

Review

The anatomical arrangement of the myocardial cells making up the ventricular mass

Robert H. Anderson^{a,*}, Siew Yen Ho^b, Klaus Redmann^c, Damian Sanchez-Quintana^d, Paul P. Lunkenheimer^c

^aCardiac Unit, Institute of Child Health, University College, 30 Guilford Street, London WC1N 1EH, UK

^bDepartment of Paediatrics, National Heart & Lung Institute, Royal Brompton Campus, Imperial College, London, UK

^cExperimental Thoraco-, Heart & Vascular Surgery, University Hospital, Munster, Germany

^dDepartment of Anatomy, Universidad de Extremadura, Badajoz, Spain

Received 24 May 2005; received in revised form 20 June 2005; accepted 22 June 2005

Summary

The architectural arrangement of the myocytes within the ventricular mass remains a highly contentious topic. It has recently been suggested by several distinguished surgeons that the overall myocardial structure is disposed in the form of a 'ventricular myocardial band'. There are, however, major anatomic deficiencies in this hypothesis, because the heart is formed on the basis of a modified blood vessel, rather than a collection of discrete muscular entities resembling the skeletal musculature. There is ample alternative evidence, nonetheless, already existing to provide a suitable explanation for the 'forceful reciprocal twisting' of the ventricular mass that is seen by cardiac surgeons during operative procedures. We provide here, therefore, a review of the anatomical studies we have performed separately and conjointly over a period of nearly 30 years. As before, we show that there is no anatomic evidence to support the concept of the 'ventricular myocardial band'. The overall arrangement is for the myocytes to be supported as the muscular components of a continuous and complex mass, the supporting collagenous fibrous matrix possessing epimysial, perimysial, and endomysial components. It had already been discussed at length during the previous century why there was no anatomic evidence to support the existence of separate 'muscles' within the ventricular continuum. There are no fibrous sheaths within the ventricular walls that permit the myofibres to be dissected on the basis of muscle bundles having a discrete origin and insertion, as is the case with the arrangement of the skeletal muscles. We have never sought ourselves, however, to deny the central helical nature of the overall architecture of the ventricular walls. The anatomic evidence supporting an overall helical nature for the ventricular myocardium has existed for over 150 years. All the available evidence, nonetheless, shows that these helical patterns are to be found throughout the walls, and in no way constitute a unique myocardial band.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Myocardium; Myocytes; Fibrous matrix; Syncytial mesh; Helix; Collagen

1. Introduction

Despite being extensively examined by anatomists over a period of more than 300 years, the architectural arrangement of the myocytes within the ventricular mass remains a highly contentious topic. A recent review in the Journal [1] promoted the concept that the overall myocardial structure was disposed in the form of a 'ventricular myocardial band'. In response to this, some of us produced a counter review [2], emphasising the anatomic flaws of this hypothesis, and pointing to the fact enunciated by Pettigrew [3] and Keith [4] almost one century ago, namely that the heart is formed on the basis of a modified blood vessel, rather than a collection of discrete entities resembling the skeletal musculature.

Despite this, our own review, when published [2], was accompanied by two invited critiques from the proponents of 'myocardial band' [5,6]. These further diatribes [5,6] addressed none of the concerns set out in our own presentation [2], offering no evidence of how the components of the alleged myocardial band were separated anatomically one from the other. Instead, they simply restated, at appreciably greater length, the spurious arguments set out in the initial account [1].

Reading these further works makes it clear to us that a major feature disturbing the supporters of the 'ventricular band' is our failure to consider the anatomic substrate for the 'forceful reciprocal twisting' that is seen by cardiac surgeons during operative procedures [5]. In reality, the literature as produced over a period of 300 years is replete with references to the helical arrangement of the ventricular mass, most notably in the extensive and superbly illustrated account given by Pettigrew [3] (Fig. 1). We summarised these earlier contributions in our investigation of the ventricular myocardium published in association with

* Corresponding author. Tel.: +44 20 7905 2295; fax: +44 20 7905 2324.
E-mail address: r.anderson@ich.ucl.ac.uk (R.H. Anderson).

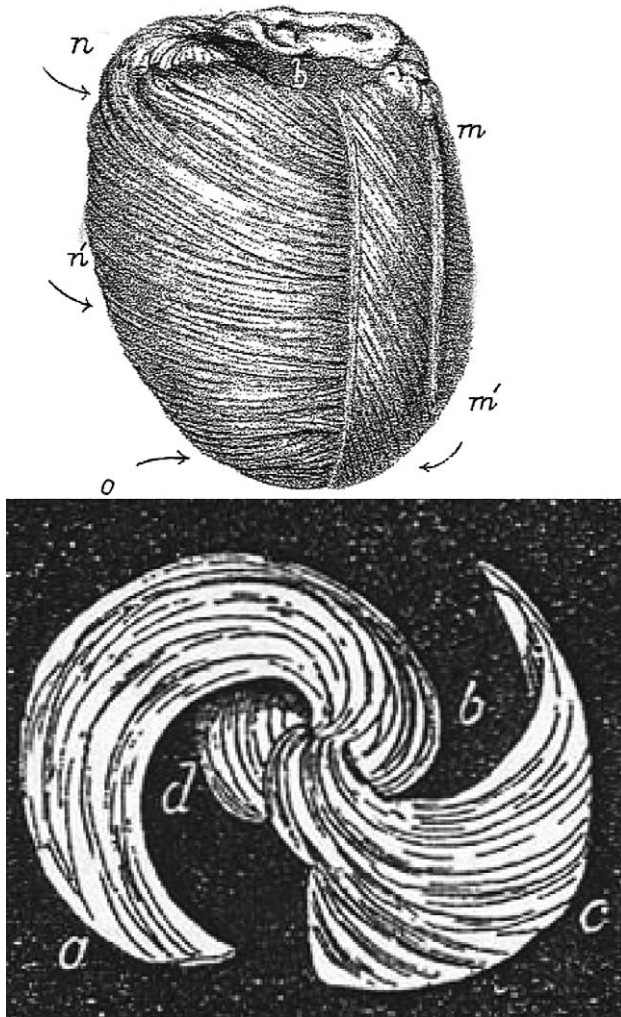


Fig. 1. Reproductions (top) of Fig. 3, from Plate XCVII, and (bottom) Fig. 174, from Volume 2 of Pettigrew's work 'Design in Nature', published in 1908 [3]. Fig. 3 shows the changing angulation of the myofibres relative to the ventricular equator with increasing depth of the ventricular wall, while Fig. 174 shows the unequivocal spiral arrangement of the fibres as they move from the superficial to the deep layers of the ventricular wall at the apex of the left ventricle.

Greenbaum and other colleagues [7]. We had concluded this earlier work by drawing attention to the 'potential dangers inherent in imposing Procrustean and over-simplified ideas on a complex biological structure' [7]. This danger has now been reinforced by Criscione and colleagues in a cogent 'Letter to the Editor' [8]. Emphasising the need for a 'continuum' approach to the conundrum of the architecture of the ventricular mass [9], they commented that, whilst such an approach is far from simple, so is the 'self-assembly and mechanical behaviour of millions of myocytes and their extracellular matrix' [8]. Since Criscione and his colleagues [8], and presumably many other mathematicians and bioengineers [9], as well as the supporters of the 'ventricular myocardial band' [5,6], seem unsure of the basis or validity of our own understanding of ventricular myocardial structure, we provide here a review of the anatomical studies we have performed separately and conjointly over a period of nearly 30 years [7,10-14]. We show again that there is no

anatomic evidence supporting the concept of the 'ventricular myocardial band'.

2. Histology of the ventricular myocardium

As emphasised by Criscione and colleagues [8], the myocardium is made up of millions of myocytes set in a matrix of connective tissue. Each individual myocyte is a long and thin cell, joined to its neighbours at its ends by intercalated discs, but also possessing multiple side-branches, which also join through intercalated discs with neighbouring myocytes. The overall alignment of the myocytes, however, is such as to permit the identification of a generalised long axis of the myocardial cells as revealed in any section taken through the ventricular wall (Fig. 2a). The myocytes themselves are supported within a continuous matrix of fibrous tissue. Each individual cell is wrapped in an endomysium, which supports the intercalated discs in binding adjacent myocytes to one another, as well as forming a so-called 'weave' around the myocytes (Fig. 2b). Struts from the weave insert into the basal lamina of each myocyte lateral to the Z-band of the sarcomeric unit, functioning so as to coordinate the transmission of force, as well as preventing slippage between the cells. Groups of myocytes are then surrounded by condensations of the endomysial weave, thus forming the perimysium (Fig. 2c), which aggregates collections of individual myocytes into the so-called myofibres. The perimysial partitions also serve to act as conduits for the blood vessels and nerves that feed the myocytes. In this respect, lest we cause potential confusion, we should emphasise that the nerves serve only to modulate the myocardial action. They do not directly stimulate the muscle cells as occurs in skeletal muscle. Activation of the myocardium, of course, depends on the integrity of the so-called conduction tissues. It is a collection of these specialised myocardial cells, the sinus node, that initiates the heartbeat. Orderly ventricular contraction is then ensured by the presence of an insulated axis of specialised cells, the ventricular conduction axis, that originates from the atrioventricular node and extends to the ventricular apex, the ventricular bundle branches being insulated by discrete fibrous sheaths as they descend on both sides of the muscular ventricular septum.

It was the perimysial fibrous sheets within the overall fibrous matrix of the ventricular mass, nonetheless, that were emphasised by LeGrice and colleagues [15] as permitting the collections of myocytes to slide alongside one another during systole and diastole. In their report, however, the group from New Zealand illustrated the fibrous sheets as producing radial partitions that extended throughout the ventricular wall, running from the endocardial to the epicardial surfaces. This is not the case. Instead, as now described accurately by Criscione and colleagues, the 'myolaminae are highly discontinuous and thus begin and end many times between the inner wall and the outer wall' [8,16]. The myriad perimysial partitions are themselves anchored within the epimysium, which surrounds the ventricular mass and protects the entire structure against disruptive degrees of stretch [17]. The overall arrangement,

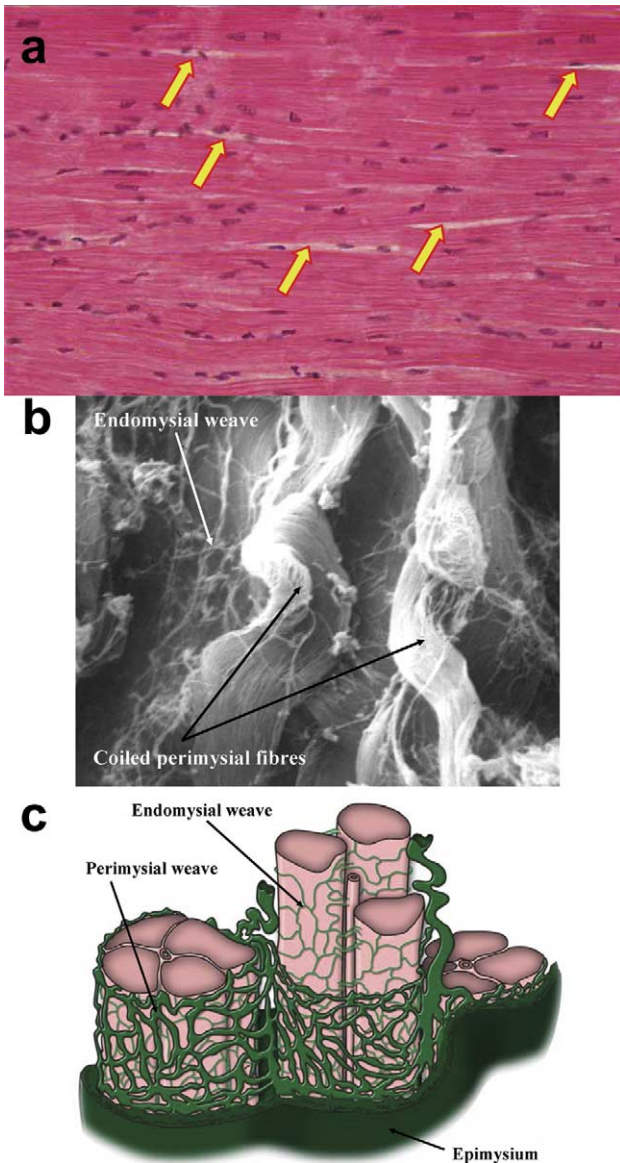


Fig. 2. (a) This section of the ventricular wall shows the basic arrangement of the myocardiocytes, which are joined to the neighbours in such a fashion that it is possible to discern their long as opposed to their short axis. The spaces between the cells (arrows) are filled by the supporting matrix of fibrous tissue. (b) This scanning electron micrograph shows the endomysial weave that surrounds each individual myocyte, and the coiled perimysial fibres that link collections of individual myocytes into so-called myofibres. (c) The cartoon shows how the supporting fibrous matrix of the mesh can be described in terms of its epimysial, perimysial, and endomysial components [13,16].

therefore, is for the myocytes to be supported as a continuous and complex mass, with epimysial, perimysial, and endomysial components (Fig. 2c) [17,18].

3. The alignment of the myofibres within the ventricular wall

When the epicardium, or epimysium, that surrounds the ventricular mass is removed by blunt dissection, thus revealing the planes of cleavage between the collections

of myocytes aggregated within the perimysial partitions, the process also demonstrates an obvious 'grain' within the myocardial architecture (Fig. 3). It has been by studying the marked variations in this 'grain' that anatomists, throughout the centuries, have considered it possible to identify various muscle bundles within the overall continuum of the ventricular walls [4,19-31], not least the notorious 'ventricular myocardial band' [4,5]. When we made our own initial descriptions, however, we were at pains to emphasise that our use of the term fibre, when referring to a collection

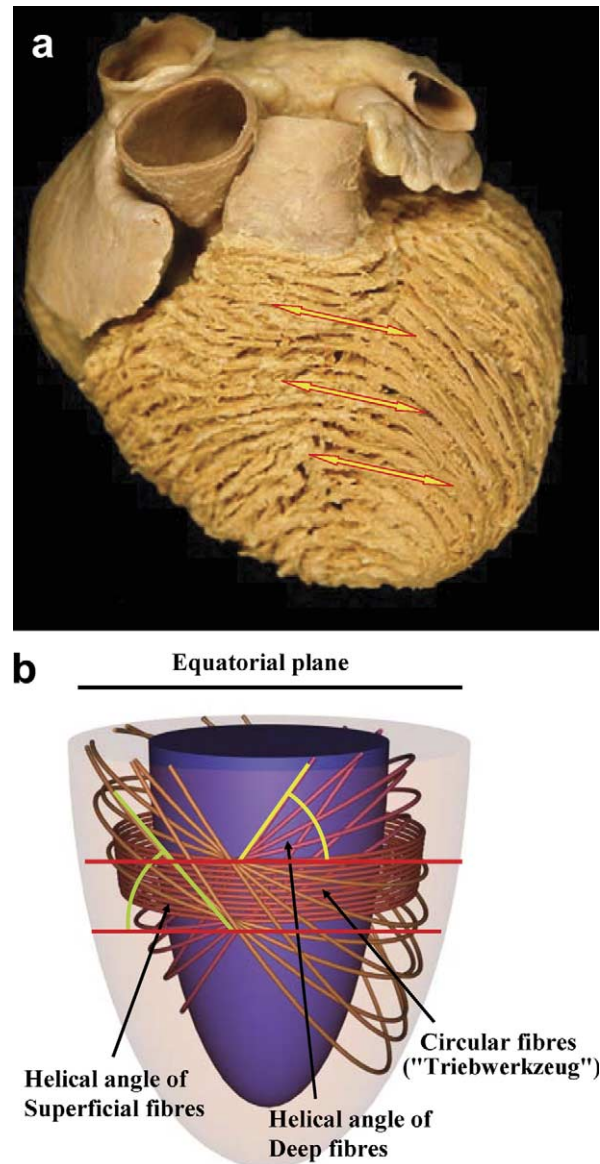


Fig. 3. (a) This normal heart has been prepared by blunt dissection, removing the epimysial component of the supporting fibrous matrix and emphasising the perimysial components that group the individual myocytes into myofibres. The long axes of the myofibres are readily seen (arrows), with the superficial myofibres enclosing both the right and the left ventricles. (b) The cartoon shows the different angles subtended by the long axis of the aggregates of ventricular myocytes relative to the equator of the left ventricle. It was this angle that was shown by Streeter and colleagues [34-39], and also by Greenbaum et al. [7], to vary at different depths within the ventricular wall. Note that the circular fibres of the middle layer are parallel to the ventricular equator.

of myocardial cells, was 'a convenient description rather than an anatomical entity' [7]. Criscione and colleagues [8] also highlight the significance of this concept when they argue in favour of the 'continuum' approach introduced by Hunter and Smaill [9]. As they indicate, it is this concept that is now adopted by most bioengineers seeking to model the function of the ventricular myocardium. It was Lev and Simkins [32], nonetheless, who first emphasised the potential dangers inherent in the quest of anatomists seeking to identify individual 'bundles' within the continuum of the ventricular walls. Grant [33] then reinforced these reservations, arguing that any concept depending on the existence of separate 'muscles' within the ventricular continuum would be spurious because of the intricate and extensive branching structure of the myocardial arrangement. Almost half a century ago, therefore, these investigators [32,33] showed how it was subjective decisions made by the dissector that produced an apparent array of individual bundles within the ventricular walls. It is pertinent, nonetheless, to review these various descriptions, if for no greater purpose than to show the multiple occasions on which these earlier workers, most notably Pettigrew [3, 26,27], described the existence of spiral configurations within the overall ventricular myocardial weave.

4. Earlier accounts of ventricular architecture

The potential functional significance of the alignment of the fibres within the ventricular walls had already been recognised by Harvey [19], albeit that he indicated his own indebtedness to Vesalius, the father of the Padovan school of human anatomy. Shortly thereafter, in the middle of the 17th century, Stensen [20] and Lower [21] had recognised and described the overall helical disposition of the 'grain' revealed by careful dissection of the ventricular walls, with Lower [21] also making the observation that the apical thin point of the left ventricle was devoid of myocardium, the endocardial and epicardial layers being continuous at this site. Then, early in the 18th century, Winslow [22] made the important observation that the walls of the two ventricles were discrete entities, albeit that the two ventricular shells were enclosed with an encircling common subepicardial layer of myocardium. Senac [23], publishing in the middle of the 18th century, extended the concept of separate ventricular layers, emphasising the helical arrangement of the inner and outer muscular coats, but also making the important observation that the left ventricle possessed a middle layer of circular fibres. Ludwig [24], a century later, endorsed this concept, and further showed that, in any cube of myocardium taken from the wall of the left ventricle, the long axis of the subendocardial fibres was more-or-less at right angles to the long axis of the fibres forming the subepicardial layer. Ludwig [24] also introduced the concept of the middle fibres forming a cylinder around the left ventricle, this idea being further developed by the end of the nineteenth century by Krehl [25], who christened the fibres the 'Triebwerkzeug'. The origin of this work is crucial to our ongoing discussions, particularly with relevance to cardiodynamics. In the German language, 'Trieb' the noun is

derived from the verb 'treiben' which means to drive, or to propel. 'Werk' has three meanings: either an action or 'opus', as used in the arts, or the factory or workplace where workmen carry out their labour, or the engine or actuator. As used in the context of the ventricles, it is the latter translation that is appropriate, so that the 'Triebwerkzeug' were envisioned by Krehl as the 'actuating fibres' of the myocardial syncytial mesh. In fact, this concept of the separate populations of longitudinal and circular fibres within the left ventricular walls had already been further developed by Pettigrew [26,27] before Krehl emphasised the potential functional significance of the middle layer for ventricular ejection [25]. Pettigrew believed it was possible to identify seven discrete layers within the left ventricular wall, albeit that, in the summary of his work published in 1908, he was careful to emphasise that 'unlike the generality of voluntary muscles, the fibres of the ventricle, as a rule, have neither origin nor insertion, that is they are continuous alike at the apex of the ventricles and at the base' [3]. Pettigrew had made the important observation that the angulation of the long axis of the fibres relative to the equatorial axis of the ventricle changed with the level within the ventricle as assessed from base to apex (Fig. 1a). He was able to show that the fibres forming the outer layer were continuous with those of the inner layer, with the transition between these layers occurring at the apex (Fig. 1b), the second outer layer reflecting back to form the second inner layer at a somewhat more basal level, the third outer layer becoming the third inner layer at a still more basal level, and the circular fibres forming a discrete cylinder around the ventricular inlet and outlet at the base. Pettigrew's overall concept, summarised in his book of 1908 [3], provides multiple illustrations of the spiral configurations sought by the supporters of the 'ventricular myocardial band' (Fig. 1b), but sets this information in the appropriate configuration of the heart arranged as a modified blood vessel. This concept of ventricular architecture was then supported by Thane, who incorporated the architectural plan when he edited the tenth edition of Quain's anatomy [28], accepted as the most authoritative treatise on human anatomy then published in the English language.

With the turn of the 20th century, there was a marked shift in anatomical opinion. This was driven initially by the studies of MacCallum [29], who investigated macerated hearts from porcine embryos. As far as we can judge, it was MacCallum [29] who was first responsible for making the analogy with skeletal muscle, ascribing a major role to the fibrous skeleton as a site for origin and insertion of the ventricular fibres. He also introduced the concept of following main pathways of ventricular fibres, believing that he was able to dissect away all the side branches of the myocardial syncytium. On this basis, he proposed that superficial fibres from one ventricle passed from an origin at the atrioventricular rings to the apex of the other ventricle, where they penetrated the ventricular wall to terminate in the papillary muscles. He continued to recognise, nonetheless, the circular band of fibres unique to the left ventricle [29], which Krehl had emphasised as the 'Triebwerkzeug' [25]. Mall then extended MacCallum's observation in the developing pig [29] to the human heart [30]. In a study that was to prove influential in dictating

anatomic thought throughout the first half of the 20th century, Mall [30] claimed to have demonstrated the existence of a series of complex spirals and loops of muscle. He identified four main groups, which he termed the deep and superficial bulbo-spiral bands, and the deep and superficial sino-spiral bands.

It was against this background that Torrent-Guasp, in the last quarter of the 20th century, first introduced his concept of the 'unique myocardial band' [34]. Despite the caveats and heuristic problems inherent in any technique employing dissection that had been emphasised by Lev and Simkins [32], and further documented by Grant [33], Torrent-Guasp claimed, as had MacCallum before him [29], that it was possible to follow the principle pathway taken by fibres as they traversed the ventricular wall. His conclusion at this early stage was that the principle pathways constituted a 'nested' set of conical spiral sheets. Within the nested sheets, he also claimed to be able to distinguish the continuity of pathways that he believed extended from the aorta to the pulmonary trunk, encircling the left ventricle in the configuration that has now become known as the 'ventricular myocardial band' [1]. It is noteworthy, however, that although Torrent-Guasp also de-emphasised the concept of the fibrous skeleton as a potential anchorage of the fibres, he offered no explanation as to the nature of the anatomical structures which permitted him to dissect out the myocardial band with the consistency he claimed to demonstrate [34].

At the same time that Torrent-Guasp [34] was purporting to show the changing angulations of the fibres forming the nested sets of conical spiral sheets, Streeter and his colleagues, in a series of studies involving hearts from dogs, pigs, and monkeys [35-40], measured the changing angles of the longitudinal axis of the aggregates of myocytes at different depths within the left ventricular wall, findings that closely parallel the earlier observations of Pettigrew [3]. The findings of Streeter and his associates [35-40] also served to underpin the unfortunate concept of 'contractility'. They had presumed, as had most others investigating cardiodynamics, that all the fibres running within the ventricular wall were orientated in tangential fashion, or at least showed minimal deviation from the tangential plane. The angle that they measured, therefore, was the one subtended by the long axis of the fibre relative to the plane of the ventricular equator (Fig. 3b). This was also the angle measured by Greenbaum and his colleagues [7], but unlike the studies of Streeter et al. [35-40], the histological investigations made by Greenbaum and his associates [7] identified, on the basis of aggregates of myocardial fibres running parallel to the equatorial plane (Fig. 4), the important circular fibres first noted by Ludwig [24], and brought into prominence by Krehl as the 'Triebwerkzeug' [25]. These circular fibres also figure prominently in the concept developed by Pettigrew [3]. It is the rapid change in angulation of the aggregates of the myocytes, emphasised by both Pettigrew [3] and Greenbaum and his colleagues [7], that permits the identification of layers within the left ventricular wall (Fig. 4), and shows that a discrete circular middle layer is lacking from the wall of the right ventricle (Fig. 5). As was emphasised by Greenbaum and colleagues [7], talking full note of the caveats emphasised by Lev and

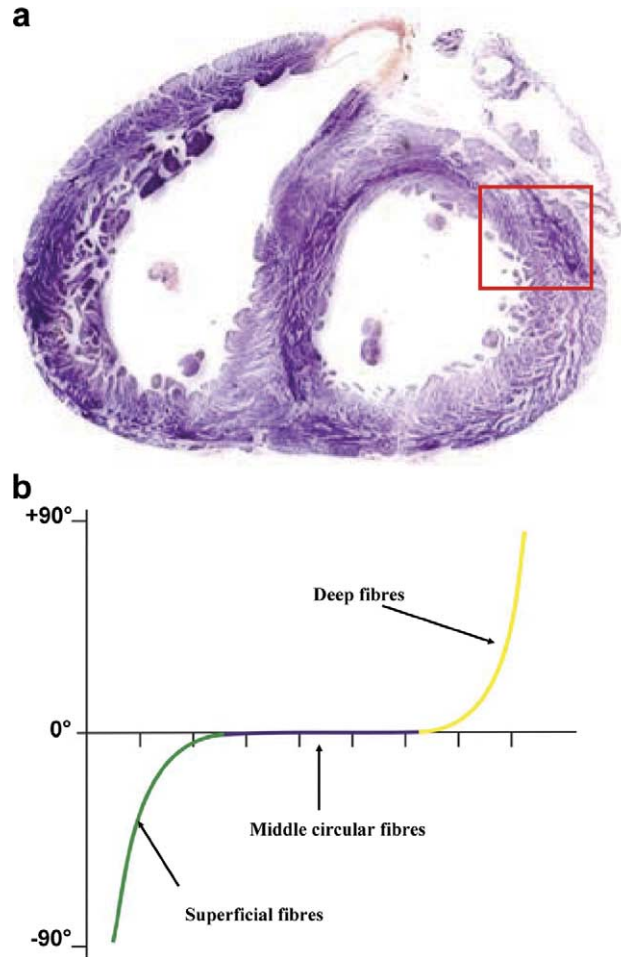


Fig. 4. The section to the left hand is taken from the ventricles close to their base. A block of myocardium was removed from the wall, as shown by the 'box', and sectioned so as to permit measurement of the angulation of the long axis of the myofibres relative to the equatorial ventricular axis (see Fig. 3b). The graph to the right hand shows the changing radial angulation of the fibres, as shown on the y-axis, with increasing depth within the ventricular wall, as shown on the x-axis. It is the rapidly changing angulation from longitudinal to circular orientation that underpins the concepts of layers within the wall, albeit that there are no fibrous partitions separating the 'layers' [7].

Simkins [32] and Grant [33], 'the concept of layers within the ventricular wall has been used to describe the appearances produced by dissection or histology. This must not be taken to imply the presence of discrete fibrous septa but rather to indicate regions within the wall where orientation appears to change little with depth, in contrast to those where it changes rapidly' [7].

5. The basic architecture of the ventricular walls

As is stressed in the letter of Criscione and colleagues [8], and as is indicated in the original approach of Hunter and Smaill [9], there is marked uniformity of structure within the ventricular wall, albeit that the manner of packing of the myocytes within the supporting matrix of fibrous tissue is such that any individual area of the wall will possess a unique morphologic pattern (Fig. 5). Thus, although it is possible to

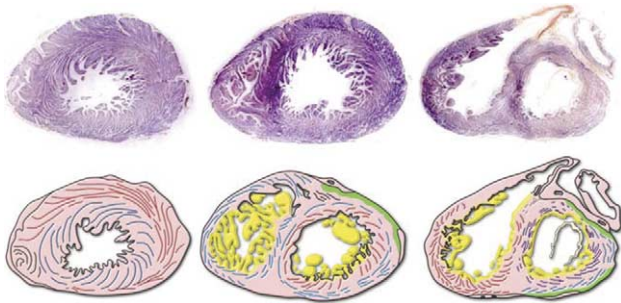


Fig. 5. This cartoon summarises the findings of Greenbaum and colleagues [7], who cut histological sections throughout the ventricular mass as shown in the upper panels, and then quantitated the angulation of the myofibres relative to the ventricular equator. The longitudinal epicardial layer is shown in green, while the longitudinal subendocardial layers are coloured yellow. The circular fibres are shown in purple, whilst fibres spiralling counterclockwise are shown in red, and clockwise spiral fibres in blue. As can be seen, there are multiple helical patterns to be seen in short axis sections taken across the ventricular mass, albeit without discrete fibrous partitions producing any 'muscle bundles'.

recognise the primary arrangement of individual myocytes, and it is then possible to distinguish a secondary pattern of aggregation of groups of the myocytes within the perimysial compartments, it is not then possible to distinguish any tertiary arrangement of reproducibly arranged myocardial bundles. Instead, the best that can be achieved is to distinguish the overall alignment of the long axis of the so-called 'myofibres' enclosed within the individual perimysial sleeves, recognising that the perimysium itself forms an intricate meshwork as it extends from the epicardial to the endocardial surfaces of the ventricular wall. In a recent issue of the Journal, we showed how the long axis of these myofibres (Fig. 6) could now be distinguished using magnetic resonance diffusion tensor imaging [41]. The purpose of our study was to validate using histology the role of resonance imaging in demonstrating the overall longitudinal alignment of the fibre bundles (Fig. 6). This work attracted still further editorial comment, commissioned not from an authority in cardiac anatomy and histology, but from one of the supporters of the ventricular myocardial band [42]. In this comment, we were severely criticised, first for failing to mention the helical arrangement of the myofibres within the ventricular wall, and second for deigning to submit our account for publication in the surgical literature. As Buckberg noted in his comment [42], the existence of helical arrangements of myofibres is evident in the illustrations we provided to demonstrate the structure of the ventricular walls. This is hardly surprising, since we have never denied the existence of such helical configurations, and they are readily seen in the majority of previously published accounts of ventricular structure [10-14,20-30], in particular the detailed account given by Pettigrew [3] (Fig. 1b). Our purpose in publishing the work was not to deny the existence of helical configurations within the walls, but rather to show the absence of any condensations of fibrous tissue within the supporting matrix that permitted these spiral formations to be dissected in the form of a unique myocardial band. In making his criticisms, Buckberg [42] conveniently ignored the fact that the 'gold standard' for publication of any

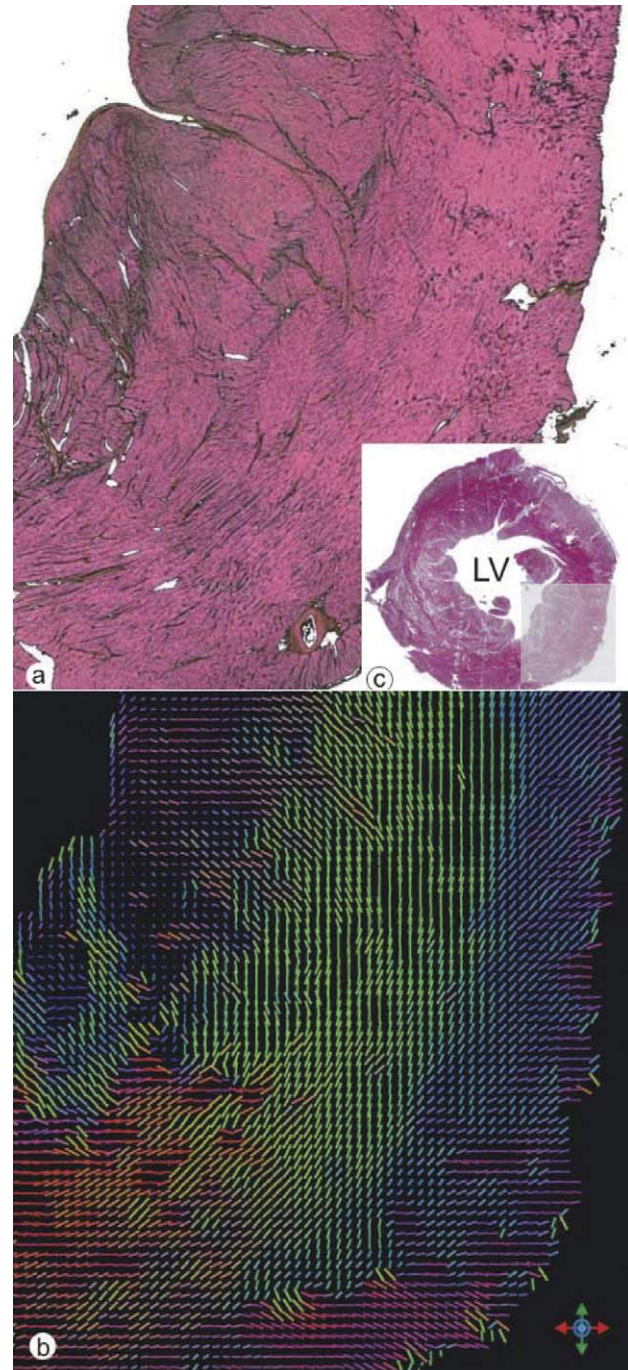


Fig. 6. These panels are reproduced, with permission, from the study of Schmid et al. [41]. They show the accuracy with which magnetic resonance diffusion tensor imaging is able to display the longitudinal orientation of the aggregations of myofibres within the ventricular wall. The left hand panel and the inset show the location of the histological section, while the right hand panel is the comparable resonance image of the segment of ventricular wall. Note that the fibrous tissue is randomly distributed to form a myocardial mesh, with no 'sheaths' enclosing specific myocardial bundles.

anatomic investigation remains the basic rules of anatomy, as taught in the dissecting room. These rules hold good irrespective of the journal in which the work is published. As we have been at pains to stress throughout our writings on this topic [2,7,10-14], there are no fibrous sheaths within

the ventricular walls that permit the myofibres to be dissected on the basis of muscle bundles having a discrete origin and insertion, as is the case with the arrangement of the skeletal muscles within the trunk and limbs. The only fibrous sheaths to be found are those that insulate the fibres of the histologically specialised ventricular bundle branches from the ventricular mass. And these are identified only with the aid of microscopic investigation. For the skeletal muscles, in contrast, with the exception of the tongue, it is the presence of these sheaths that permits anyone to demonstrate, by dissection, the basic muscular arrangement, be the prosector an experienced anatomist or the tyro beginning his or her studies in the dissecting room. This is not the case for the heart, and nor is it the case for the tongue. Intricate patterns of muscular aggregates can certainly be demonstrated by dissection of the ventricular walls. But, since the muscle fibres are attached to each other, as they are in the tongue, there is no discrete and uniform arrangement of muscle bundles, simply because the ventricular walls lack any tertiary anatomic arrangement.

As stressed above, the best that can be achieved when dissecting the walls, or observing the pattern of the myofibres as revealed in histological sections, is to note the change in orientation of the long axis of the bundles of fibres enclosed within the perimysial condensations of fibrous tissue (Fig. 4). Then, as was stressed previously by Greenbaum and associates [7], the myofibres in the immediately subendocardial and subepicardial parts of the wall are oriented in longitudinal fashion relative to the ventricular equator, with changing angulations when measured on a radial axis. At the base of the left ventricle, however, there is a distinct collection of circular fibres oriented parallel to the ventricular equator (Fig. 3). They are readily distinguished in cross-sections of the ventricular mass, sections which also demonstrate the rapid change in angulation of the outer and inner layers relative to the middle circular fibres. The rapid change in angulation is confirmed by measurements of the angulation as assessed relative to the radial axis [7] (Fig. 4). As we have emphasised, it is these circular myofibres that represent the 'Triebwerkzeug', or actuating fibres, recognised by Krehl [25], and subsequently confirmed by several other anatomists [29,30]. There is no description of these circular fibres in the account given by Torrent-Guasp of his multiple dissections. This is surprising, since they have been noted by very many distinguished anatomists [4,23-30], and they were an obvious feature of our own dissections [7,10-12]. This omission by Torrent-Guasp is the more important, since because of the existence of the circular fibres, the septum 'belongs' to the left ventricle. In this respect, von Segesser, in his own introduction to the ongoing debate [43], pointed to a cleavage plane at the base of the ventricular septum, commenting that it acted as a useful guide for the surgeon removing the free-standing subpulmonary infundibulum as part of the Ross procedure. We also recognise the existence of this plane, which is readily seen in long axis sections of the ventricular mass. It has nothing to do, however, with the alleged 'myocardial fold' that Torrent Guasp [1] claims to permit the right ventricle to be unwrapped from the left

ventricle as part of a ventricular band. Rather the plane of cleavage at the ventricular base is simply the point of access of the septal perforating arteries as they enter the crest of the ventricular septum. The plane of cleavage itself disappears once the perforating arteries have ramified within the ventricular septal myocardium. Buckberg [42] suggests that Fig. 6 from our work produced in association with Schmid and his colleagues [41] 'may indeed show the transverse elements defined by Torrent-Guasp for the basal loop'. We can reassure Buckberg that we reviewed our results with the greatest of care in efforts to discern the various components of the ventricular myocardial band. Had they existed, we would have described them. Unfortunately for the supporters of the ventricular myocardial band, there is no anatomic evidence to support this concept. As we have stressed, when describing anatomy, it is the rules of anatomy which must be obeyed. We can reassure Buckberg, nonetheless, that there is a vast amount of evidence to support the overall concept of a helical arrangement of the bundles of myofibres to be found within the ventricular walls. We have never doubted this fact, which was first emphasised by Senac as long ago as the 18th century [23]. The spiral, or helical, configurations are to be found throughout the ventricular walls, representing no more than the overall alignment of the long axis of the myofibres within the supporting fibrous matrix, as emphasised in the detailed account provided by Pettigrew to explain the spiral 'design in nature' [3]. Intriguingly, nonetheless, when the angulation of these bundle is measured having cut the ventricular wall with a circular knife (Fig. 7), evidence emerges for the existence of two discrete populations of myocytes, those that are oriented in tangential fashion relative to the epicardial surface of the wall, and those that intrude in relatively radial fashion. It was this dualistic arrangement that we emphasised in our earlier review [2], one that attracted such severe criticism from the supporters of the unique myocardial band [5,6]. It seems that, in their urge to restate their own unorthodox concept of the arrangement of the ventricular mass, the potential functional significance of our own findings may have escaped their attention. As Buckberg emphasises in his commentary [42],

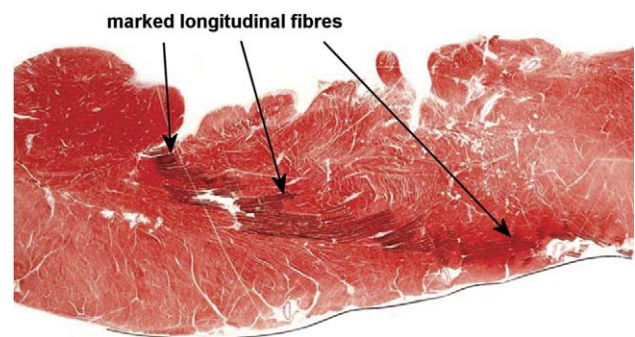


Fig. 7. This section through the short axis of the ventricular wall has been cut with a circular knife, making it possible to cut the fibres along their long axis over greater distances than in typical sections taken through the wall. When tracing the long axis of the myofibres, as marked in black, it is possible to discern a spiral tract that runs from the epicardium (bottom) to the endocardium (top).

a view with which we are in complete agreement 'the fibre orientation reported in the literature supports a helix, and exclusion or denial of this central architecture is not an acceptable way to introduce the surgical world into methods that are new in our literature'. The comments prepared by the supporters of the myocardial band [5,6] show that the distance between morphologists and physiologists, which seemed historically to be insurmountable, continues to exist. Perhaps it was because of this that physiologists and surgeons, like Torrent-Guasp, started to do their own morphology, albeit using inadequate tools. We recognise fully the need to correlate the structure of the ventricular muscle with its function. But with regard to structure, this must be done following the rules of anatomy, and not those of physiology or surgery. It is our mission, therefore, to restate the anatomical situation, since those such as Buckberg [42] seem to have failed to grasp that we have never sought to deny the central helical nature of the overall architecture of the ventricular walls. All the available evidence shows that this helical structure is to be found throughout the walls, and is in no way arranged as a unique myocardial band. Paradoxically, by continuing to provide uncritical support of the myocardial band, it is Buckberg [42] himself who will continue to prevent those working in the surgical world appreciating the 'continuum' of myocardium and supporting fibrous matrix which represents the true structure of the ventricular walls.

Acknowledgements

Robert H. Anderson is supported by grants from the British Heart Foundation together with the Joseph Levy Foundation. Research at the Institute of Child Health and Great Ormond Street Hospital for Children NHS Trust benefits from R&D funding received from the NHS Executive. Klaus Redmann and Paul P. Lunkenheimer are supported by grants from the Deutsche Forschungsgemeinschaft, the Ernst und Berta Grimmke Stiftung and the Karl und Lore Klein Stiftung.

References

- [1] Torrent-Guasp F, Kocica MJ, Corno A, Komeda M, Cox J, Flotats A, Ballester-Rodes M, Carreras-Costa F. Systolic ventricular filling. *Eur J Cardiothorac Surg* 2004;25:376-86.
- [2] Lunkenheimer PP, Redmann K, Anderson RH. The architecture of the ventricular mass and its functional implications for organ-preserving surgery. *Eur J Cardiothorac Surg* 2005;27:183-90.
- [3] Pettigrew JB. Design in nature. vol. 2. London: Longmans, Green, and Co.; 1908 p. 506-518.
- [4] Keith A. The functional anatomy of the heart. *Br Med J* 1918;361-3.
- [5] Torrent-Guasp F, Kocica MJ, Corno AF, Komeda M, Carreras-Costa F, Flotats A, Cosin-Aguillar J, Wen H. Towards new understanding of the heart structure and function. *Eur J Cardiothorac Surg* 2005;27:191-201.
- [6] Buckberg GD. Architecture must document functional evidence to explain the living rhythm. *Eur J Cardiothorac Surg* 2005;27:202-9.
- [7] Greenbaum RA, Ho SY, Gibson DG, Becker AE, Anderson RH. Left ventricular fibre architecture in man. *Br Heart J* 1981;45:248-63.
- [8] Criscione JC, Rodriguez F, Miller CD. The myocardial band: simplicity can be a weakness. *Eur J Cardiothorac Surg* 2005;28:363-4.
- [9] Hunter PJ, Smaill BH. The analysis of cardiac function: a continuum approach. *Prog Biophys Mol Biol* 1988;52:101-64.
- [10] Anderson RH, Becker AE. Cardiac anatomy. An integrated text and colour atlas. London: Gower Medical Publishing; 1980 p. 5.14-5.26.
- [11] Sánchez-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* 1990;138:352-8.
- [12] Sánchez-Quintana D, Anderson RH, Ho SY. Ventricular myoarchitecture in tetralogy of fallot. *Heart* 1996;76:280-6.
- [13] Lunkenheimer PP, Müller RP, Konermann C, Lunkenheimer A, Kohler F. Architecture of the myocardium in computed tomography. *Invest Radiol* 1984;19:273-8.
- [14] Lunkenheimer PP, Redmann K, Cryer CW, Sánchez-Quintana D, Ho SY, Anderson RH, Batista RV. Left ventricular mechanical activity reduced by partial left ventriculectomy. *Ann Thorac Surg* 2000;69:1257-9.
- [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 Heart Circ Physiol* 1995;269:H571-H82.
- [16] Harrington KB, Rodriguez F, Cheng A, Langer F, Ashikaga H, Daughters GT, Criscione JC, Ingels NB, Miller DC. Direct measurement of transmural laminar architecture in the anterolateral wall of the ovine left ventricle: new implications for wall thickening mechanics. *Am J Physiol Heart Circ Physiol* 2005;288:H1324-H30.
- [17] Borg TK, Caulfield JB. The collagen matrix of the heart. *Fed Proc* 1981;40:2037-41.
- [18] Robinson TF, Cohen-Gould L, Factor SM. The skeletal framework of mammalian heart muscle: arrangement of inter- and pericellular connective tissue structures. *Lab Invest* 1983;49:482-98.
- [19] Harvey W. An anatomical disquisition on the motion of the heart and blood in animals (1628). In: Willis FA, Keys TE, editors. *Cardiac classics*. London: Henry Kimpton; 1941. p. 17-19.
- [20] Stensen N. De musculis et glandulis observationum specimen, cum epistolis anatomica. Amsterdam: P le Grand; 1664 p. 90.
- [21] Lower R. Tractatus de corde. London: J Allestry; 1669.
- [22] Winslow JB. Observations sur les fibres du coeur et sur ses valvules. Histoire (et Mémoires) de l'Académie Royale des Sciences (Paris) 1711 (1714) pt 2:151-6.
- [23] Senac JB. Traité de la structure du coeur. Paris: J Vincent; 1749.
- [24] Ludwig C. Ueber den Bau und die Bewegungen der Herzventrikel. *Z rationell Med* 1849;7:189-220.
- [25] Krehl L von. Beiträge zur Kenntniss der Füllung und Entleerung des Herzens. Abhandlungen der Mathematisch-Physischen Classe der Königlich-Sächsischen Gesellschaft der Wissenschaften, 1881;17:340-383.
- [26] Pettigrew JB. On the arrangement of the muscle fibres in the ventricles of the vertebrate heart, with physiological remarks. *Phil Trans Roy Soc* 1865;154:445-500.
- [27] Pettigrew JB. On the arrangement of the muscular fibres of the ventricular portion of the heart of the mammal. *Proc Roy Soc Lond* 1860;10:433-40.
- [28] Thane DG. Quain's Elements of Anatomy. 10 ed 1890.
- [29] MacCallum JB. On the muscular architecture and growth of the ventricles of the heart. *Johns Hopkins Hosp Rep* 1900;9:307-35.
- [30] Mall FP. On the muscular architecture of the ventricles of the human heart. *Am J Anat* 1911;11:211-66.
- [31] Robb JS, Robb RC. The normal heart. Anatomy and physiology of the structural units. *Am Heart J* 1942;23:455-67.
- [32] Lev M, Simkins CS. Architecture of the human ventricular myocardium, technique using a modification of the mall-samacCallum method. *Lab Invest* 1956;5:396-409.
- [33] Grant RP. Notes on the muscular architecture of the left ventricle. *Circulation* 1965;32:301-8.
- [34] Torrent-Guasp F. The cardiac muscle. Madrid: Fundacin Juan; 1973.
- [35] Streeter Jr DD, Bassett DL. An engineering analysis of myocardial fiber orientation in pig's left ventricle in systole. *Anat Reek* 1966;155:503-11.
- [36] Streeter Jr DD, Sponitz HM, Patel DJ, Ross Jr J, Sonnenblick EH. Fiber orientation in the canine left ventricle during diastole and systole. *Circ Res* 1969;24:339-47.
- [37] Streeter Jr DD, Vaishnav RN, Patel DJ, Spotnitz HM, Ross J, Sonnenblick EH. Stress distribution in the canine left ventricle during diastole and systole. *Biophys J* 1970;10:345-63.

- [38] Streeter Jr DD, Hanna WT. Engineering mechanics for successive states in canine left ventricular myocardium. I. Cavity and wall geometry. *Circ Res* 1973;33:639-55.
- [39] Streeter DD Jr, Hanna WT. Engineering mechanics for successive states in canine left ventricular myocardium. 2. Fiber angle and sarcomere length. *Circ Res* 1973;33:656-64.
- [40] Ross MA, Streeter DD. Non uniform subendocardial fiber orientation in the normal macaque left ventricle. *Eur J Cardiol* 1975;3:229-41.
- [41] Schmid P, Jaermann T, Boesiger PF, Niederer PF, Lunkenheimer PP, Cryer CW, Anderson RH. Ventricular myocardial architecture as visualised in postmortem swine hearts using magnetic resonance diffusion tensor imaging. *Eur J Cardiothorac Surg* 2005;27:468-74.
- [42] Buckberg GD. New technology and old responsibilities. Editorial comment. *Eur J Cardio-thorac Surg* 2005;27:472-4.
- [43] von Segesser LK. The myocardial band: fiction or fact? *Eur J Cardiothorac Surg* 2005;27:181-2.