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The Contribution of Left Ventricular Muscle Bands to Left Ventricular Rotation: Assessment by a 2-Dimensional Speckle Tracking Method

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Abstract

Background— Torsion is an essential component of left ventricular (LV) function. Systolic rotation, as a component of torsion, winds the heart muscle up like a spring, setting up recoil for early diastole. We used a new two-dimensional (2D) speckle tracking strain method to study differences in twisting in sub-endocardial and sub-epicardial layers of the left ventricle in open-chest pigs. Our aim was to identify the relative contributions of the inner or outer layers of the LV wall to rotation and hence systole.

Methods— 23 juvenile pigs were imaged in the short axis, epicardially, to obtain images at a level just below the papillary muscles with high frequency (14MHz) ultrasound. Speckle tracking software using scan line files was used to measure the torsional contribution of septum, anterior, posterior and inferior LV wall segments. Two zones on the septum were evaluated separately: one with apparent circumferential fiber orientation in the inner layer and one with a speckle pattern suggesting longitudinal fiber orientation on the right ventricular aspect of the septum. Pressure rate changes (dp/

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dt) during the cardiac cycle, were measured as an index of LV function and correlated with the regional torsion.

Results—Mean peak rotations measured by speckle tracking echocardiography at the apex showed counterclockwise rotation of LV septal wall ($10.68^{\circ} \pm 2.67$ for the inner layer and $8.27^{\circ} \pm 1.73$ for the outer layer). The time difference for time to peak rotation was 213.22 ± 77.95 ms and 241.17 ± 54.67 ms for inner and outer layers, respectively. Significant differences were shown between the inner and outer layer of the LV for both rotation ($p < 0.0001$) and timing of rotation ($p = 0.02$). The dp/dt measurements correlated well with the inner rotation magnitude of the LV and with the difference of in short axis rotation between inner and outer layers of the LV wall.

Conclusions— Inner and outer layers of the LV wall, especially at the septum, have different rotational behaviors. When used with very high-resolution imaging, this method could contribute to the understanding of functional contributions of the LV wall and their relative contribution to cardiac segmental twisting.

Keywords

ventricular function; echocardiography; tissue Doppler imaging

BACKGROUND

Rotation during contraction is an essential component of left ventricular (LV) function. LV torsion is developed from the difference in twist of the apex with respect to the base, along with concomitant longitudinal shortening. Torsion plays an important role in the mechanics of filling and ejection of the left ventricle.^{1,2} The systolic motion of the left ventricle consists of twisting the apex of the heart in counter clock-wise direction around its long axis when viewed from the apex, as characterized by Arts *et al.*² The systolic rotation winds the heart muscle up like a spring, setting up recoil for early diastole. Experimental and clinical studies showed that LV rotation is an early marker of changes in LV function, while twist is a robust parameter of myocardial function.^{3,4}

In recent years, cardiac magnetic resonance imaging (MRI) has advanced rapidly with development of a new tagging technique. The use of tagging to assess twist in the short axis view provides a non-invasive method by which to measure this unique parameter of LV wall motion.^{4,5} However, the mesh spacing is relatively large and with frame rates generally low, detailed studies of the time course of regional twist throughout the cardiac cycle in different layers of the LV wall, have yet to be published.

In this study, a new two-dimensional (2D) speckle tracking strain method was used to study cardiac segmental twisting in an open-chest animal model by examining high frequency, high resolution images, which allow the tracking of twisting in all segments of the left ventricle without angle dependence. Previous work by our group has validated the accuracy of twist determination in an *in vitro* study⁶ and another validation study using MRI⁷ has been conducted.

METHODS

Animals and Echocardiography System

Twenty-three juvenile **healthy** open chest pigs, weighing 2.3–5.1 kg (3.93 ± 0.75 kg) were used for the study. Eight were studied before the pericardium was opened. All animal procedures were approved by the Animal Care and Use Committee of Oregon Health & Science University.

Following sedation with intravenous telazole (1mg/kg), mechanical ventilation was established via surgical tracheotomy and anesthesia was maintained using isoflurane (1–3%) and oxygen. Temperature, ECG and arterial gas tensions were closely monitored and maintained within the normal ranges. Following open insertion of a femoral artery catheter for continuous invasive blood pressure measurements, the heart was exposed through midline sternotomy. The animals were fully anticoagulated (activated clot times > 240s) with repeated bolus injections of heparin (500iu/kg).

The pigs were scanned in a short axis view at a level just below the papillary muscles, using a Vivid 7 ultrasound system (GE/VingMed Ultrasound AS N-3190 Horton, Norway) using a high frame rate (151–223 frames per second) setting and an i13L high frequency (12 – 14MHz) linear array probe. The plane of imaging was angled so that the LV cross-section was made as circular as possible.

Hemodynamic Measurements

High fidelity dp/dt was recorded as a functional index of global LV function. A 12F micromanometer-tipped catheter (Cordis Laboratories) was placed in the LV through the apex. A 12F left Judkins catheter (Cordis Laboratories), placed from the femoral artery, was advanced to the ostium of the left main coronary artery for drug infusions. Measurements of heart rate, dp/dt, and peripheral arterial pressure were made by averaging at least 15 beats for each experimental condition. Data was digitally recorded at 300 Hz with a personal computer equipped with a multi-channel analog-to-digital converter and stored on disk for later offline analysis.

Using customized software (SonoMetrics®, Digital Ultrasonic Measurement System, Version 6.0, SonoMetrics Corporation, Stevenson), LV peak positive and negative dp/dt (+dp/dt, -dp/dt) were calculated offline. The relationship between the rotational contributions of the 5 wall segments (Septum, anterior, lateral, inferior and posterior) to twist as well as that of the inner and outer layers in the septum was determined.

LV Rotation and Rotation Rate (Twist)

The 2D high frame rate images in scan line format were analyzed by the speckle tracking 2D strain program, which determines a similarity, solution of motion and speckle patterns determined by the sum of absolute difference in gray scale between frames. The software was used to analyze the twist contribution of the septum, anterior, lateral, posterior and inferior LV wall segments. Two zones on the septal segment – one with apparent circumferential fiber orientation in the inner layer and one with speckle pattern suggesting longitudinal fiber orientation closer to the right ventricular aspect of the septum – were consistently visualized and were evaluated separately (Figures 1 & 2).

LV rotational rate and rotational degree were measured. Speckle tracking sample volumes were placed over the septum, anterior, posterior, and septum segments for assessing the rotation and rotation rate in the myocardium and were set to include the inner or the outer third of the myocardium in end-diastole by positioning the region and adjusting its width. Peak rotational times for the myocardial layers were determined from the onset of the QRS to peak rotational amplitude. A score for the statistical likelihood of the correlation was displayed by the analysis program. **Only images with a score of 2 or less indicating high correlation were accepted.**

Statistics

All data are expressed as mean $\pm$ standard deviation. Linear regression analysis was used to determine the correlation between the degrees of twisting and the twisting rate of the short-axis segments for inner and outer layers and positive and negative dp/dt and the times to peak

rotation for myocardial segments and for the inner and outer layers of the left septum were compared by t-test and the 95% of the confidence interval was determined so as to test for significant differences between the layers.

Interobserver Viability

Two independent observers processed and measured images for 16 of the study animals rotation and rotation rate separately. These results were compared and found the correlation.

RESULTS

Mean systolic rotation magnitude for the whole of the short axis done by speckle tracking echocardiography was counterclockwise by $10.68^{\circ} \pm 2.67$ and $8.27^{\circ} \pm 1.73$ for the inner and outer layers of the LV wall ($p < 0.0001$), respectively. Time to peak systolic rotation was 213.22 ± 77.95 msec and 241.17 ± 54.67 msec for inner and outer layers, respectively ($p = 0.034$). The diastolic mean peak rotation was $-6.18^{\circ} \pm 2.68$ and $-4.85^{\circ} \pm 2.53$ for inner and outer layers. Time to the diastolic mean peak was 378.39 ± 121.18 msec and 420.43 ± 125.64 msec for inner and outer layers. The peak rate of rotation for LV wall was $63.26 \pm 18.17^{\circ}/\text{sec}$ and $48.07 \pm 12.75^{\circ}/\text{sec}$ for the inner and outer layers of the LV wall, respectively, while the highest rate of reversed rotation of LV wall was $-50.70 \pm 9.22^{\circ}/\text{sec}$ and $-37.90 \pm 9.31^{\circ}/\text{sec}$. The time to peak rotation rate was 229.83 ± 57.21 msec and 260.39 ± 54.82 msec for inner and outer layers, while time to the peak reversed rotation rate was 380.78 ± 77.76 msec and 428.52 ± 91.48 msec for inner and outer layers.

Significant differences were shown between the inner and outer layers for systolic and diastolic rotation ($p < 0.0001$ and $p = 0.001$) and timing to peak positive and negative rotation ($p = 0.019$ and $p = 0.018$). Significant differences were also shown for the systolic vs diastolic rotational rate of LV wall ($p = 0.003$ and $p = 0.024$).

Figure 2 illustrated characteristic regional contributions for the different segments towards twist in the apical view of the heart. The zones with greatest systolic and diastolic rotation and highest rotation rates were mostly at the septum, followed by the anterior and lateral segments (Table 1). There were significant differences in peak systolic rotation between the inner and outer layers of the septum ($p = 0.01$) and for the anterior-lateral ($p = 0.01$) segments, but not for inferior ($p = 0.13$), posterior ($p = 0.28$) and anterior ($p = 0.18$) segments.

dp/dt

Systolic +dp/dt had good correlation with **CCW** peak rotation for the inner layer ($y = -0.005x - 3.628$, $r^2 = 0.839$) (Figure 3). Peak rotation for the outer layer did not correlate with peak dp/dt magnitude: $y = -0.003x - 4.989$, $r^2 = 0.336$ (Figure 4). Peak +dp/dt correlated well with the difference in peak rotation between inter and outer layers ($y = -0.002x + 1.069$, $r^2 = 0.857$) (Figure 5).

Negative dp/dt showed good correlation with peak diastolic rotation for the inner layer ($y = -0.006x + 1.585$, $r^2 = 0.811$, Figure 6) but the correlation with -dp/dt was poor for the outer layer ($y = -0.003x + 4.347$, $r^2 = 0.475$, Figure 7). Peak -dp/dt correlated very well with the difference between inner and outer rotation ($y = -0.002x - 0.241$, $r^2 = 0.885$, Figure 8).

The mean rotations for data obtained with the pericardium closed and open were 11.32 ± 2.6 and 12.01 ± 2.6 degrees, respectively ($p = 0.864$). The data showed the rotation before and after pericardial opening had no significant difference and was highly correlated.

Interobserver Variability

Interobserver variability was tested using 16 randomly selected loops by a second observer (XKL), revealing a good correlation between the two independent observers measured by results for mean peak rotation ($y = 0.887x + 1.204$, $r^2 = 0.884$).

DISCUSSION

Ultrasound imaging is among the most widely used investigational technologies in cardiology. In this study, we have demonstrated that the inner and outer layers of LV wall have different torsional behaviors in the LV torsional deformation as assessed by 2D speckle tracking.

The 2D speckle tracking method for measuring the rotation of the heart has been shown to be a reliable method compared with sonomicrometry and MRI.⁹ Recently, a number of studies have appeared related to LV torsion as determined by ultrasound and by MRI.^{6,7,10,11,12} Our study describes 2D high frequency tracking method delineating the rotational behavior of LV myocardium inner and outer layers. In our study, there was a significant difference for the maximal rotation degree between inner and outer layers of the left ventricle in the short-axis view at the apical level.

We also found the highest rotation magnitude and rotational rate at the inner layer of the left ventricle were found in the septum, while the highest values for rotational rate at the outer layer was widely spread between the septum, anterior and inferior segments. Therefore, these segments appear to contribute different levels to the functional twisting of the left ventricle. According the theory that Torrent-Guasp proposed,^{13,14,15} the inner septum should be the part of the muscle band which contributes to rotational behavior. Our findings support this theory.

It is of interest that close correlation existed for inner twist as well as the difference between inner and outer twist and twist rate, and positive and negative dp/dt. The difference between the actions of the layers is a direct demonstration of muscle shear, which relates closely to inotropic function.

Limitations

In our study, we used open-chest pigs. Imaging was therefore under optimal experimental conditions. An open pericardium could change the myocardial rotation. Nonetheless, ten of the 23 animals had both closed and opened-pericardium studies, and there were no significant differences between the rotational degrees of the closed and open pericardium.

The very high frame rates and very high ultrasound imaging frequencies we used would not be obtainable in most human studies. Clear views of the short axis images are, however, possible in many subjects and of the high quality necessary for good quality speckle analysis, particularly in patients with good echo windows. Validation studies in healthy subjects and those with myocardial disease are necessary.

CONCLUSIONS

The inner and outer layers of the LV wall have different rotational behavior. The greatest rotation of the inner layer of the septum; the greatest rotation of the outer layer was in septal and anterior segments. The high resolution images we obtained and analysed allowed us to make observations which may be related to the orientation of myocardial bands within the left ventricle and to their relative contribution to segmental twisting.

References

1. Mailloux GE, Bleau A, Bertrand M, Petitclerc R. Computer analysis of heart motion from two-dimensional echocardiograms. *IEEE Trans Biomed Eng* 1987;34:356–364. [PubMed: 3596619]
2. Arts T, Veenstra PC, Reneman RS. Epicardial deformation and left ventricular wall mechanisms during ejection in the dog. *Am J Physiol Heart Circ Physiol* 1982;243:379–390.
3. Helle-Valle T, Edvardsen T, Amundsen B, Smith H, Torp H, Smiseth O. New non-invasive method for assessment for LV rotation-speckle tracking echocardiography. *Circulation* 2004;110(Suppl III):III-674.
4. Lorenz CH, Pastorek JS, Bundy JM. Delineation of normal human left ventricular twist throughout systole by tagged cine magnetic resonance imaging. *J Cardiovasc Magn Res* 2000;2:97–108.
5. Henson RE, Song SK, Pastorek JS, Ackerman JJ, Lorenz CH. Left ventricular torsion is equal in mice and humans. *Am J Physiol – Ht & Circ Physiol* 2000;278:1117–1123.
6. Ashraf M, Rein AJ, Lysyansky P, de la Cruz JS, Jensen AJ, Nelson SL. Improved delineation of myocardial twist by a new two-dimensional strain analysis method: An in vitro study. *Circulation* 2005;112(Suppl II):II765.
7. Notomi Y, Setser RM, Shiota T, Martin-Miklovic MG, Weaver JA, Popovic ZB, Yamada H, Greenberg NL, White RD, Thomas JD. Assessment of left ventricular torsional deformation by Doppler imaging: A validation study using tagged magnetic resonance imaging. *Circulation* 2005;111:1141–1147. [PubMed: 15738351]
8. Ylmaz H, Minareci K, Kabukçu M, Sancaktar O. Diastolic blood pressure-estimated left ventricular dp/dt. *Echocardiography* 2002;19:89–93. [PubMed: 11926969]
9. Helle-Valle T, Crosby J, Edvardsen T, Lysegeen E, Amundsen BH, Smith H, Rosen BD, Lima AC, Torp HD, Ihlen H, Smiseth OA. New non-invasive method for assessment for left ventricular rotation-speckle tracking echocardiography. *Circulation* 2005;112:3149–3156. [PubMed: 16286606]
10. Urheim S, Edvardsen T, Torp H, Angelsen B, Smiseth OA. Myocardial strain by Doppler echocardiography. Validation of a new method to quantify regional myocardial function. *Circulation* 2000;102:1158–1164. [PubMed: 10973846]
11. Castro PL, Greenberg NL, Drinko J, Garcia MJ, Thomas JD. Potential pitfalls of strain rate imaging angle dependency. *Biomed Sci Instrum* 2000;36:197–202. [PubMed: 10834232]
12. Gilman G, Khandheria BK, Hagen ME, Abraham TP, Seward JB, Belohlavek M. Strain rate and strain: a step-by-step approach to image and data acquisition. *J Am Soc Echocardiogr* 2004;17:1011–1020. [PubMed: 15337972]
13. Torrent-Guasp F, Buckberg GD, Clemente C, Cox JL, Coghlan HC, Gharib M. The structure and function of the helical heart and its buttress wrapping I: The normal macroscopic structure of heart. *Sem Thorac Cardiovasc Surg* 2001;13(4):301–319.
14. Buckberg GD, Clemente C, Cox JL, Coghlan HC, Gharib M, Torrent-Guasp F. The structure and function of the helical heart and its buttress wrapping IV: Concepts of dynamic function from normal macroscopic helical structure. *Sem Thorac Cardiovasc Surg* 2001;13(4):342–357.
15. Buckberg GD, Cox JL, Coghlan HC, Torrent-Guasp F. The structure and function of the helical heart and its buttress wrapping V: Anatomic and physiologic consideration in the health and failing heart. *Sem Thorac Cardiovasc Surg* 2001;13(4):358–383.

Figure 1.
The color band shows the zone for speckle track of rotation of the outer layer in this figure.

Figure 2.

These are images of the counterclockwise rotation of the outer (left) and inner (right) layers of the LV wall. The different segments of septum, anterior, lateral, posterior and inferior had different contributions to the twisting of the LV. The septal area of the inner layer had the highest regional contribution to twist.

Figure 3.
Correlation of peak rotation for the inner layer and +dp/dt.

Figure 4.
Correlation of peak rotation for the outer layer and +dp/dt.

Figure 5.
Correlation of the difference in peak rotation between inner and outer layers and +dp/dt.

Figure 6.
Correlation of peak rotation for the inner layer and $-dp/dt$.

Figure 8. Correlation of the difference in peak rotation between the inner and outer layers and $-dp/dt$.

Table 1

The distribution of peak rotation in segments

Location of Segment	Inner Layer		Outer Layer	
	Systolic Peak CCW Rotation Degree *	Diastolic Peak CW Rotation Degree *	Systolic Peak CCW Rotation Degree *	Diastolic Peak CW Rotation Degree *
Septum	-14.2 ± 2.9 *	12.1 ± 4.7 *	-12.6 ± 4.4 *	10.2 ± 4.2 *
Anterior	-5.3 ± 2.8	4.8 ± 1.9	-5.5 ± 2.4	4.8 ± 2.4
Lateral	-5.0 ± 2.3	4.3 ± 1.9	-5.8 ± 2.6	4.4 ± 2.0
Inferior	-5.5 ± 2.6 *	5.4 ± 2.9 *	-5.2 ± 2.6	3.8 ± 0.9 *
Posterior	-3.3 ± 2.0 *	3.4 ± 1.1	-4.8 ± 1.8 *	3.5 ± 2.2

The details of the regional twist values comparing inner and outer layers for systole and diastole.

* P< 0.05 between inner and outer layers for systolic or diastolic values.