of the HVMB (Figure 16) is not any discrete anatomical entity, but simply the term used to describe the area where the subepicardial fibers of the basal loop (left segment) make a 180-degree turn and become the subendocardial fibers of the apical loop (descendant segment). This three-dimensional fold is clearly visible as 180-degree twist in unraveled HVMB (Figures 9, 10D) and in paper-strip models of the HVMB (Figure 11B,C). The basal loop of the HVMB contains predominantly horizontal fibers directions (in two-dimensions) that surround and fully embrace the ventricular bases. (Figure 10B,C). The existence of the central fold preserves the continuity of these loops within the ventricular mass, as well as the longitudinal axial continuity of adjacent segments in the unfolded band. Accordingly, when wrapped, a spiral is formed from fibers with pronouncedly different fiber orientations in three-dimensional space.

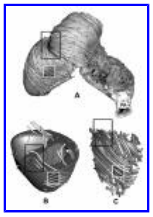


Figure 16 – Central fold of the HVMB. A) Anatomical specimen (bovine heart) demonstrating 180-degree spiral turn of the basal loop (black rectangle). Dotted line depicts the posterior linear border of the right ventricle (i.e. the borderline between right and left segments of the basal loop). White rectangle emphasizes the principal fiber direction at the level of smooth ascendant-to-descendent segment transition. B and C) Constructive volume geometry representations of corresponding areas (black and white rectangles) obtained from rabbit heart. *(Modified and reproduced with kind permission from Aron V. Holden, School of Biomedical Sciences, University of Leeds and Min Chen, Department of Computer Science, University of Wales Swansea).*

3.5. The apical loop of the HVMB

The apical loop of the HVMB is another part of the ventricular mass with pronounced difference in predominant fiber orientation, since descendant segment fibers and the ascendant segment fibers cross each other at a 90-degree angle around the apex (Figure 17). This spiral turn at the apex mirrors the central fold of the HVMB, thereby preserving the longitudinal axial continuity of these two segments of the ventricular mass in three-dimensional space as the heart is refolded. The apex of this "minor spiral" was previously called the "vortex cordis"[20].

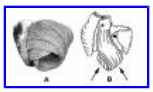


Figure 17 – The apical loop of the HVMB. Anatomical specimen (A) and cartoon (B) showing the 90-degree spiral turn of the descendant and the ascendant segment fibers around the apex (black arrows). Black asterisk indicates the site of HVMB central fold.

4. Concluding remarks

"Sol Incit Omnibus"
(Francisco Torrent-Guasp)

Within the ventricular mass - size, shape, connections and orientation in a three-dimensional space, of every single constituent determine its functional behavior. This kind of spatial dependence allows the ventricular myocardial mass to be considered as the source of interdependent vectorial forces (i.e. electrical and mechanical), being generated on different length and time scales (Figure 18D). The ultimate net result of these vectorial forces is to translate uniaxial sarcomere shortening into efficient three-dimensional deformation of the ventricular cavity[44-46,60-65]. The complex architecture of the ventricular mass creates multiple inhomogeneities of electrical and mechanical loads at the cellular and the microscopic tissue level, that cause cardiac function to be "stochastic in nature". However, at macroscopic level, these stochastic events become averaged and appear consistent with a continuous medium[30-40]. This dialectic coexistence of complexity and simplicity, discreetness and continuity, suggests the existence of certain rule-based assignment, which *"may be applied equally well to all the ventricular myocardial fibers"*[21], enabling the ventricular myocardial mass to assemble abundant, dynamic, stochastic vectorial forces and produce apparently smooth, averaged, continuous, global response[30,40].

A single sarcomere, symbolizing the essence of heart's ability to work, viewed as the arbitrary "quantum of continuity" presents a fractal, which holds the secrets of complex interactions of form and function. Functional architecture of the sarcomere is applicable, on self-similarity basis, in all other scales, up to the complex geometry of the ventricular mass[67-69]. Longitudinal sliding of the principal contractile proteins produces the changes in isoclinal sarcomere length. The orientation of force vector generated in this manner coincides with principal (i.e. longitudinal) axis of the sarcomeral contractile proteins. Its magnitude depends on complex interaction with Z-line proteins protecting the sarcomere them from excessive length changes. The Z-line protein complexes are connected with cellular membrane and subsequently with extra cellular matrix and connective tissue, allowing the myocardial cell to exchange the "information" about active and passive forces with neighboring cells. They are also connected with central "computer of the cell" (i.e. the nucleus), which translates these information into language of genetics, producing, by need, regulatory and structural proteins for short and long-term adjustments of stress and strain.

Therefore, three-dimensional functional architecture of the single sarcomere is adjusted to produce the active force along its principal longitudinal axis. The magnitude of this force is normally controlled by passive forces, developed by complex Z-line proteins, acting along different directions. Changing the magnitude of scope, we may find this fractal design of form and function preserved along increasing length scales. Thus, it has been proved that electrical impulses propagate more rapidly along rather than across the axis of the constituent fibers. In addition, the myocardial cells perform their functions by developing net tension along their longitudinal axes. Both facts do not exclude the existence and the importance of non-longitudinal electrical and mechanical forces, just like the forces developed by principal contractile proteins are not the only forces developed within the sarcomere (Figure 18A,B,C).

The FSM concept (Figure 18B,C) appropriately comprehends the integration of structure and function at microscopic length scales. Accordingly, the concept of "laminar sheets" (Figure 18C) perfectly suites the understanding of myocardial form and function on a tissue block level, providing the finite element of the complex geometrical structure, which allows a mathematical modeling of the ventricles with acceptable degrees of freedom. However, the HVMB concept (Figure 18E,F) defines the principal, cumulative vectors, integrating the tissue architecture (i.e. form) and net forces developed (i.e. function) within the ventricular mass. Arbitrary, there are four principal curvilinear vectors within ventricular myocardial mass, named after corresponding segments of the HVMB. According to their predominant orientation in three-dimensional space, they are grouped in two homologue pairs, named after corresponding loops of the HVMB. As idealized approximation of reality, HVMB concept integrates the ventricular form and function into single helicoid three-dimensional vector. Appropriate mathematical formulation of this spatial and temporal continuum may lead to new constitutive equations of the ventricular myocardium, which might overcome the current limitations required to create a mathematical model of the heart[26].



Figure 18 – A) Photomicrograph of the single sarcomere with two-headed arrow line depicting the principle of structural and functional "longitudinality" B and C) Principle of structural and functional "longitudinality" on microscopic, cellular (B) and tissue block (C) levels. D) A myriad of spatially and temporary dependent finite vectorial forces within ventricular mass. E and F) HVMB as the spatial and temporal continuum integrating the tissue architecture (i.e. form) and net forces developed (i.e. function) within the ventricular mass (see the explanation in the text). *(D: reproduced with kind permission from Peter J. Hunter, The University of Auckland, Bioengineering Institute).*

The helical ventricular myocardial band of Torrent-Guasp conveys an important message (i.e. "Sol Incit Omnibus")[70]. The marvelous architecture of this organ is "big enough" for all of us – "FSM, laminar-sheet and HVMB people".

Kohl, Noble, Winslow and Hunter have nicely formulated this message, paraphrasing Hegel's dialectics: *"The logic of life will neither be recognized without precise understanding of the manifold of components that give rise to biological function, nor without a clear conception of the dynamic interactions between individual components on every level of functional integration. Likewise, the logic of life lies exclusively neither in the most incredible detail, nor in the most sweeping synopsis. Neither integrationism, nor reductionism, is self-sufficient. Both are obligatory to our quest for knowledge"*[26].

The fundamental question should be: "What do we really know about normal and diseased heart structure and function?", rather than becoming boxed-in by prior conceptions. We cannot continue to develop new diagnoses and therapies for heart diseases, without serious scientific consensus on these fundamental questions. That goal shall be helped by further understanding of the helical ventricular myocardial band of Torrent-Guasp.

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