Apical Rotation Assessed by Speckle-Tracking Echocardiography as an Index of Global Left Ventricular Contractility

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**Background**—Left ventricular (LV) apical rotation and twist can be estimated noninvasively by speckle-tracking echocardiography (STE). In this study, we tested whether apical rotation is an accurate index of LV contractility.

**Methods and Results**—We measured LV basal and apical rotation by STE in 11 open-chest anesthetized mongrel dogs under 8 different inotropic stages before and after ligation of either left anterior descending (n = 6) or circumflex coronary artery (n = 5). We measured LV pressure simultaneously with a high-fidelity pressure catheter and calculated LV ejection fraction (EF) with the biplane Simpson method and 2D echocardiography. Maximal positive dP/dt (dP/dt\text{max}) was used as the gold standard measurement of LV contractility. We compared LV twist and apical rotation and EF against dP/dt\text{max} by linear mixed model. LV apical rotation and twist showed dose-dependent increases and decreases after dobutamine and esmolol infusion, respectively. However, basal rotation did not change significantly during different inotropic conditions. There was a stronger association between dP/dt\text{max} and LV twist (R\textsuperscript{2}=0.747, P<0.001) and apical rotation (R\textsuperscript{2}=0.726, P<0.001) than between dP/dt\text{max} and EF (R\textsuperscript{2}=0.408, P<0.001), and this trend was more apparent with coronary ligation irrespective of the ligation site. There was also a high association between dP/dt\text{max} and apical rotation alone, both with (R\textsuperscript{2}=0.805, P<0.001) and without (R\textsuperscript{2}=0.748, P<0.001) coronary ligation. Apical rotation alone showed comparable accuracy to LV twist. Apical rotational velocity also showed a high association with dP/dt\text{max} (R\textsuperscript{2}=0.669, P<0.001) and LV twist (R\textsuperscript{2}=0.892, P<0.001).

**Conclusions**—Apical rotation assessed by STE is an effective noninvasive index of global LV contractility and is more closely related to dP/dt\text{max} than LV EF. *(Circ Cardiovasc Imaging. 2009;2:123-131.)*

**Key Words:** contractility • ventricular rotation • echocardiography

Left ventricular (LV) rotation, in addition to radial thickening and longitudinal shortening, is important for effective LV pumping action.\textsuperscript{1-3} LV twist motion, induced by apical counterclockwise and basal clockwise rotation, leads to LV wringing or torsional deformation during systole, and this action is believed to generate the required pumping power. Ventricular muscle band theory has provided the morphological basis for LV rotation or twist.\textsuperscript{4} It has been reported that, without LV rotation, the normal LV ejection fraction (EF) cannot be achieved by radial and longitudinal motion alone.\textsuperscript{5,6} Moreover, LV twist, coupled with the ensuing untwist motion, plays a major role in the performance of LV systolic and diastolic functions.\textsuperscript{7,8}

**Clinical Perspective see p 131**

LV rotation is sensitive to changes in both regional and global LV functions,\textsuperscript{9-12} so quantification of LV rotation or twist can be used to assess LV systolic function. Noninvasive measurement of LV twist or rotation by speckle-tracking echocardiography (STE)\textsuperscript{13,14} or MR\textsuperscript{15,16} shows great promise. However, several issues must be solved before there is a widespread clinical adoption of these techniques for noninvasive measurement of LV twist or rotation. The accuracy of STE for measuring LV torsion or rotation has been validated by invasive sonomicrometry,\textsuperscript{11} but validation with invasive indices of LV contractility is not yet available. Several studies have demonstrated significant correlation between LV torsion and EF, a widely used clinical index of LV systolic function.\textsuperscript{14,17,18} However, the relative accuracy of LV twist against EF under a wide range of contractility conditions or under regional wall motion abnormality (RWMA) has not been seriously investigated. Moreover, a recent report concluded that it was not feasible to measure LV torsion because of difficulty in obtaining reliable measurements of basal rota-
tion. Considering the relatively low degree of basal rotation compared with apical rotation, apical rotation alone may be possibly used for assessment of LV contractility. The accuracy and feasibility of using apical rotation to assess LV contractility has not yet been tested.

There were two main objectives of our study. First, we determined whether LV twist or apical rotation measured by STE could be used as a noninvasive, quantitative index of contractility under various conditions featuring a wide range of LV inotropic status, including RWMA. Second, we compared the relative accuracy of LV twist or apical rotation measurements with LVEF values. We took simultaneous measurements of maximal positive dP/dt (dP/dtmax) and LV rotation following various pharmacological interventions under a wide range of LV contractility conditions in an open-chest canine model with and without coronary artery ligation.

**Methods**

**Animals**

This study was reviewed and approved by the Institutional Animal Care and Use Committee of Asan Institute for Life Sciences, Asan Medical Center. The committee abides by the Institute of Laboratory Animal Resources guide. Eleven mongrel dogs, weighing 26.5 ± 0.5 kg (range, 23.0 to 30.5 kg), were initially anesthetized by intramuscularly injecting atropine sulfate (0.05 mg/kg) and a mixture of zolazepam and tiletamine (7 mg/kg). The dogs were intubated with an endotracheal tube, mechanically ventilated (rate, 15/minute; tidal volume 250 to 300 mL) using oxygen (1.0 L/minute), and maintained with enflurane (2% to 2.5%). The dogs were placed on a water blanket controlled at 38°C. The right femoral artery, left carotid artery, and right jugular vein were isolated and cannulated with introducer sheaths. Arterial blood pressure was monitored using a fluid-filled catheter together with a single-lead ECG connected to an oscilloscopic multichannel recorder. A 5F catheter with a dual high-fidelity pressure sensor (Millar Instruments) was advanced, after adequate calibration, from the left carotid artery to the LV under echocardiographic guidance. The dP/dtmax, an invasive index of LV contractility, was continuously monitored throughout all experiments. Thoracotomy was performed in the right lateral decubitus position for echocardiographic measurements, and the pericardium was not opened.

A wide range of LV inotropy status was used for each animal: (1) baseline, (2) dobutamine 5 μg/kg per minute, (3) dobutamine 10 μg/kg per minute, (4) dobutamine 20 μg/kg per minute, (5) esmolol 100 μg/kg per minute, (6) esmolol 200 μg/kg per minute, (7) esmolol 300 μg/kg per minute, and (8) esmolol 400 μg/kg per minute. A period of stabilization (20 to 30 minutes) was allowed between each stage. After getting simultaneous hemodynamic and echocardiographic data under pharmacological modulation of inotropic status without coronary ligation, coronary artery ligation was performed by tying a blind stitch over the left anterior descending (n = 6) or left circumflex artery (n = 5). Hemodynamic (dP/dt) and echocardiographic data were acquired simultaneously again after coronary ligation in multiple stages, as described earlier. RWMA developed immediately after coronary ligation and, after confirmation of stable LV pressure by a high-fidelity pressure catheter and no change of RWMA by echocardiography, data acquisition was done. It usually took 10 minutes to have stable LV pressure and RWMA after coronary ligation.

**Echocardiography**

Two-dimensional and STE studies were performed using a Vivid 7 ultrasound machine (GE Medical Systems) equipped with a multifrequency transducer (MS) and second harmonic imaging. Two-dimensional images of the LV were obtained from the apical 4- and 2-chamber views, and LV volumes were calculated by Simpson method. Parasternal basal and apical short-axis planes were used for measurement of basal and apical rotation. Frame rates (84.8 ± 2.1;
range, 83.8 to 88.5 frames/second) and probe frequency (range, 3 to 4 MHz) were adjusted during apnea to allow for better image acquisition. The basal level was marked from the tip of the mitral valve, and the apical level was defined just proximal to the level showing LV cavity obliteration at the end-systole. We attempted to make the LV as circular as possible and took great care to get a high frame rate without significant loss of 2-dimensional image quality by optimizing sector width and image depth. Three consecutive beats were digitally saved in cine loop format for subsequent analysis with a dedicated software package (EchoPAC workstation 7.0.1, GE Medical Systems).

LV apical or basal rotation was calculated as the average angular displacements of 6 myocardial segments along the central axis (Figure 1). By convention, counterclockwise LV rotation (as viewed from the apex) was expressed as a positive value and clockwise LV rotation was expressed as a negative value. The net difference in peak rotation angles at the two short-axis levels (basal and apical) was used to calculate LV twist. Rotational velocity curve could be

Figure 2. Representative images of apical (A) and basal (B) rotation angles with corresponding rotational velocity curves (C and D).
automatically obtained after calculating apical or basal rotation (Figure 2). The peak rotational velocity (degrees/second) was measured in the curve and compared with dP/dt\text{max} and LV twist. Offline analyses were performed independently by a colleague with no knowledge of dP/dt\text{max} or LVEF values.

**Statistical Analysis**

Data are expressed as mean±SD or percentages where appropriate. Repeated measure ANOVA was performed to examine the pharmacological effects of β-adrenergic modulation on various physiological parameters. Linear mixed models were performed between dP/dt\text{max} and noninvasive indices of LV contractility (LV twist, apical or basal rotation, peak apical rotational velocity, and EF) and also among noninvasive indices. The generalized \( R^2 \) value was used to compare strength of association for each variables, as it measures how much variability of dependent variable is explained by the independent variable.\(^1^9\) To compare the generalized \( R^2 \) value for each linear mixed model with same dependent variable, we used bootstrap technique (100 replicates).\(^2^0\) All statistical analyses were performed with SAS software version 9.1 (SAS Institute), and a \( P \) value less than 0.05 was considered statistically significant.

**Results**

Changes of basal and apical rotation under different inotropic effects of pharmacological interventions before and after coronary ligation are shown in Figures 3 and 4. LV twist, apical rotation, and basal rotation showed significant differences during pharmacological modulation of β-adrenergic receptor activity, with and without coronary ligation. However, dose-dependent changes with pharmacological modulation were observed in apical rotation, but not in basal rotation. Significant linear trends from baseline were observed with inotropics in apical rotation before coronary ligation (positive inotropics, \( P<0.001 \); negative inotropics, \( P<0.001 \)) and after ligation (positive inotropics, \( P<0.001 \); negative inotropics, \( P<0.001 \)). Similar trends were observed for LV twist before ligation (positive inotropics, \( P<0.001 \); negative inotropics, \( P<0.001 \)) and after ligation (positive inotropics, \( P<0.001 \); negative inotropics, \( P<0.001 \)). However, basal rotation showed different results. Although a significant linear trend from baseline was observed with negative inotropics (\( P=0.0006 \)) before ligation, there was no significant linear trend from baseline to positive inotropics (\( P=0.67 \)) before ligation. After ligation, basal rotation showed inverse trends: from baseline to negative inotropics, there was no significant linear trend (\( P=0.20 \)), but significant linear trend from baseline was observed with positive inotropics (\( P<0.0001 \)). Moreover, the proportion of basal rotation to contribute to LV twist was very small compared with apical rotation (Figures 3 and 4).

**Figure 3.** Inotropic effects on apical rotation (A), basal rotation (B), and left ventricular twist (C) without coronary artery ligation.

**Figure 4.** Inotropic effects on apical rotation (A), basal rotation (B), and left ventricular twist (C) with coronary artery ligation.
LV twist showed parallel changes with pharmacological modulation of β-adrenergic receptor activity, and the association between LV twist and \( \frac{dP}{dt_{\text{max}}} \), an invasive measure of LV contractility, is shown in Figure 5. There was a significant association with coronary ligation (\( R^2 = 0.791, P < 0.001 \)) and without coronary ligation (\( R^2 = 0.777, P < 0.001 \)). A modest association between LVEF and \( \frac{dP}{dt_{\text{max}}} \) was observed before coronary ligation (\( R^2 = 0.580, P < 0.001 \)) and after coronary ligation (\( R^2 = 0.318, P < 0.001 \)). The generalized \( R^2 \) values between LV twist and \( \frac{dP}{dt_{\text{max}}} \) were significantly higher than those between LV twist and \( \frac{dP}{dt_{\text{max}}} \) (Table 1).

Figure 6A through 6C shows the association between LV twist and EF. Although there was a good association overall, the \( R^2 \) values were quite different with coronary ligation (\( R^2 = 0.389, P < 0.001 \)) and without (\( R^2 = 0.754, P < 0.001 \)) coronary ligation. Figure 6D through 6F shows the association between apical rotation and \( \frac{dP}{dt_{\text{max}}} \). There was a strong association with coronary ligation (\( R^2 = 0.805, P < 0.001 \)) and without coronary ligation (\( R^2 = 0.748, P < 0.001 \)). The \( R^2 \) values between apical rotation and \( \frac{dP}{dt_{\text{max}}} \) were not significantly different from those between LV twist and \( \frac{dP}{dt_{\text{max}}} \) (Table 1). However, apical rotation and apical rotational velocity are more closely related to \( \frac{dP}{dt_{\text{max}}} \) than LVEF (Table 1). Apical rotational velocity also showed a high association with \( \frac{dP}{dt_{\text{max}}} \) (\( R^2 = 0.669, P < 0.001 \)) and LV twist (\( R^2 = 0.892, P < 0.001 \); Figure 7).

The association between \( \frac{dP}{dt_{\text{max}}} \) and noninvasive measures of LV contractility under ligation of different coronary arteries is shown in Figure 8 and Table 2. LV twist (\( P = 0.016 \)), apical rotation (\( P = 0.007 \)), and apical rotational velocity (\( P = 0.009 \)) were more closely related to \( \frac{dP}{dt_{\text{max}}} \) than LVEF after ligation of left anterior descending coronary artery. More close relationships of LV twist (\( P < 0.001 \)), apical rotation (\( P < 0.001 \)), and apical rotational velocity (\( P < 0.001 \)) to \( \frac{dP}{dt_{\text{max}}} \) than LVEF were also observed after ligation of left circumflex coronary artery. The generalized \( R^2 \) value between LV twist and \( \frac{dP}{dt_{\text{max}}} \) was not different from those between apical rotation and \( \frac{dP}{dt_{\text{max}}} \) during ligation of either left anterior descending (\( P = 0.078 \)) or circumflex coronary artery (\( P = 0.54 \)).

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

**Discussion**

In this controlled animal study, we have found that apical rotation, not basal rotation, exhibited dose-dependent changes in response to pharmacological modulation of inotropic status. Apical rotation and LV twist were highly correlated with \( \frac{dP}{dt_{\text{max}}} \), an invasive index of LV contractility, under a variety of LV inotropic conditions, irrespective of coronary ligation and development of RWMA. Although there was also a modest association between \( \frac{dP}{dt_{\text{max}}} \) and LVEF, a comparison of the \( R^2 \) values demonstrated that a more accurate measure of LV contractility is provided by LV twist or apical rotation alone, rather than LVEF. These observations suggest that STE measurement of apical rotation alone provides a noninvasive assessment of LV contractility. This technique has a promise for use in routine clinical practice.

**LV Rotation as a Contractility Index**

In routine clinical practice, assessment of LV contractility is one of the most important parameters provided by echocar-
diographic examination. Quantitative echocardiographic indices of ventricular systolic function, such as EF, ventricular volumes, stroke volume, and fractional shortening, are believed to mainly reflect radial thickening and longitudinal shortening of LV during systole, but it has been recently documented that both structural anisotropy and the regional inhomogeneity of mechanical shortening and lengthening sequences in the LV wall result in a highly efficient global function of the normal heart.21 These findings support that simple transverse or circumferential muscle contraction cannot explain all aspects of LV performance. MRI studies have confirmed that the predominant heart motions during normal cardiac action include LV twisting with oblique fiber orientation.1,22 Moreover, with muscle fiber shortening of only 15%, the estimated EF is ∼30% after transverse or horizontal fiber orientation. This increases to 60% if there is oblique fiber orientation.23 Recent clinical introduction of muscle band theory and the demonstration of sequential mechanical shortening of different myocardial segments23,24 strongly support the importance of LV rotation to generate sufficient power for cardiac pumping.

Although LV rotation or twist has been reported to be sensitive to inotropic status, there is little validation of such data using an invasive index of LV systolic function, have not been seriously investigated. It is necessary to assess the clinical usefulness of noninvasive measurements of LV rotation or twist.

In this study, we documented dose-dependent changes in apical rotation and LV twist following dobutamine and esmolol infusion. Apical rotation is highly sensitive to ischemia and becomes abnormal within a few seconds after coronary ligation or balloon occlusion.12,25 In our studies, coronary ligation promptly reduced apical rotation and twist, as well as dP/dt max with high R² values. Interestingly, both LV twist and apical rotation were more closely related to dP/dt max than LVEF after ligation of either left anterior descending or circumflex coronary artery. The pharmacological- and ligation-mediated changes that we observed agree with the findings from previous studies that have used other methods.9,12,25 In a segmental analysis using MRI, it was reported that anterior and posterior ischemia resulted in a reduction of LV twist in the anterior regions but not in the posterior regions.11 Unique fiber rearrangements or ischemia-induced global shape alterations have been suggested as possible explanations for this finding. Our study confirmed a strong association between dP/dt max and apical rotation or LV twist, irrespective of coronary ligation or ligation sites. This suggests that apical rotation can serve as a marker of global, not local, LV contractility.

Our results showed that apical and basal rotation responded differently to pharmacological modulation of LV inotropy. Apical rotation showed clear dose-dependent changes following modulation of the β-receptor, but basal rotation exhibited no significant changes. This trend appeared with or without coronary ligation. These results agree with the previous reports.13,26

The relative insensitivity of basal rotation to inotropy modulation with absent association between basal rotation and LVEF14,27 may have clinical implications. The maturation process of the LV twist involves augmentation of apical counter-clockwise rotation during adulthood and a decrease in basal clockwise rotation.28 Because assessment of rotation by STE is less accurate for the basal level than the apical level,13,14 measurement of apical rotation alone (rather than calculation of LV twist) might provide a simple and accurate alternative for assessment of LV contractility. Our results show good association between dP/dt max and apical rotation, irrespective of coronary ligation and no significant difference in accuracy between LV twist and apical rotation measurements.

Relative Accuracy of Apical Rotation Against EF

Previous studies have demonstrated an association between LV twist and EF.14,17,18 However, the accuracy of these two indices, based on comparison with an invasive measurement of LV contractility (the gold standard), was not investigated. Our study shows that LV twist and EF were associated with dP/dt max. However, comparison of R² values demonstrated that LV twist or apical rotation alone provides a more accurate measure of LV contractility than does LVEF. LV dP/dt max, an invasive measure of LV contractility in this study, is a relatively load-independent index of systolic
EF is well known to be a load-dependent index of LV contractility, but some reports have suggested different effects of preload and afterload on LV rotation or twist. For example, in an excised heart experiment, both preload and afterload affected LV rotation or twist. On the other hand, in an intact human heart, LV twist was reported to be relatively insensitive to the changes of preload and afterload. In addition to this discrepancy, it should be noted that development of RWMA significantly decreased the accuracy of LVEF. Before coronary ligation, the generalized $R^2$ value between $dP/dt_{\text{max}}$ and EF was 0.580, and this decreased significantly after ligation ($R^2 = 0.318$; Figure 5). In addition, the generalized $R^2$ value between LVEF and twist for all experimental conditions was 0.617, similar to the previous reports. The generalized $R^2$ value before ligation was 0.754, and this decreased to 0.389 after ligation (Figure 6). Thus, development of RWMA following coronary ligation adversely affects the accuracy of LVEF. We believe that inaccurate LV volume calculation, despite application of biplane Simpson method, could explain the dramatic decrease of accuracy.

**Limitations**

The relatively small changes in basal rotation following modulation of inotropy may be because of inherent limitation in application of STE to LV short-axis images. Longitudinal motion of the LV causes the myocardium to move in and out of the image plane, and this is more pronounced at the LV base. Because the LV apex is essentially stationary, this difference might result in regional differences in response to inotropy changes. A clinically more important issue is whether LV twist or rotation can be used as a noninvasive reliable index of LV contractility. Considering the good

![Figure 6. Association of left ventricular twist with EF (A through C) and $dP/dt_{\text{max}}$ with apical rotation (D through F).](image_url)

![Figure 7. Association between apical rotational velocity and $dP/dt_{\text{max}}$, apical rotation, and left ventricular twist.](image_url)
correlation between invasive dP/dt\textsubscript{max} and apical rotation shown in this study, we conclude that there is no additive benefit in adding measurements of basal rotation to the algorithm, and that our methods are appropriate.

Different coronary anatomic features between dogs and humans, and potential effects of ligation locations need to be clarified. In contrast to man, the heart of dog is left coronary preponderant, and usually left circumflex artery is the largest of the coronary arteries with large subepicardial collaterals.\textsuperscript{31,32} The left circumflex coronary artery and left anterior descending coronary artery each supply $\approx$40% of the myocardium and the right coronary artery $\approx$15% in the dog.\textsuperscript{31} Thus, one may argue that our observation of excellent association between apical rotation and invasive dP/dt\textsubscript{max} after ligation of left circumflex artery may not work in a different coronary vascular system. However, as we changed inotropic status before and after coronary ligation and showed excellent associations between apical rotation and dP/dt\textsubscript{max}, we believe that this potential limitation does not preclude our conclusions.

**Conclusions**

This study demonstrates that apical rotation measurement by STE is an effective noninvasive index of global LV contractility. Association between these indices was excellent after a wide range of pharmacologically modulated inotropy. This association occurs irrespective of coronary ligation, and apical rotation is a better index of global LV contractility than LVEF. Measurement of apical rotation has potential as a reliable noninvasive index of global LV contractility in clinical settings.

**Table 2.** \(R^2\) Values of LV Contractility Indices After Coronary Ligation

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<th>(R^2)</th>
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<td><strong>After LAD ligation</strong></td>
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<td><strong>After LCX ligation</strong></td>
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LAD, left anterior descending coronary artery; LCX, left circumflex coronary artery.

**Acknowledgments**
The authors thank Sung-Cheol Yun, PhD, for providing excellent assistance in statistical analysis.

**Disclosures**
None.

**Sources of Funding**
This study was supported by the CardioVascular Research Foundation, Seoul, South Korea.
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Kim et al

References


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Circ Cardiovasc Imaging, 2009;2:123-131; originally published online January 26, 2009; doi: 10.1161/CIRCIMAGING.108.794719
Circulation: Cardiovascular Imaging is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-9651. Online ISSN: 1942-0080

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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