Impact of Longitudinal Cardiac Rotation on Mitral and Tricuspid Atrioventricular Annular Diastolic Motion

Zoran B. Popović, MD, PhD; Chirapa Puntawangkoon, MD; David Verhaert, MD; Neil Greenberg, PhD; Allan Klein, MD; James D. Thomas, MD; Richard A. Grimm, DO

Background—It is unknown whether longitudinal rotation (LR), often seen in cardiac resynchronization therapy candidates, may affect mitral annular early diastolic (E') velocities and tricuspid annular motion. We assessed whether (1) LR affects the amplitude and timing of septal and lateral mitral annular E' velocities and tricuspid annular systolic and E' velocities and (2) if systolic strain heterogeneity seen in cardiac resynchronization therapy patients with LR extends into diastole.

Methods and Results—Ninety-nine cardiac resynchronization therapy candidates with suitable baseline echocardiograms were identified. Early diastolic (E') and systolic myocardial velocities of the tricuspid annulus and E' velocities of the septal and lateral part of the mitral annulus were analyzed from tissue Doppler images. Longitudinal rotation and basal systolic and diastolic strain rates were analyzed by speckle-tracking. LR correlated with lateral mitral annular E' (r=0.45, P<0.001), tricuspid annular E' (r=−0.3, P=0.003), and with a difference between septal and lateral mitral annular E' velocities (r=−0.49, P<0.001) but not with septal mitral annular E' velocity. LR also correlated with tricuspid annular systolic velocity (r=0.60, P<0.001). After categorizing the patients according to the quartiles of their LR, we showed that with decreasing quartile number, heterogeneity of systolic (P=0.003) but not diastolic (P>0.1) strain rates increased.

Conclusions—LR direction and magnitude correlates with the amplitude of, and relative differences between, diastolic velocities of tricuspid, lateral mitral, and septal mitral annulus, which are a cornerstone of diastolic function assessment. LR is associated with systolic but not with diastolic regional heterogeneity. (Circ Cardiovasc Imaging. 2010;3:368-374.)

Key Words: pacing ■ diastole ■ echocardiography

Longitudinal cardiac rotation (LR) is a rocking motion of the heart that can best be appreciated in a horizontal (4-chamber) long-axis view, where the heart silhouette exhibits a clockwise or counterclockwise rotation during systole. This motion is frequently seen in heart failure patients and is typically clockwise in subjects with nonischemic cardiomyopathy (Supplemental Video 1A) but sometimes may be counterclockwise in ischemic cardiomyopathy. The degree of clockwise LR has been linked to decreased septal long-axis systolic myocardial velocities, with blunting of the velocity of the wall in the direction of LR (depressed long-axis systolic velocities of the lateral wall in patients with clockwise LR as opposed to depressed septal wall velocities in patients with counterclockwise LR).
underlies the phenomenon of LR. Based on the observation that QRS duration appears to have a small impact on the degree of LR,\(^2\) we hypothesized that the pattern of LR could be related with a specific pattern of systolic or heterogeneity of regional diastolic function. Therefore, we also determined the association of LR with 2-dimensional strain derived measures of regional diastolic function.

**Methods**

**Study Population**

In the present study, we present the data of 99 of 100 patients already published in a previous report.\(^3\) A single missing patient is not presented because of the technical issues (corruption of the digital data stored on a disk). Briefly, patients were identified retrospectively by a search of our echocardiographic database for subjects who were cardiac resynchronization therapy (CRT) candidates (ie, New York Heart Association functional class III or IV symptoms despite optimal pharmacological therapy with ejection fraction $\leq 35\%$ and either ECG evidence of QRS $>120$ ms or preexisting right ventricular pacing), and had a preimplantation echocardiogram of satisfactory quality performed on a Vivid 7 ultrasound machine (Vingmed, GE Medical, Horten, Norway) during the period of March 2003 to October 2006. The cause of heart failure was ischemic cardiomyopathy ($\geq 50\%$ angiographically verified luminal diameter narrowing at least 1 major coronary artery or documented history of prior myocardial infarction or coronary revascularization) or idiopathic dilated cardiomyopathy.

Additionally, we studied 10 age-matched healthy control subjects who were randomly selected from our data base of 122 volunteers, all with negative history of cardiovascular disease and with normal physical examination that included blood pressure measurement, ECG, and lipid panel status.

**Echocardiography Methods**

LV ejection fraction and LV end-systolic and end-diastolic volumes were performed by Simpson biplane echocardiography. The timings of mitral valve opening and closure were determined from the pulsed-wave Doppler tracings of transmural diastolic inflow, whereas the timing of aortic valve opening and closure were determined from the pulsed-wave Doppler tracings of the LV outflow tract.

LR was analyzed in the apical 4-chamber view using speckle-tracking software (EchoPac, GE Medical) as previously described.\(^4\) In brief, the region of interest is applied over the LV myocardium in an apical 4-chamber view. The software automatically tracks down rotational rate of myocardial motion with reference to the center of gravity of the region of interest (Supplemental Video 1B). To obtain rotation, rotational rate is integrated over a single cardiac cycle, defined by the R waves of the ECG. Finally, end-systolic LR is defined as the rotation at the time of aortic valve closure. In accordance with engineering notation, the negative sign indicates clockwise rotation and a positive sign signifies counterclockwise rotation. Normal values for LR were published previously.\(^2\) We also used the same software to analyze longitudinal strain rate of basal LV and RV walls.\(^5\) For this purpose, we analyzed basal systolic and early diastolic longitudinal strain rates in a subgroup of 38 patients in whom both 4-chamber and 2 chamber views were obtained with a frame rate of $>50$ frames per second. A total of 4 basal LV segments and 1 basal RV free wall segment were analyzed per patient. The amplitude and timing of systolic and E\(^\prime\) longitudinal strain rate of basal LV and basal RV wall were assessed in subgroup of patients from each quartile. The software was also previously validated for the assessment of longitudinal strains.\(^9\)

Tissue Doppler (TDI) images of the apical 4-chamber view were analyzed to obtain timings (referenced to the R wave of the QRS complex) and amplitudes of myocardial velocities at septal and lateral MA and lateral TA (Figure 1). All amplitudes of E\(^\prime\) velocities were expressed as positive numbers. Traces of myocardial velocity profiles for 3 cardiac cycles were exported for each patient. From these profiles we obtained the septal and lateral MA timing and amplitudes of peak E\(^\prime\) velocities and calculating the following 2 parameters: (1) the difference in amplitude between the peak E\(^\prime\) velocities at the septum and lateral (S-L) MA with the lateral E\(^\prime\) velocity as the reference, and (2) the time difference between peak E\(^\prime\) velocity events at septum and lateral MA, again with reference to the lateral E\(^\prime\) peak velocity.

**Interobserver and Intraobserver Data Variability**

Intraobserver and interobserver variability for LV volumes, LR, and LV TDI velocities in CRT candidates has been previously de-
server and interobserver variability for TA E'/H11006 mean SD of the difference between 2 measurements. The intraobserver variability was assessed independently by a second observer. Variability is expressed as a percentage, and in the case of the TDI velocities, we assessed data of 10 randomly selected subjects. Data were measured in a 4-chamber view twice by a same observer and independently by a second observer. Variability is expressed as a percentage. For the strain rates, we assessed data of 10 randomly selected subjects. Data were measured in a 4-chamber view twice by a same observer and independently by a second observer. Variability is expressed as a percentage.

To assess interobserver and intraobserver variability of measurements of TA TDI velocities and systolic and E' longitudinal strain rates, we assessed data of 10 randomly selected subjects. Data were measured in a 4-chamber view twice by a same observer and independently by a second observer. Variability is expressed as a percentage. For the strain rates, we assessed data of 10 randomly selected subjects. Data were measured in a 4-chamber view twice by a same observer and independently by a second observer. Variability is expressed as a percentage. For the strain rates, we assessed data of 10 randomly selected subjects. Data were measured in a 4-chamber view twice by a same observer and independently by a second observer. Variability is expressed as a percentage. For the strain rates, we assessed data of 10 randomly selected subjects. Data were measured in a 4-chamber view twice by a same observer and independently by a second observer. Variability is expressed as a percentage.

Statistical Analysis
Results are expressed as means±SD unless otherwise stated. Statistical analysis was performed using SPSS 15.0 software (SPSS Inc, Chicago, Ill). Comparisons between ischemic and nonischemic patients were performed by unpaired t test.

Simple linear regression was performed to assess association between parameters. To assess the sensitivity of the ratio between early velocity of mitral inflow (E) and E'/H11032 velocity (S-L) amplitude difference was 2.61±1.08 cm/s. LR of healthy volunteers has already been published.3

Impact of LR on Diastolic Atrioventricular Annular Motion
LR affected diastolic velocities of the lateral TA and the septal and lateral MA differently. With increasing (less

Results
Of a total of 99 patients (age, 64±13 years), 77% were male and 53% had ischemic cardiomyopathy. Baseline data are shown in the Table. The average E' S-L time interval was 22±49 ms, and E' velocity (S-L) amplitude difference was 2.61±1.08 cm/s. LR of healthy volunteers has already been published.3

Table. Patient Clinical and Echocardiographic Data According to Quartiles of Longitudinal Rotation

<table>
<thead>
<tr>
<th></th>
<th>All Patients</th>
<th>Quartile 1</th>
<th>Quartile 2</th>
<th>Quartile 3</th>
<th>Quartile 4</th>
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<tr>
<td>n</td>
<td>99</td>
<td>25</td>
<td>25</td>
<td>24</td>
<td>25</td>
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<tr>
<td>Age, y</td>
<td>63.8±13.3</td>
<td>58.6±13.5</td>
<td>66.1±13.1</td>
<td>63±13.6</td>
<td>67.5±12.1</td>
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<tr>
<td>Sex, M/F</td>
<td>76/23</td>
<td>15/10</td>
<td>19/6</td>
<td>20/4</td>
<td>22/3</td>
</tr>
<tr>
<td>Ischemic CMP, n*</td>
<td>52</td>
<td>3</td>
<td>13</td>
<td>15</td>
<td>21</td>
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<tr>
<td>QRS duration, ms</td>
<td>152±32</td>
<td>150±27</td>
<td>153±27</td>
<td>147±29</td>
<td>157±43</td>
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<tr>
<td>EDV, mL</td>
<td>238±82</td>
<td>251±81</td>
<td>251±88</td>
<td>232±93</td>
<td>219±64</td>
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<tr>
<td>ESV, mL</td>
<td>180.75</td>
<td>199±77</td>
<td>194±77</td>
<td>170±81</td>
<td>157±60</td>
</tr>
<tr>
<td>EF</td>
<td>0.26±0.10</td>
<td>0.25±0.09</td>
<td>0.26±0.12</td>
<td>0.26±0.07</td>
<td>0.27±0.10</td>
</tr>
<tr>
<td>LR, degrees</td>
<td>−2.3±3.7</td>
<td>−6.8±2.3</td>
<td>−3.5±0.6</td>
<td>−1.2±0.8</td>
<td>2.5±1.5</td>
</tr>
</tbody>
</table>

*CMP indicates cardiomyopathy; EDV/ESV, end-diastolic/end-systolic volume; and EF, ejection fraction.*

P<0.001 for the difference between quartiles.

Impact of LR on Diastolic Atrioventricular Annular Motion
LR affected diastolic velocities of the lateral TA and the septal and lateral MA differently. With increasing (less
(clockwise) LR, lateral TA E’ velocity decreased, whereas lateral E’ velocity increased and septal E’ velocity remained unchanged. (Figure 2A to 2C). As a result, patients with pronounced clockwise rotation had a diminished difference between 2 mitral E’ velocities, whereas patients with pronounced counterclockwise rotation had pronounced differences between the septal and lateral mitral E’ velocities (Figure 3). Figure 4 shows the curves of annular velocities obtained by averaging individual velocity curves obtained from patients belonging to Quartile 1 (Fig 4A) and Quartile 4 (Fig 4B). As can be observed, Quartile 1 patients had exaggerated amplitude of tricuspid annular velocities, whereas, in contrast to the normal occurrence of lateral MA velocities having a larger amplitude, amplitudes of septal and lateral MA velocities were almost identical, although with different shape during systole. In contrast, Quartile 4 patients had depressed TA velocities, but with normal dominance of lateral versus septal MA velocities.

To assess whether the sensitivity of E/E’ measurement on LR is clinically relevant, we correlated the LR with the values of septal and lateral E/E’ ratio after correcting for E-wave velocity. As expected, septal E/E’ ratio was not sensitive to longitudinal rotation. In contrast, lateral E/E’ ratio was very sensitive ($P<0.0001$), with the slope parameter of $-0.30$, indicating that for every 1-degree LR increase, lateral E/E’ would decrease by 0.3.

**Impact of LR on Diastolic and Systolic Strain Rate Heterogeneity**

In a subsequent step, we evaluated whether regional heterogeneity of systolic function induced by QRS prolongation is carried over into diastole. There were 38 patients who satisfied that criterion of a frame rate $>50$ frames per second, with 10, 11, 7, and 10 patients in Quartiles 1, 2, 3, and 4, respectively. As expected, there was a significant heterogeneity of systolic strain rate amplitudes, with septum having lower values than lateral wall. As previously suggested, this heterogeneity decreased with increasing rank of quartiles. In other words, patients in Quartile 1 had more pronounced strain rate heterogeneity than patients with Quartile 4 (Figure 5A). In contrast to this, there was no difference in timing of peak systolic strain between quartiles (Figure 5B), although the timing of peak systolic strain rate showed a consistent septal-to-lateral gradient ($P<0.001$). This indicates that factors other than dispersion in timing of mechanical activation contribute to strain rate heterogeneity. More importantly, whereas intersegment differences in the amplitude of the peak E wave of a diastolic strain rate persisted ($P<0.0001$), no differences between quartiles were detected, indicating that factors that are responsible for systolic strain rate heteroge-

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**Figure 3.** Relationship between LR and septal-lateral difference in amplitudes of peak early diastolic velocities measured at the septal and lateral MA.

**Figure 4.** Direction of LR and the shape of Doppler myocardial velocity curves. Mean tissue Doppler myocardial velocity curves of the tricuspid and mitral annuli were obtained by averaging individual velocity curves across all patients in Quartile 1 of LR (A) and across all patients in Quartile 4 (B). Bars indicate standard errors.
neity dissipate before diastole (Figure 5C). Also, no difference in the timing of peak E wave of a diastolic strain rate was detected either between segments or between quartiles (Figure 5D).

Quartiles of LR did not influence the amplitude or the timing of both systolic and early diastolic strain rates of the RV free wall ($p>0.1$ for all 4 comparisons).

**Discussion**

In this study, we showed that the rocking motion of the heart quantified by LR strongly affects diastolic mitral and tricuspid annular velocities. With a clockwise LR, lateral MA $E'$ velocity becomes lower, septal MA $E'$ velocity is unchanged, and TA $E'$ velocity becomes higher. This could have implications for the noninvasive assessment of LV diastolic function and filling pressures in patients with severe systolic dysfunction, as the lateral MA $E'$ velocity is affected by the presence of detectable LR.

Additionally, we demonstrated that the impact of LR on diastolic annular velocities is not associated with differences in diastolic strain rate between the septum and the opposing lateral wall. Rather, it is a passive, or carry-over effect, induced by differences in strain rates during systole.

**LR and MA $E'$ Velocities in the Assessment of Diastolic Function**

In a last decade, MA $E'$ velocity has emerged as a cornerstone of diastolic function assessment.$^{3,12,13}$ Recently published American Society of Echocardiography Recommendations for the Evaluation of LV diastolic function have proposed new algorithms using left atrial volume and a combination of septal and lateral $E'/E$ MA velocities as the sole parameters to discriminate between normal diastolic function, athletic heart, and diastolic dysfunction. Similar algorithms were also developed for the noninvasive estimation of LV filling pressures.$^{14}$ Our observation suggests that the diagnostic accuracy of (especially lateral) $E'/E$ MA velocities may be compromised in the presence of prominent rocking motion of the heart. As an example, patients with a LR of $-10$ degrees will have their lateral $E/E'$ ratio 3 points higher than patients with LR of 0 degrees. These values are well within a clinically significant change of $E/E'$ and could inappropriately lead to patient misclassification.$^{14}$

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**Figure 5.** Amplitudes (A and B) and timings, relative to the onset of the R wave (C and D), of peak regional systolic and early diastolic longitudinal strain rate according to quartiles. Bars indicate standard error of mean. S indicates peak systolic strain rate.
Moreover, our results may partially explain the results of a recent study from our institution, which showed that tissue Doppler-derived indices of LV filling pressures poorly correlate with invasive measurements in the setting of advanced decompensated heart failure.15

**LR and Regional Heterogeneity of LV Function**

We have previously shown that LR is frequently seen in heart failure associated with increased QRS duration and that LR may serve as a marker of regional heterogeneity of systolic function.1 Increased QRS duration not only results in temporal heterogeneity, or “dyssynchrony” (segments having different time-to-peak contraction), but also causes amplitude heterogeneity (segments showing differences in magnitude of contraction).16–18 In left bundle-branch block, one can observe low-amplitude, early- or double-peaking contractions of the early depolarized septal segments, whereas lateral segments usually have high-amplitude, late-peaking contractions.17,19 In this study, we show that there is a uniform increase of time-to-peak systolic strain rate (temporal heterogeneity or “dyssynchrony”) from septum toward the lateral wall, in line with most of the patients having a left bundle-branch block type of conduction abnormality, independent of the degree of LR. However, although the amplitude of strain rate (ie, contraction) was heterogeneous and expectedly increased from the septum toward lateral wall, this pattern was most prominent in patients with the most prominent clockwise longitudinal rotation (ie, Quartile 1) and gradually disappeared in higher quartiles. An associated question is whether systolic heterogeneity propagates into diastole. Although it appears that repolarization heterogeneity is more pronounced in the presence of conduction abnormality,20 it is poorly understood whether this translates into heterogeneity of mechanical function during relaxation. In the present study, we show that whereas septal segments demonstrate smaller diastolic strain rate than lateral segments, the timing of peak diastolic strain rates of different segments occurred at almost the same time. Additionally, there were no between-group differences in either amplitude or temporal heterogeneity. This suggests that regional differences in the mechanical activation sequence during systole are attenuated or even disappear during the rest of the cardiac cycle. Interestingly, Spragg et al21 have shown that in the presence of a left bundle-branch block, the action potential duration is shortened in the early-stretching, late-activated lateral segments, whereas it is prolonged in the early activated, late-loaded septum. In other words, because of short action potential duration, late-activated lateral wall can “catch-up” with the septal wall and start repolarization at the same time. As a result, peak mechanical relaxation (as assessed by diastolic strain rate) can simultaneously occur in the septum and the lateral wall, regardless of left bundle-branch block or LR presence.

**Ischemic Cardiomyopathy, E′ Annular Velocities, and LR**

In patients with ischemic heart disease and preserved systolic function, local scar or ischemia is associated with decreased regional E′ velocities.22 However, for E′ velocity to be able to detect scar, there should be no whole-heart translation. LR is one of the measures of heart translation, and its presence makes E′ velocities less dependable for detecting scar. Patients with clockwise longitudinal rotation (who frequently have nonischemic cardiomyopathy) have lateral E′ velocities lower than septal ones, without having lateral wall scar. In contrast, patients with ischemic cardiomyopathy appear to have more frequently minimal, or counterclockwise, LR.1 One possible reason is interaction between scarring and left bundle-branch block. Patchy scarring can attenuate or reverse systolic septal-lateral strain differences seen in left bundle-branch block, which appear to be one of the drivers of large clockwise LR often seen in nonischemic cardiomyopathy. As a result, a smaller lateral E′ than septal E′ does not necessarily mean lateral scar, or vice versa. In practical terms, this means a presence of global decrease of systolic function, especially if it is associated with the presence of conduction abnormality, decreases the specificity of tissue Doppler in diagnosing the presence and distribution of scar or ischemia.

**Limitations**

This was a retrospective study performed on a relatively small number of patients. Additionally, we could analyze strain rates in only 38 of our patients. Because no invasive measurements were done, we can only speculate whether LR affects estimation of LV filling using MA E′ velocity. Findings of this study should be confirmed by a prospective study with a larger population in the future. Finally, frame rates of 50 frames per second may be too low to accurately capture strain rate. However, similar frame rates were previously used and have been shown to satisfactorily reflect invasive indices of LV function.23

**Conclusion**

We have shown that clockwise LR is associated with lower E′ velocities of the lateral, mitral, and higher E′ velocities of tricuspid annulus. Counterclockwise LR, in turn, is associated with opposite findings. This indicates that the assessment of ventricular diastolic function using E′ velocity may be more difficult in the setting of detectable LR. Also, we have additionally shown that the impact of LR on diastolic velocities is passive and is probably induced by differences in strain rates during systole.

**Disclosures**

None.

**References**


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**CLINICAL PERSPECTIVE**

Longitudinal cardiac rotation, a rocking motion of the heart that can be appreciated in a horizontal long-axis view, is frequently seen in heart failure patients and is typically clockwise in subjects with nonischemic cardiomyopathy. It is uncertain if longitudinal rotation affects diastolic velocities of the mitral annulus, which are of paramount importance in the assessment of diastolic function. In this study of 99 candidates for cardiac resynchronization therapy, we show that longitudinal rotation direction and magnitude correlate with the amplitude of, and relative differences between, diastolic velocities of tricuspid, lateral mitral, and septal mitral annulus, which are a cornerstone of diastolic function assessment.

Interestingly, longitudinal rotation was associated with systolic but not with diastolic regional heterogeneity.
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