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Noninvasive Assessment of Myocardial Mechanics of the Left Ventricle in Rabbits Using Velocity Vector Imaging

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Background: Our study aimed to investigate the feasibility of velocity vector imaging (VVI) to analyze left ventricular (LV) myocardial mechanics in rabbits at basal state.

Material/Method: The animals used in this study were 30 New Zealand white rabbits. All rabbits underwent routine echocardiography under VVI-mode at basal state. The 2-dimensional (2-D) echocardiography images acquired included parasternal left long-axis views and short-axis views at the level of LV mitral valve, papillary muscles, and apex. Images were analyzed by VVI software.

Results: At basal state, longitudinal LV velocity decreased from the basal to the apical segment ($P<0.05$). In the short axis direction, the highest peak myocardial velocity was found between the anterior septum and anterior wall for each segment at the same level; the peak strains and strain rates (SR) were the highest in the anterior and lateral wall compared to other segments (all $P<0.05$). During systole, LV base rotated in a clockwise direction and LV apex rotated in a counter-clockwise direction, while during diastole, both LV base and apex rotated in the direction opposite to systole. The rotation angle, rotation velocity and unwinding velocity in the apical segment were greater than the basal segment ($P<0.05$).

Conclusions: VVI is a reliable tool for evaluating LV myocardial mechanics in rabbits at basal state, and the LV long-axis short-axis and torsional motions reflect the normal regular patterns. Our study lays the foundation for future experimental approaches in rabbit models and for other applications related to the study of human myocardial mechanics.

MeSH Keywords: **Anterior Wall Myocardial Infarction • Blood Flow Velocity • Echocardiography, Doppler • Heart Ventricles**

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Background

Velocity vector imaging (VVI) is a new echocardiographic technique based on 2-dimensional (2-D) gray-scale imaging, with spatial coherence of ultrasonic ultrasound, dot tracing, and contour tracing, and is used for analysis of myocardial tissue motion and velocity [1]. VVI acquires information on the amplitude and phase of 2-D pixels, and uses real-time speckle tracking algorithm to determine the displacement motion and vectoral direction of myocardial tissues to obtain the actual information on the direction of activity, velocity, distance, and phase of regional myocardial tissues [2]. Compared with previous imaging techniques, VVI has the advantages of being and angle-independent and highly reproducible, which makes it an exciting tool for research applications to evaluate the circumferential, radial and longitudinal velocities, and the strain and strain rates in various disease settings [3,4]. VVI has quickly become the latest technology employed for analysis of myocardial mechanics and regional heart function, and can also be used to quantify parameters such as strain and strain rate and circumferential direction of long and short axis, myocardial velocity, and the precise measurement of synchronization between left ventricular (LV) function and LV wall motion [5].

Myocardial mechanics play an important role in cardiac mechanics and involves the mechanical characteristics of tension, length (L), and speed of cardiac muscular motion [6]. An assessment of myocardial mechanics using VVI may reflect the state of cardiac function and reveal invaluable prognostic information in cardiovascular disease conditions, for example in idiopathic dilated cardiomyopathy and coronary artery disease. Accordingly, multiple studies reported that VVI is a better approach compared to other methods, such as measurement of LV ejection fraction, in determining the heart function [7–9]. In practice, myocardial mechanics is evaluated from 3 VVI parameters: strain, strain rate, and tissue velocity [10]. The velocity parameter conveys information on the risk of diastolic heart failure, while the cardiac strain and strain rate, derived from the velocity data, conveys information on tissue deformity and ventricular function. Strain is defined as relative myocardial deformation that measures changes in the length (L) of myocardium in relation to its original length (OL). Strain rate is defined as the deformation rate of the myocardium, which conveys the rate of shortening or lengthening of the tissue [11]. Beginning in the 1990s, tagged magnetic resonance imaging (tMRI) has been widely used to detect various heart diseases. However, several new methods have been developed to overcome the significant disadvantages of tMRI, mainly its high cost and low frame rate [12]. In this context, VVI technique has become a popular approach for measurement and evaluation of myocardial mechanics [13]. A feature-tracking echocardiography using vector velocity imaging (VVI) measures the myocardial strain, strain rate (SR), and velocity

of the regional myocardium through a combination of speckle tracking, mitral annulus motion, tissue-blood border detection, and the periodicity of the cardiac cycle using R-R intervals. Thus, VVI is a promising tool in clinical applications for evaluation of myocardial motion and ventricular function, devoid of the inherent limitations of Doppler echocardiography [14–16]. Previously, the clinical potential of VVI was evaluated in specific diseases or therapies such as myocardial ischemia, cardiac transplantation, myocardial infarction, or pericardial adhesion [15,17–19]. The present study evaluated the feasibility of VVI to analyze the LV myocardial mechanics in normal New Zealand white rabbit, an animal model widely used in cardiovascular disease research [20], to understand the mechanical characteristics of cardiac structures in rabbits and to lay the foundation for future studies related to human myocardial mechanics.

Material and Methods

Ethical statement

A total of 30 New Zealand white rabbits were used in this study. All procedures related to animal experiments and animal care were approved by Medicine Ethics Review Committee of the Second Xiangya Hospital of Central South University. Animal experiments were conducted in accordance with Public Health Service Policy on Humane Care and Use of Laboratory Animals, Guide for the Care and Use of Laboratory Animals (Institute of Laboratory Animal Resources, National Research Council, 1996). All efforts were made to minimize suffering and reduce the number of animals used for the study.

Study subjects

All New Zealand white rabbits (1.5–2.5kg), including 15 males and 15 females, were obtained from the Laboratory Animal Center of the Second Xiangya Hospital of Central South University. The current study was performed using color Doppler ultrasonography (3D-CDU) (Acuson Sequoia 512), with 7.0 MHz transducer frequency and 50 frames/s frame rate of dynamic gray scale imaging.

Echocardiography and VVI parameters

All rabbits were examined by echocardiography at basal state. Echocardiography was performed using speckle-tracking program, VVI (version 3.0). The 2-D echocardiography images were acquired, which included the parasternal left long-axis views and short axis views at the level of LV mitral valve, papillary muscles and apex. All 2-D echocardiographic images from 3 cardiac cycles were analyzed by VVI software. Myocardial velocity, strain and strain rate curve for each segment in long-axis

and short-axis view of the LV and rotational angles and rotational velocities curve in short-axis view of the LV were obtained based on a 16-segment model of the American Society of Echocardiography [21]. Segmental myocardial peak systolic velocities (V_s) and peak diastolic velocities (V_d) were measured from LV velocity curves. Segmental myocardial peak systolic strain (S_s) was also obtained from the strain curve. Myocardial peak systolic strain rate (SR_s) and peak diastolic strain rate (SR_d) for each segment was measured from the strain rate curve. From the rotation and velocity curves, peak apical rotation, peak apical rotation velocity, peak apical untwist velocity and peak basal rotation, peak basal rotation velocity, and peak basal untwist velocity were measured. All data were measured continuously from 3 cardiac cycles and the average was calculated.

Statistical analysis

Statistical analysis was performed using SPSS 18.0 software. All data are expressed as mean \pm SD. Statistical significance of multiple measurement data was analyzed using variance with the significance level at 0.05. A P -value of less than 0.05 was used to define a significant difference.

Results

Longitudinal and diagonal velocity vector diagram

In the longitudinal direction, the myocardial motion in LV pointed to the apical segment of the heart in systole, while in diastole the myocardial motion pointed to the basal segment of the heart, and the motion vectors decreased from basal to apical segment. In the brachy-diagonal direction, the cardiac muscle moved to the center of left ventricle in systole. Simultaneously, there was a clockwise rotation in the basal segment of heart with opposite rotation in the apical segment. Moreover, the direction of myocardial motion was also in opposite directions during systole and diastole.

Regional LV velocity, strain, and strain rate measurements

As illustrated in Figures 1 and 2, the velocity curves in the long and short axes were both composed of positive and negative waveform. The positive waveform represented movement toward the reference in systole. By contrast, the negative waveform represented the myocardium moving away from the reference in diastole. The strain curve was a negative waveform with a unimodal wave. The myocardium shortened in systole and lengthened in diastole and returned to its OL at the end of diastole (myocardial L in end diastole which marked as zero in the curve). The strain rate curve showed a negative waveform in the systolic period and a positive waveform in

diastolic period, which represented myocardial shortening in systole and lengthening in diastole, respectively.

VVI of the left ventricle

The VVI parameter of the LV in long and short axes is shown in Tables 1 2, respectively. The longitudinal velocity of LV decreased from basal to apical segments ($P < 0.05$), whereas the peak strain and strain rate did not change significantly ($P > 0.05$). In the posterior left ventricle, the peak systolic velocity in middle segment and peak diastolic velocity in basal and middle segments were significant higher than the other segments of interventricular septum ($P < 0.05$). For short axis, there were significant differences of velocity, strain and strain rate between the segments. Specifically, the velocity in anterior septal and anteroseptal was significantly higher than the lateral, posterior and inferior walls ($P < 0.05$). Strain and strain rate in anterior wall and lateral wall were also significantly higher than in the other segments ($P < 0.05$). Rotation of the base (clockwise) and apex of left ventricle (counter-clockwise) in opposite directions during systole and diastole were observed from the apex. The rotation angle, rotation velocity and unwinding velocity in the apex were higher than the basal segment ($P < 0.05$) and the twist angle of the left ventricle was $10.76 \pm 2.24^\circ$ (Table 3, Figure 3).

Discussion

VVI, a new B-mode echo technique, is angle-independent and can evaluate radial, circumferential, and longitudinal velocities, and strain [22]. Our study examined the characteristics of myocardial mechanics in New Zealand white rabbits by using VVI. Our results clearly detected 3-D motions in the LV, including the contraction movement along the long axis and short axis of the heart, and the twist motion along the long axis of the heart from the heart apex to the heart bottom [5,12]. The significance of these results is that the unique 3-D structure of myocardial fiber is a key factor of ventricular mechanical characteristics and vasomotion, and plays an important role in LV ejection and filling [23].

Our findings also revealed that at basal state, the direction of long axis in myocardium of rabbits shows velocity differences, with basal segment exhibiting the peak velocity, followed by the middle and apical segments [1]. This result suggested that contraction of descending myocardial fiber causes the heart bottom to move up to the heart apex, while the heart apex is relatively fixed. However, the peak values of regional strain and strain rate showed no significant difference between the basal, middle, and apical segments, indicating uniform deformation of LV wall in the long-axis direction of the myocardium [14,24]. The explanation for this result might be that the motion along the short axis involves concentric exercise of left

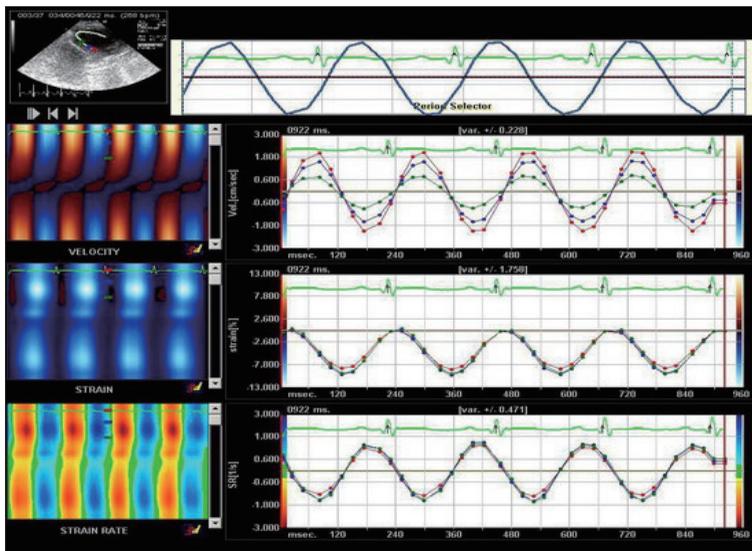


Figure 1. The velocity curve along the long axis to assess the myocardial mechanics of the left ventricle in rabbits at basal state.

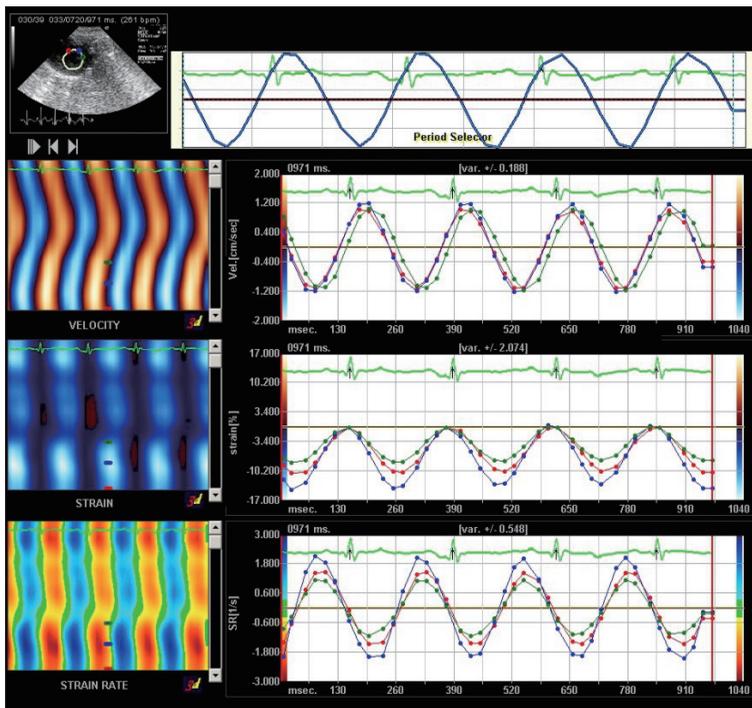


Figure 2. The velocity curve along the short axis to assess the myocardial mechanics of the left ventricle in rabbits at basal state.

ventricle, i.e., muscle contraction leading to muscle shortening, and the circumferential motion has a tangential relationship with LV. Concentric exercise is measured by the velocity of myocardial motion and is the result of coordinated contraction of 3 layers of myocardial fibers, while circumferential motion is measured by myocardial strain and strain rate and is generally determined by the contraction of annular myocardial fibers in the middle of the ventricle.

Our results also demonstrated that peak velocity, strain, and strain rate in the short axis of individual segments at the same level showed significant differences between each other. The

peak velocities of both anteroseptal and anterior LV walls were higher than the lateral, posterior, and inferior. The peak strains and strain rates of both anterior and lateral LV walls were higher than the rest of the segments, which can be explained by the fact that the anterior and lateral LV walls are mostly composed of middle circular myocardial fibers [25]. It is accepted that the configuration of myocardial fibres determines the displacement of ventricular walls [25].

In systole, the base rotates clockwise and the apex rotates counter-clockwise, resulting in twisting of the heart [26]. In diastole, the base rotates counterclockwise and the apex rotates

Table 1. Velocity vector imaging parameters in each segment of long axis ($\bar{x}\pm s$).

	VVI parameters				
	Vs (cm/s)	Vd (cm/s)	Ss (%)	SRs (S ⁻¹)	SRd (S ⁻¹)
Interventricular septum					
Basal segment	2.50±0.45	-2.41±0.41	-21.70±7.65	-2.14±0.86	2.29±0.81
Middle segment	1.89±0.24*	-1.97±0.27*	-21.05±7.44	-2.14±0.84	2.26±0.87
Apical segment	1.49±0.79*	-1.55±0.24*	-22.06±8.02	-2.18±0.84	2.28±0.78
Posterior left ventricle					
Basal segment	2.72±0.72	-2.74±0.81 [#]	-23.16±4.92	-2.37±1.11	2.41±0.83
Middle segment	2.35±0.64* [#]	-2.31±0.66* [#]	-23.59±4.85	-2.33±1.08	2.42±0.84
Apical segment	1.65±0.39*	-1.57±0.33*	-23.06±4.88	-2.40±1.10	2.40±0.79

VVI – velocity vector imaging; Vs – systolic velocity; Vd – diastolic velocity; Ss – systolic strain; SRs – systolic strain rate; SRd – diastolic strain rate; * comparisons of the two adjacent segments in same ventricular wall, P<0.05; [#] compared with interventricular septum in the same segment, P<0.05.

Table 2. Velocity vector imaging parameters in each segment of short axis under basic condition ($\bar{x}\pm s$).

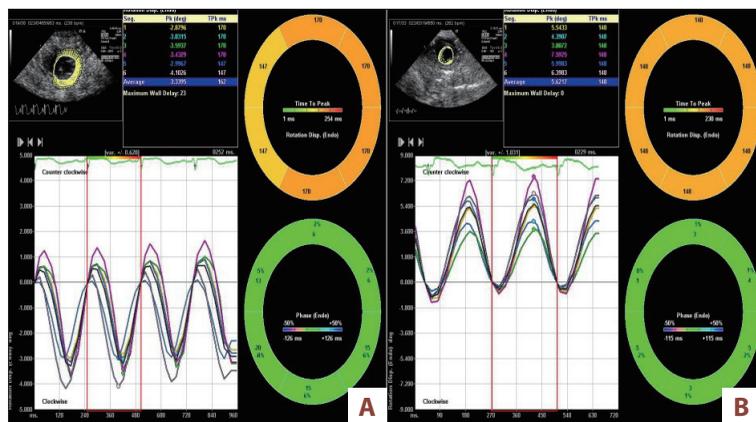
	VVI parameters				
	Vs (m/s)	Vd (cm/s)	Ss (%)	SRs (S ⁻¹)	SRd (S ⁻¹)
Papillary valve level					
Anterior septal	2.45±0.18	-2.26±0.57	-18.85±3.28 ^{#,&}	-1.97±0.26 ^{#,&}	1.81±0.32 ^{#,&}
Anterior wall	2.22±0.15*	-2.16±0.35	-20.74±3.33	-2.21±0.32	2.20±0.33
Lateral wall	1.77±0.34 [#]	-1.74±0.17* [#]	-21.34±2.27	-2.28±0.26	2.26±0.65
Posterior wall	1.67±0.35* [#]	-1.46±0.32* [#]	-18.75±4.36 ^{#,&}	-2.11±0.32 ^{&}	2.10±0.34 ^{&}
Inferior wall	1.36±0.25* [#]	-1.32±0.43* [#]	-18.86±3.25 ^{#,&}	-1.94±0.34 ^{#,&}	1.85±0.33 ^{#,&}
Posterior septal	1.84±0.24* [#]	-1.75±0.32* [#]	-18.47±2.27 ^{#,&}	-1.96±0.34 ^{#,&}	1.83±0.33 ^{#,&}
Papillary muscle level					
Anterior septal	2.29±0.46	-2.10±0.27	-20.03±2.29 ^{#,&}	-2.15±0.26 ^{#,&}	2.13±0.35 ^{#,&}
Anterior wall	2.11±0.11*	-1.97±0.18	-21.54±3.31	-2.34±0.32	2.33±0.34
Lateral wall	1.66±0.13* [#]	-1.52±0.45*	-22.36±3.24	-2.37±0.27	2.36±0.45
Posterior wall	1.58±0.12* [#]	-1.34±0.18* [#]	-18.86±2.33 ^{#,&}	-2.08±0.34 ^{#,&}	2.22±0.35
Inferior wall	1.25±0.12* [#]	-1.26±0.15* [#]	-20.42±2.23 ^{#,&}	-2.04±0.33 ^{#,&}	2.05±0.35 ^{#,&}
Posterior septal	1.68±0.12* [#]	-1.60±0.32* [#]	-19.80±3.45 ^{#,&}	-2.02±0.32 ^{#,&}	1.97±0.32 ^{#,&}
Apical level					
Anterior wall	2.09±0.12	-1.95±0.12	-22.35±3.23	-2.48±0.32	2.47±0.33
Lateral wall	1.55±0.14 [#]	-1.52±0.14 [#]	-24.26±3.23 [#]	-2.50±0.31	2.53±0.35
Inferior wall	1.20±0.13 [#]	-1.18±0.14 [#]	-21.42±3.24 ^{#,&}	-2.28±0.32 ^{#,&}	2.23±0.36 ^{#,&}
Interventricular septum	1.62±0.13 [#]	-1.48±0.35 [#]	-21.20±3.34 ^{#,&}	-2.10±0.31 ^{#,&}	2.08±0.34 ^{#,&}

VVI – velocity vector imaging; Vs – systolic velocity; Vd – diastolic velocity; Ss – systolic strain; SRs – systolic strain rate; SRd – diastolic strain rate; * comparisons with anterior septal at same level, P<0.05; [#] comparisons with anterior wall at same level, P<0.05; [&] comparisons with lateral wall at same level, P<0.05.

Table 3. Left ventricular rotational variables in basic condition ($\bar{x}\pm s$).

	VVI parameters		
	Rotation angle ($^{\circ}/s$)	Rotation velocity ($^{\circ}/s$)	Unwinding velocity ($^{\circ}/s$)
Apex	-2.90 ± 0.82	-44.61 ± 8.83	43.30 ± 8.93
Heart bottom	$7.88\pm 1.20^*$	$77.16\pm 7.91^*$	$-76.19\pm 6.87^*$

VVI – velocity vector imaging; * comparisons with heart bottom, $P < 0.05$.

**Figure 3.** (A, B) The twist curve along the short axis to assess the myocardial mechanics of the left ventricle in rabbits at basal state.

clockwise, leading to untwisting [26]. During these 2 processes, significant differences between the apical and basal rotation were observed, particularly our results showing that the rotation angle, rotation rate, and reverse rotation rate of the apex were all significantly higher than the corresponding values observed for the base. This illustrated the predominant role of the apex in heart torsion. Based on the collective results obtained from this study, it is reasonable to speculate that VVI is a helpful tool for evaluating the mechanical characteristics of left ventricle myocardium. Consistent with our results, Lynne et al. reported the use of VVI in cardiac magnetic resonance (CMR) imaging and suggested that VVI was reproducible for analysis of strain of LV myocardial mechanics in hypertrophic cardiomyopathy (HCM) [24]. Further, Dae-Hee et al. compared VVI with speckle tracking echocardiography (STE) and showed that VVI was significantly better at determining the major apical and basal rotation, as well as parameters related to twist, and proposed the use of VVI in other contexts such as heart function, left atrial function, and regional myocardial function [12]. Thus, VVI parameters allow qualitative and quantitative assessment of myocardial motion and both our results and observations from previous studies demonstrate the feasibility of VVI for assessment of ventricular myocardial mechanics [27].

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Conclusions

Our VVI results reveal that contraction of left ventricle myocardium along the long axis and short axis of the heart, as well as the twist motion, happens with regularity. Further, our results strongly support the use of VVI to evaluate the mechanical characteristics of left ventricle myocardium, and demonstrate the feasibility of using VVI in diagnostic imaging in humans and in pre-clinical models of cardiovascular diseases in New Zealand white rabbits.

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Conflicts of interest

The authors have declared that they have no competing interests.

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