Review

Morphological and functional evidences of the helical heart from non-invasive cardiac imaging

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Summary

The non-invasive study of cardiac mechanics has been improved after the recent introduction of advanced magnetic resonance and echocardiographic imaging techniques. Tagged and diffusion-sensitive cardiac magnetic resonance allows the study of myocardial torsion dynamics as well as the anatomical disposition of myocardial fibers. Local myocardial strain and synchronicity of myocardial contraction can also be determined with Doppler tissue imaging (DTI) echocardiography. Published results with these techniques demonstrate a mechanical behavior that is a consequence of a myocardial helical fiber orientation and strongly support the evidence of the double-loop single muscular band model described by Torrent-Guasp.

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1. Introduction

Improved understanding of cardiac action requires a blending of structure/function relationships. This interaction is improved by advanced cardiac imaging techniques that have become a useful tool for the study of coordinating cardiac anatomy and function. The helical arrangement of cardiac muscle fibers is known for more than 500 years \cite{1}, although it has not been known until recently that non-invasive studies with diffusion tensor magnetic resonance imaging (MRI) have been able to depict that complex spatial organization of the left ventricular (LV) myocardial fibers \cite{2} (Fig. 1). Boettler et al. \cite{3} recently used Doppler tissue imaging (DTI) echocardiography to confirm that the interventricular septum is a morphologically and functionally bilayered structure (Fig. 2). These anatomical and physiologic observations agree with the myocardial band spatial arrangement described by Torrent-Guasp early in the 1960s \cite{4}. The determination that Torrent-Guasp's myocardial band anatomical description shall have a significant impact on our hemodynamic thinking requires demonstration that the functional aspects of cardiac mechanics and their relation-ships to the anatomical helical arrangement of the myocardial band clearly reflects ideal biologic mechanisms.

The cardiac helical fiber concept was described in 1969 (twisting motion of the left ventricle with angular displacement = torsion of the apex relative to the base) and mathematically provides a better approximation of normal ejection fraction than the conventional circumferential fiber model \cite{5}. Torrent-Guasp's anatomical description of the myocardial fiber helical orientation in a double-loop single myocardial band introduces a structural model that allows a geometric basis that may enhance understanding of myocardial mechanics \cite{6}. According to the anatomical double-loop arrangement of the myocardial band, the variation of the ventricular volume should take place by successive torsion and reciprocal torsion movements of the myocardial band.

This paper shall present objective data that is obtained from non-invasive imaging techniques, studies of tagging and diffusion from cardiac magnetic resonance, and evaluations by Doppler tissue imaging echocardiography that confirm the presence of the myocardial fibers, and thereby support the myocardial band concept proposed by Torrent-Guasp.

2. Cardiac magnetic resonance tissue tagging

The study of cardiac muscle kinematics has been largely improved after the introduction of MRI tissue tagging techniques \cite{7}. The depiction of myocardial fiber orientation...
is fundamental to understand ventricular mechanics. Tagged MRI allows the study of myocardial strain. Specific myocardial regions can be labeled to track their deformation (strain) during the cardiac cycle, using selective radiofrequency excitation to produce a few saturated parallel planes within the heart wall [8]. Improvements in the initial tagging technique have been achieved with the complementary spatial modulation of magnetization (CSPAMM) method [9], thereby increasing the persistence of tag signals and thus permitting analysis during the full cardiac cycle that includes the diastolic period.

3. Left ventricular twist tagged cine-MRI assessment

The first description of the complete systolic time course of myocardial motion using tagged cine-MRI was published by Lorenz et al. [10]. These investigators observed that during LV isovolumic contraction, the myocardial twist is counterclockwise when seen from the apex. However, later in systole, the base of the LV changes the rotation to the clockwise direction, whereas the apical segments continue counterclockwise (Fig. 3). This integrated mechanical behavior of the left ventricular myocardium results from the spatial arrangement of the myocardial fibers. A helical fiber orientation in a single direction would not produce this peculiar torsion and reciprocal torsion of the left ventricle observed by tagged cine-MR, unless there is consideration of a double-loop spatial arrangement of the myocardial fibers in an oblique pattern [11]. In fact, an alternating distribution of laminar sheets can be observed in histological sections of the myocardial wall and biomechanical studies have shown that the distribution of stress and strain in biological tissue is strongly dependent on fiber orientation [12]. Harrington et al. [13] measured two alternating groups of sheet angles in transverse sections of the anterolateral wall of the ovine left ventricle, and reported that mean fiber angles progressed nearly linearly from $-41^\circ$ (SD 11) at the epicardium to $+42^\circ$ (SD 16) at the endocardium. This peculiar distribution of two families of sheets agrees with the spatial arrangement of the myocardial band proposed by Torrent-Guasp et al. [14].
Geerts et al. [15] supplied evidence in Fig. 4 that measurement of the cross-over of the myocardial layers displays a transmural component of muscle fiber direction that is a helical function of the longitudinal position; these data thereby fulfill the contributions of the ascending and descending segments of the apical loop of the ventricular myocardial band described by Torrent-Guasp.

4. The myocardial twist explains cross-fiber shortening

The myocardial twist relates fiber orientation to local wall deformation and explains the mechanism of systolic wall thickening. Rademakers et al. [16] concluded, after a tagged MRI three-dimensional strain analysis of the LV myocardium, that the interaction between the different layers of the myocardial fibers is the primary source of wall thickening. A significant correlation between regional thickening and endocardial cross-fiber shortening was observed, while no correlation was found between myocardial fiber strain and wall thickening. Waldman et al. [17] has suggested that rearrangement of laminar myocardium is the proposed mechanism that explains paradoxically large cross-fiber shortening. On the other hand, Costa et al. [18] stated that normal LV mechanics involves considerable deformation of the myocardial wall laminar sheets. These investigators observed that in the LV anterior free wall the myocardial sheets become thinner from end-diastole to end-systole. This occurs with a substantial sheet extension that is transverse to the muscle fibers and varies in a transmural and regional fashion. However, these authors could not identify the specific mechanisms by which myocyte contraction is converted to sheet extension and interlaminar shear. A distinct possibility is that the double-loop arrangement of the myocardial fiber sheets may reflect a unifying mechanism that could easily explain this action. The sequential contraction of the myocardial band results in a progressive shortening and lengthening of the myocardial band segments that is determined by the spatial arrangement of fibers. This hypothesis is partially confirmed in the elegant report of Tseng et al. [19] using diffusion-sensitive MRI, where the systolic strain across transmural depth of myocardial fiber orientation displayed a directional change going from maximal to minimal shortening between epicardial and endocardial layers. This spatial arrangement would produce a paradoxical cross-fiber shortening along the myocardial wall depth, whereas fibers that rotate away from the direction of greatest shortening would continue to shorten in a proportionally small constant amount.

5. The systolic ventricular strain pattern

Tissue-tagged cardiac MRI has demonstrated a progressively improving spatial and temporal resolution. Moore et al. [20] published the data of three-dimensional systolic strain patterns in the normal human LV, obtained with tagged MRI sequences with temporal and spatial resolutions of 32.5 ms and 6 mm, respectively. Their observations agree with the predicted deformation of the LV myocardium according to the double-loop myocardial band model: in systole, the base of the heart descents toward the apex, while the apex remains relatively still. An LV long-axis torsion produced by the domination of the epicardial muscular fibers is observed, which spiral from the apex to the base in a clockwise direction as viewed from the base. The torsion serves to increase fiber contraction at the epicardium and decrease it at the endocardium. Recently, Notomi et al. [21] validated the usefulness of Doppler tissue imaging against tagged MRI for the assessment of the left ventricular deformation that produces torsion. Doppler tissue imaging introduces the advantage of a better temporal resolution, and allows a simple and less expensive method for the measurement of the temporal evolution of LV torsion in systole and early diastole. Consequently, DTI facilitates the assessment of the relationship between systolic torsion and diastolic suction, a measurement that is either based upon the cylinder model of Ingels et al. [22], or upon the Torrent-Guasp model [23] whereby contraction of a ventricular myocardial band creates a muscular force for suction.
6. Diastolic mechanics of the LV

The diastolic period is crucial for LV filling but few published papers deal with the mechanistic reasons for this diastolic phenomenon. Although it is fully accepted that LV filling is facilitated by the negative pressure produced within the normal LV, the causative mechanisms for this phenomena have not been fully understood. Analysis of the hemodynamic tracings of the aorta and left ventricle show that early diastole, just before rapid filling occurs, exists during the isovolumic phase of systole; this interval is conventionally called isovolumic relaxation. Several hypotheses have been proposed to explain causes of the powerful suction that produces the early rapid LV diastolic filling. The most accepted one is that ventricular twisting in systole stores potential energy, probably via titin, the giant spring like molecule that resists both excessive shortening and elongation of the sarcomere [24]. When the active contraction ends, titin may force rapid untwisting (elastic recoil), lowering pressure in the LV, particularly at the apex, and effectively lead to suction of blood into the ventricle once the mitral valve opens [25].

An alternative cause relates to the Torrent-Guasp hypothesis that involves the double-loop myocardial band spatial arrangement that contains a descending and ascending segment of the apical loop of the myocardial band, whereby end-systolic contraction of the ascending band has a paradoxical effect in the longitudinal LV strain pattern, thereby enlarging ventricular long axis by its shortening to raise the shortened base of the ventricle [23] toward its normal diastolic position (Fig. 5). That regional contraction would continue during the isovolumic relaxation period and coincide with the end of shortening of the previously contracted segments (descending band), and thus facilitate the reciprocal twisting force that generates diastolic suction. Solomon et al. [26] describe that the onset of LV relaxation during normal ejection occurs at 34 ± 3% of the systolic time, occurring at a 16% time interval after the onset of ejection, but significantly before the time interval been traditionally considered. These data confirm that LV relaxation is a progressive phenomenon that coincides with myocardial contraction.

Although the term 'diastole' has been always ascribed to myocardial relaxation from an academic vantage point, we consider this premise to present an obstacle to future acceptance of the fact that the early ventricular filling may be considered as a systolic (contraction) phenomenon. Tagged cardiac MRI reports of analysis of the diastolic phenomena are scarce, but there are a few selected papers that support Torrent-Guasp hypothesis. Karwatowski et al. [27] compared diastolic long-axis LV myocardial velocity measured from MR images and LV filling measured by Doppler echocardiography. They observed that the onset of early diastolic long-axis wall motion preceded early diastolic blood flow in all patients (Fig. 6). This observation confirms that the ascent of the ventricle originates from an intrinsic myocardial force, rather than blood flow distending a passive ventricle.

7. Active contraction of the ascending myocardial band or passive relaxation?

Experimental data obtained by Castella et al. [28] supports the Torrent-Guasp hypothesis by showing active contraction of the ascending segment of the apical loop during rapid deceleration of the left ventricular pressure tracing. Although no relaxation existed during this rapid filling period, more evidence is needed to confirm that early diastolic LV suction is due to, in part, an active myocardial contraction. Fogel et al. [29] analyzed LV diastolic strain and wall motion by myocardial tissue tagging MRI in normal infants and concluded that diastolic mechanics is not homogeneous. A diastolic higher circumferential lengthening strain at the lateral wall was observed in all three LV short-axis section wall motions studied and LV diastolic rotation became more clockwise (negative) during motion from the atrioventricular valve to the apex. Furthermore, each one of the studied LV short-axis sections exhibited a trend for pronounced clockwise rotation of all the anterior wall regions. This observation is consistent with the dog model observations of Rademakers et al. [30] showing that the percent of LV untwisting was significantly greater in the...
cepts are against academic orthodoxy[31], but this natural that opposition exists, since Torrent-Guasp’s published data on ventricular mechanics physiology agree resultant function. This analysis suggests that most of the standing how left ventricular morphology interfaces with the increasing number of manuscripts on cardiac physiology

8. Conclusions

It is a good sign for scientific evolution to recognize that the increasing number of manuscripts on cardiac physiology are becoming matched with renewed interest in understanding how left ventricular morphology interfaces with resultant function. This analysis suggests that most of the published data on ventricular mechanics physiology agree with the underlying geometric theory that is based on the model of the myocardial band helical heart. It remains natural that opposition exists, since Torrent-Guasp’s concepts are against academic orthodoxy[31], but this geometric infrastructure has stimulated global interaction to further understand the interaction of normality[32]. More importantly, we may learn how our better understanding of myocardial form can improve our understanding of disease and how it alters function. This matching of structure and action is the infrastructure of our advancing knowledge about cardiac normality and myocardial dysfunction [32].

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References


