Investigating myocardial motion by MRI using tissue phase mapping

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Abstract

Objective: Velocity-encoded phase contrast magnetic resonance imaging (MRI) provides a tool to quantify regional myocardial wall motion of the entire heart. It allows the acquisition of three-directional velocity vector fields with high spatial resolution that reflect the temporal evolution of myocardial velocities over the cardiac cycle. In contrast to other imaging modalities such as echocardiography left ventricular performance can be assessed without limited anatomical or functional coverage. Methods: Compared to other techniques that quantify local myocardial contractility (e.g. implanted ultrasonic crystals) by means of regional displacement, phase contrast MRI provides information about local and global left ventricular velocities (i.e. motion) by utilizing the intrinsic motion sensitivity of MRI. The resultant motion components of contraction, expansion, rotation, lengthening, and shortening of the left ventricle are described in high spatial and temporal detail. Phase contrast measurements were performed in 12 healthy volunteers with a respiratory-gated technique in order to achieve a high temporal resolution of 13.8 ms to demonstrate the detailed assessment of global and regional myocardial motion. Results: Data revealed details in left ventricular motion patterns that were previously not seen in phase contrast measurements and are only known from echocardiography. For all volunteers, characteristic myocardial motion patterns and locally different radial (i.e. contraction and expansion), rotational (i.e. twisting and untwisting) and longitudinal (i.e. lengthening and shortening) motion components could be detected with high accuracy. Conclusions: The phase contrast MRI technique for high temporal resolution velocity mapping is therefore very promising for the investigation and better understanding of the myocardial motion in normal subjects and patients with disturbed left ventricular performance and may validate further testing of different models of cardiac structure.

Keywords: Magnetic resonance imaging; Tissue phase mapping; Sequential cardiac motion; Helical ventricular myocardial band

1. Introduction

The assessment of dominant myocardial motion components such as contraction, rotation and shortening throughout the cardiac cycle provides insight into myocardial mechanics and the effect of fiber action on left ventricular performance. Different imaging invasive and noninvasive modalities, such as echocardiographic tissue Doppler imaging (TDI), magnetic resonance imaging (MRI), or implanted ultrasonic crystals have been reported for the assessment of global and regional myocardial motion. The phasic myocardial action involves a form function relationship, and the underpinnings of this interaction requires the evaluation of such imaging data of cardiac with respect to a structural model that generates the sequential motions observed by the different imaging modalities. Cardiovascular MRI permits the noninvasive assessment of global and regional cardiac function [1–3]. It provides reliable tools for a true 3D description of cardiac motion and has no limitations in terms of observable regions or affection of measured velocities such as in TDI [4,5]. A number of studies have already demonstrated its usefulness to investigate the complex myocardial deformation associated with the action of left ventricular myocardial fibers [6–8]. The dynamics of cardiac action become evident from magnetic resonance imaging measurements which permit the detailed analysis of different motion components such as rotation and twisting, narrowing, shortening, lengthening and widening of the ventricular chamber [9].

The two most common MRI methods to measure myocardial motion are tagging [10] and phase contrast velocity mapping (tissue phase mapping, TPM) [11,12]. Myocardial tagging is based on the displacement of a spatial saturation grid over the cardiac cycle and is primarily used to calculate strain rates [13]. TPM directly encodes the velocity of myocardial motion into the MR signal [14] and has proven to be a robust tool for the assessment of global and regional myocardial motion [15,16]. TPM offers high spatial resolution of the functional information (1–3 mm) which is limited in tagging by the number and density of the tag lines (4–8 mm). Since both methods, tagging
and TPM, are typically based on multiple breath-held 2D measurements, the temporal resolution is limited by the length of the breath-hold period to 30–80 ms. This limitation was addressed by developing a respiratory-gated free-breathing method for TPM data acquisition that allows measurements with a temporal resolution comparable to TDI [17].

Furthermore, TPM quantifies regional myocardial wall motion with sensitivity comparable to implanted ultrasonic crystals [18] and displays high correlation for left ventricular myocardial velocities with TDI measurements in healthy volunteers [19].

Baseline TPM information in 12 healthy volunteers is reported to demonstrate the feasibility of detailed analysis of regional myocardial motion, and to relate the cumulative results to dominant motion components associated with left ventricular performance. The results are presented on an exemplary basis to introduce the range of different data analysis and visualization modes that include myocardial motion corresponding to contraction/expansion (narrowing/widening) and clockwise/counterclockwise rotation (twisting) in short-axis orientation and shortening/lengthening along the long-axis direction. This work demonstrates the potential of TPM for the investigation and better understanding of the myocardial motion in normal subjects and patients (e.g. with diastolic dysfunction) and may help to clarify and distinguish different models of cardiac structure such as the band-model [20].

2. Materials and methods

2.1. Data acquisition

All experiments were performed on a Siemens Sonata 1.5 T scanner (Siemens Medical Solutions, Erlangen, Germany). Measurements were performed with a four-element phased array body coil on healthy volunteers. Human studies were approved by the local ethics committee and informed consent was obtained from all subjects.

Two-dimensional TPM images were acquired in 12 healthy volunteers with an MR sequence as described previously [12,15] with an in-plane spatial resolution of 1.3 mm × 1.3 mm. Using a navigator-guided technique that allows data acquisition during free-breathing a temporal resolution of 13.8 ms could be achieved [17]. Three slices (8 mm thickness) in short-axis view (basal, mid-ventricular, and apical) were acquired in all measurements.

2.2. Post-processing

Data post-processing was performed on a personal computer using customized software programmed in Matlab (The Mathworks Inc., Natick, MA, USA). Following contour segmentation of the epicardial and endocardial borders of the left ventricle and bulk motion correction based on subtraction of global translation velocities from the local velocity components [12], the measured in-plane velocities were transformed into an internal polar coordinate system positioned at the center of mass of the segmented left ventricle. As a result, motional parameters are described in terms of a cylindrical coordinate system based on radial ($V_r$), tangential (circumferential, $V_{\theta}$) and longitudinal ($V_z$) velocities leading to a more adapted representation of the myocardial motion corresponding to contraction/expansion ($V_r$ narrowing/widening) and clockwise/counterclockwise rotation ($V_{\theta}$, twisting) in short-axis orientation and shortening/lengthening ($V_z$) along the long-axis direction (see also Fig. 1, top right for a graphic representation of the different motion components). Radial velocities were defined as positive for contraction, tangential velocities as positive for clockwise rotation, and longitudinal velocities were defined as positive for motion from the base towards the apex (i.e. shortening).

In order to investigate regional variations of myocardial velocities, vector field plots and color-coded maps for each velocity component can be visualized for each phase of the cardiac cycle. For better orientation velocity vector fields and motion components were overlaid onto corresponding anatomical images (see also Figs. 1 and 2). Analysis of the temporal evolution of global myocardial motion patterns or in selectable regions of interests (ROIs) was performed using plots of time courses of each velocity component. In addition, the segmented myocardial contours were used to determine the myocardial wall thickness.

For the analysis of global or regional cardiac motion features, velocity components were averaged over the entire segmentation mask or in selected ROIs, resulting in velocity time courses for each volunteer. For a cumulative assessment of myocardial motion, the obtained time courses were averaged over all volunteer measurements with the temporal resolution of 13.8 ms for each acquired slice and each velocity component. The temporal axis was normalized to end systole in order to avoid temporal jitter due to different heart rates.

Fig. 1 shows the post-processing steps from the acquired data to the visualization of the myocardial motion. The magnitude images shown in the figure are required for contour segmentation, while additional motion encoded images (not shown) contain the functional information about myocardial motion. The velocity transformation (in-plane velocities from the short-axis images) from x- and y-velocities to radial ($V_r$) and tangential (circumferential, $V_{\theta}$) velocities is schematically depicted on the right side of Fig. 1. Pixelwise arrow plots of the measured in-plane velocity components in a basal short-axis slice are shown for systolic and diastolic cardiac frames reflecting contraction/rotation and expansion.

3. Results

It is well known from echocardiography that LV action involves different motion components. In addition to contraction/expansion and shortening/lengthening the myocardial motion also exhibits complex twisting and untwisting motions over the cardiac cycle. MR imaging permits the detailed spatial and temporal assessment of these individual motion components. As an example Fig. 2 shows the visualization of velocity information contained in the TPM data (temporal resolution of 13.8 ms) for a systolic and diastolic cardiac frame in a mid-ventricular slice location in a healthy volunteer acquired during free breathing. In the upper row (a) pixelwise arrow plots of the in-plane velocity component are shown. The temporal evolution of global...
motion components (left column) as well as corresponding color-coded maps of the individual myocardial motion components representing contraction/expansion (radial, b), rotation (tangential, c) and shortening/lengthening (longitudinal, d) are shown in the three rows below the arrow plots. The two cardiac time frames that were selected for the color-coded display of local myocardial velocity components are indicated by the circles in the corresponding velocity time courses (left column). The large arrows in (a) represent the mean velocities in eight left ventricular angular areas of equal size for better visualization (see also supplemental movie-file http://www.xxx/arrowPlot_media-l.avi). The time courses reflect the global myocardial motion pattern such as contraction indicated by positive radial velocities and expansion indicated by negative radial velocities. They reveal features in the myocardial motion such as two distinct negative peaks during diastole (b) or complex rotational behavior indicated by several changes of the rotational direction (c) (see also Fig. 4).

In order to illustrate typical normal motion components, LV performance during four characteristic time frames within the cardiac cycle are depicted in Fig. 3, while major features are summarized in Table 1. The selected time frames include isovolumetric contraction (IVC), mid-systole, isovolumetric relaxation (IVR), and mid-diastole for basal, mid-ventricular and apical slice positions. Motion components are described in terms of contraction/expansion, rotation (clockwise/ counterclockwise) and lengthening/shortening.

During IVC the entire LV performs a counterclockwise rotation. In mid-systole during the contraction phase (narrowing), the base has changed its rotational direction resulting in the well-known velocity twist with an opposite rotation of basis and apex. During IVR the apex performs a clockwise rotation whereas basal and mid-ventricular locations show an early expansion in antero-septal and anterior regions with simultaneous (mild) clockwise rotation. In mid-diastole the entire LV performs an expansion (widening) and lengthening including a slight counterclockwise rotation in basal and mid-ventricular slice positions. Corresponding pixelwise arrow plots of the in-plane velocity component (containing contraction/expansion and rotation) are shown in Fig. 3 demonstrating the velocity twist with an inversion of
rotation between IVC and mid-systole and a counter-rotation of basal and apical slices during mid-systole.

This dominant motional behavior shown for a single volunteer in Fig. 3 represents typical myocardial performance and could also reproducibly be detected in all subjects of our volunteer study. This is also evident from Fig. 4 which shows time courses over the cardiac cycle of global radial (blue), tangential (pink), and longitudinal (yellow) velocities. The graphs represent the dominant motion components in a basal, mid-ventricular and an apical slice averaged over
12 healthy volunteers with a temporal resolution of 13.8 ms. The counter-rotation (twisting) of basal and apical slices is clearly evident from the time courses of rotational velocities (pink) during late systole with positive values in the basal slice, values around zero in the mid-ventricular slice and negative values in the apical slice (arrows 1). During diastole the tangential velocities show a different and complex motion pattern in different slice locations.

Radial velocities (blue) evolve similarly during systole (contraction) in all locations, whereas motion patterns during diastole (expansion) demonstrate a somewhat different behavior. A small biphasic pattern during the IVR and early diastole is clearly visible in all slices (arrows 2). The motion pattern of the longitudinal velocities (lengthening and shortening, yellow) is similar in all slices except for decreasing amplitudes towards the apex. The small biphasic pattern during early diastole for all slice locations that was also observed for radial velocities during the same cardiac phase is clearly visible (arrows 2).

Specifically, during IVR basal slices demonstrate a continuing clockwise rotation even after radial motion is reversed (i.e. transition form contraction to expansion) while apical slices change rotational direction to clockwise motion during the same period. Following rapid motion towards the base during diastole, the longitudinal motion patterns (lengthening of the LV) demonstrate an overshoot in all three slices indicated by the positive velocity peaks (arrows 3). Averaged left ventricular wall thickness is given by the black curve (scale on the right side of the diagrams), and displays ongoing thickness during the isovolumetric phase at the end of systole. The temporal axis was normalized to end systole in order to avoid temporal jitter due to different heart rates.

In addition to the assessment and analysis of global motion features (see Figs. 2 and 4), TPM offers the opportunity to

![Figure 3](https://example.com/fig3.png)

**Table 1**

Motion components in basal, mid-ventricular, and apical slice positions corresponding to the arrow plots shown in Fig. 3 and the global time courses in Fig. 4

<table>
<thead>
<tr>
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<th>IVC</th>
<th>Mid-systole</th>
<th>IVR</th>
<th>Mid-diastole</th>
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<tr>
<td>Base</td>
<td>Counterclockwise rotation</td>
<td>Onset of shortening</td>
<td>Clockwise rotation</td>
<td>Onset of lengthening</td>
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<td></td>
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<td></td>
<td>Contraction</td>
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<td>Shortening</td>
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<tr>
<td>Mid</td>
<td>Counterclockwise rotation</td>
<td>Onset of shortening</td>
<td>Contraction</td>
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<td></td>
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<td>Shortening</td>
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<td>Apex</td>
<td>Counterclockwise rotation</td>
<td>Onset of shortening</td>
<td>Counter-clockwise rotation</td>
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<td>Contraction</td>
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evaluate local myocardial action in user-selected regions of interest. Fig. 5 shows an example for this regional analysis and demonstrates the usefulness of TPM for the detection of locally varying motion patterns. Radial myocardial motion in two distinct regions of a mid-ventricular slice location is illustrated by time courses of radial velocities representing contraction and expansion. The motion pattern (temporal resolution = 13.8 ms) averaged over 12 healthy volunteers) in the inferoseptal area (red) consists of two distinct negative peaks during diastole whereas the diastolic relaxation starts later in the inferolateral area (blue) showing only one negative peak. The temporal axis was normalized to avoid temporal jitter due to different heart rates.

4. Discussion

The results presented in this paper demonstrate the potential of MRI using TPM for a detailed assessment of myocardial motion with a temporal resolution comparable to TDI measurements. Baseline studies were done in healthy volunteers and displayed a reproducible range of different data analysis and visualization modes that include myocardial motion corresponding to contraction/expansion (narrowing/widening) and clockwise/counterclockwise rotation (twisting) in short-axis orientation and shortening/lengthening along the long-axis direction.

The presented volunteer measurements with the high temporal resolution reveal detailed motion patterns during diastole that are only known from TDI measurements such as the small biphasic wave of brief duration during isovolumetric relaxation (see Fig. 2) [21]. These detailed motion patterns might help in the investigation and better understanding of the myocardial motion in normal subjects and patients (e.g. with diastolic dysfunction) with regard to different models of cardiac fiber structure such as the already mentioned band-model [20].

It has recently been proposed that the descending and ascending segments of the band-model act as an agonist-antagonist muscular leading to the assumption that systolic ventricular filling is due to muscular contraction of the ascendant segment rather than simple relaxation of the cardiac muscle [22]. This is supported by recent sonomicrometer tracings showing that ongoing systolic ascending contraction occurs during the rapid ventricular filling phase, while shortening halts in the descending segment [23]. Since TPM allows for an acquisition of myocardial motion of the entire ventricles with high temporal resolution, it may help elucidating the ambiguities of ventricular filling. Furthermore, surgical therapies aimed at reducing the left ventricular volume to treat heart failure might benefit from new insights in myocardial motion when taking into account the functional implications of excising certain segments of the myocardium in order to optimize surgical results.

Further studies are warranted in order to correlate the findings of this study to other measurements of phasic cardiac
actions such as ultrasonic crystals and echocardiography recordings. One intent for the accumulation of these detailed motion patterns is to define if this information allows better understanding of the myocardial motion in normal subjects and thereby interfaces with the helical ventricular myocardial band models of cardiac fiber structure [24]. Fig. 6 shows sonomicrometer crystal tracings reflecting the distance evolution (i.e. shortening/widening) of crystal pairs over the cardiac cycle in two different regions of the myocardial wall, one in the subepicardial anterior wall and the second in the subepicardial posterior wall as depicted on the heart image on the left. The crystal pair placed in the anterior wall clearly shows a temporal delay of shortening as well as widening compared to the pair placed in the posterior wall [23] during the rapid filling phase, previously called IVR. Such detailed investigations of myocardial wall motion are very useful and necessary in order to understand the myocardial structure and to help explaining phenomena such as the ambiguities of ventricular filling [22]. It was demonstrated that TPM offers a method that allows such detailed assessments (as demonstrated in Fig. 6) of data acquired noninvasively in human subjects in arbitrary regions of the myocardium (see also Fig. 5).

The acquisition of three-directional velocity data over the entire left ventricle provide velocity fields that must be somehow related to the myocardial fiber structure. Therefore, the velocity fields might allow an extraction of surrogate parameters which contain relevant information on the structure and orientation of the muscle fibers of the left ventricle providing significant information for pre- and post-surgical evaluation of patients e.g. with a dilated left ventricle. The presented TPM measurements suggest that this high temporal resolution technique may be valuable for the detection of the efficacy of pharmaceutical or other therapeutical procedures.

A technical limitation of this study is related to the long acquisition time needed to acquire TPM data for a single slice of about 5 min for a temporal resolution of 13.8 ms. Scan time may be reduced by the use of radial acquisition strategies and parallel imaging techniques in combination with imaging at the higher field strength in order to compensate for SNR loss associated with parallel imaging.

5. Conclusion

In conclusion, high temporal resolution TPM provides insight into global and local myocardial wall motion with high spatial and temporal detail. The resulting myocardial velocities have the potential to provide valuable information in the evaluation of global and regional systolic and diastolic function in cardiac pathologic processes.

References