

## Components of Left Ventricular Ejection and Filling in Patients With Aortic Regurgitation Assessed by Speckle-Tracking Echocardiography

Vaida Mizarienė<sup>1,2</sup>, Silvija Bučytė<sup>1</sup>, Diana Žaliaduonytė-Pekšienė<sup>2</sup>, Regina Jonkaitienė<sup>2</sup>, Jūratė Janėnaitė<sup>1</sup>, Jolanta Vaškelytė<sup>1,2</sup>, Renaldas Jurkevičius<sup>2</sup>

<sup>1</sup>Institute of Cardiology, Medical Academy, Lithuanian University of Health Sciences,

<sup>2</sup>Department of Cardiology, Medical Academy, Lithuanian University of Health Sciences, Lithuania

**Key words:** aortic regurgitation; speckle-tracking echocardiography; left ventricular rotation; strain.

**Summary.** The aim of our study was to evaluate left ventricular (LV) longitudinal, radial, and rotational function and its relationship with conventional LV parameters of systolic and diastolic function in patients with aortic regurgitation (AR) by speckle-tracking echocardiography.

**Material and Methods.** A total of 26 asymptomatic patients with moderate AR, 34 patients with severe AR, and 28 healthy controls were included into the study. LV rotation and longitudinal and radial strain were measured offline using speckle-tracking imaging.

**Results.** The systolic longitudinal strain ( $-18.3\%$  [SD, 2.18%] vs.  $-21.0\%$  [SD, 2.52%],  $P < 0.05$ ) and strain rate ( $-1.08\text{ s}^{-1}$  [SD, 0.13  $\text{s}^{-1}$ ] vs.  $-1.27\text{ s}^{-1}$  [SD, 0.15  $\text{s}^{-1}$ ],  $P < 0.05$ ) were significantly lower and apical rotation ( $11.3^\circ$  [SD, 4.99°] vs.  $8.30^\circ$  [SD, 4.34°],  $P < 0.05$ ) as well as rotation rate ( $82.72^\circ/\text{s}$  [SD, 28.24  $^\circ/\text{s}$ ] vs.  $71.00^\circ/\text{s}$  [SD, 28.04  $^\circ/\text{s}$ ],  $P < 0.05$ ) were significantly higher in the patients with moderate AR compared with the control patients. The LV systolic basal rotation, systolic radial strain, and diastolic radial strain rate were significantly reduced in the patients with severe AR compared with the control patients. The global longitudinal, radial strain, and LV systolic diameter were the independent predictors of LV ejection fraction in the patients with AR ( $R^2 = 0.77$ ). The LV systolic basal rotation in the control patients, diastolic longitudinal strain rate and systolic longitudinal strain in the patients with moderate and severe AR, respectively, were independent predictors of LV diastolic filling.

**Conclusions.** LV long-axis dysfunction with an increased apical rotation was present in the patients with moderate AR, while LV radial function and systolic basal rotation were found to be reduced in more advanced disease. LV diastolic filling depended on diastolic and systolic LV strain and rotation components in the patients with AR.

### Introduction

Chronic aortic regurgitation (AR) is characterized by left ventricular (LV) dilatation caused by diastolic LV volume overload and formation of ellipsoidal LV cavity along the long axis (1–3).

In the LV myocardial wall, the myofiber geometry changes from a right-handed helix in the subendocardium to a left-handed helix in the subepicardium (4). In the midwall of the left ventricle, fibers are aligned circumferentially (5). All the layers of the myocardium play a role in effective LV pump function.

Previously, the long-axis function in most of cases was assessed by M-mode echocardiography in the measurements of mitral annulus excursions or tissue Doppler echocardiography in the measurements of myocardium velocity (6–9), which can detect early myocardial dysfunction in asymptomatic patients with severe AR (10, 11). In the last decade,

new echocardiographic modalities, such as strain (deformation) analysis, have been developed, which is considered one of the methods for quantifying global and regional myocardial function. Strain is currently measured by two methods: tissue Doppler imaging and speckle-tracking echocardiography (12, 13). The latter method enables the assessment of strain parameters in different directions and rotational LV function. There are scarce data in the literature where LV function was assessed by speckle-tracking echocardiography in patients with chronic AR. LV dilation can determine the changes of different LV motion forms and their impact on LV ejection and filling in AR.

The aim of our study was to evaluate LV longitudinal, radial, and rotational function and its relationship with the conventional LV parameters of systolic and diastolic function in patients with AR by speckle-tracking echocardiography.

### Materials and Methods

**Study Population.** The study population comprised 88 participants: 26 patients with moderate

Correspondence V. Mizarienė, Department of Cardiology, Medical Academy, Lithuanian University of Health Sciences, Eivenių 2, 50028 Kaunas, Lithuania  
E-mail: vaidamizariene@gmail.com

AR, 34 patients with severe AR, and 28 healthy subjects (control group). Severity of AR was assessed according to the recommendations for evaluation of the severity of native valvular regurgitation with 2-dimensional and Doppler echocardiography (14).

The patients were recruited from the inpatient and outpatient Departments of Cardiology, Hospital of Lithuanian University of Health Sciences. The control group consisted of healthy volunteers who had no history of any cardiac disease and serious noncardiac disease, were normotensive, and had no ischemic signs on resting ECG. A total of 32 investigated persons were excluded from the study due to inadequate quality of echocardiographic images to be included into speckle-tracking analysis.

All the patients provided written informed consent for participation in the study. Procedures were approved by the Local Ethics Committee.

**Echocardiography.** Both conventional echocardiography and speckle-tracking echocardiography were performed using Vivid 7 (GE-Vingmed Ultrasound AS, Horten, Norway) with an M3S transducer. All images were acquired by a single cardiologist with the subject lying in the left lateral decubitus position. Standard transthoracic echocardiographic measurements were performed according to the guidelines of the American Society of Echocardiography (15), and LV mass was derived from the Devereux-modified cube formula. Transmitral and aortic flows were recorded using pulsed Doppler echocardiography. The sample volume with a fixed length of 2.0 mm was placed between the tips of the mitral leaflets and at the level of the LV outflow tract, respectively. Averaged pulsed-wave spectral tissue Doppler values of the septal, anterior, lateral, and inferior sides of the mitral annulus were used for the assessment of peak early diastolic mitral annular velocity ( $E'$ ). Frame rate was adjusted between 50–90 frames/s, and the cine-loop of 3 consecutive beats was stored for offline speckle-tracking analysis (EchoPac PC, GE Vingmed). Images were acquired during end-expiratory apnea. Apical 4-chamber and 2-chamber views were used for longitudinal strain analysis. Parasternal short-axis views at the base (at the tips of the mitral valve leaflets), at the level of papillary muscles, and at the apex (with the minimal circular LV cavity at end-systole) were used for radial strain and rotation analysis.

Before speckle-tracking analysis, the timings of aortic and mitral valve opening and closure were assessed using pulsed-wave Doppler recordings of aortic and transmitral flows. The interval between two subsequent closures of the mitral valve was used for regional strain and rotation analysis.

LV endocardium was traced at end systole, and then the software-generated region of the interest was adjusted to an optimal width of myocardial wall. In each echocardiographic view, the myocar-

dium was automatically divided into 6 segments. The apical short-axis view was manually adjusted to 4 myocardial segments. The results of software-generated acceptable tracking were approved manually. The deformation and rotation values of each segment were collected from the result window. The peak systolic values of strains and rotation were used for analysis. The longitudinal strain was calculated as a longitudinal strain average of the septal, lateral, anterior, and inferior LV walls. The radial strain was calculated as a strain average at the basal, midventricular, and apical levels. In the same way, the longitudinal and radial systolic and diastolic strain rates and systolic and diastolic rotation rates were calculated. For the analysis, diastolic strain and rotation rate at early diastolic LV filling were used.

LV twist was calculated as the net difference between LV rotation angles obtained from basal (clockwise) and apical (counterclockwise) short-axis planes. LV torsion was calculated as the LV twist normalized with respect to ventricular diastolic longitudinal length between the LV apex and the mitral plane ( $[\text{apical LV rotation} - \text{basal LV rotation}] / \text{LV diastolic longitudinal length}$ ).

**Statistical Analysis.** The data were analyzed using the SPSS statistical software (SPSS v.15.0 for Windows, SPSS, Inc., Chicago, IL, USA). Continuous variables are presented as mean (SD). Continuous variables were compared using one-way analysis of variance, and the Fisher test was applied for the post hoc comparison. The chi-square test was used to determine differences in categorical variables. To measure the strength of an association between 2 continuous variables, the Pearson correlation was employed. Left ventricular end-systolic diameter, systolic basal and apical rotation, and systolic longitudinal and radial strain were included into multiple forward regression analysis to determine the independent predictors of LV ejection fraction in AR patients. Determinants of the  $E/A$  ratio (early diastolic transmitral flow velocity [ $E$ ] and atrial systolic velocity [ $A$ ] ratio) and  $E'$  were explored by entering left ventricular end-diastolic diameter, left atrium anteroposterior diameter, myocardial mass, systolic basal and apical rotation, systolic longitudinal and radial strain, left ventricular twist and torsion, systolic and early diastolic rate of basal and apical rotation, radial and longitudinal strain into forward multiple regression analysis. Determinants of the  $E'$  and  $E/E'$  ratio (early diastolic transmitral flow velocity [ $E$ ] and early diastolic mitral annular velocity [ $E'$ ] ratio) were explored by entering LV end-diastolic diameter, left atrium anteroposterior diameter, myocardial mass, systolic basal rotation, LV torsion, systolic longitudinal strain, systolic basal rotation rate, systolic and early diastolic longitudinal strain rates into forward multiple regression analysis. A  $P$  value of  $<0.05$  was considered statisti-

cally significant.

Intraobserver variability was assessed for the measurements of systolic longitudinal strain in the septal and lateral walls, systolic radial strain at the basal and apical levels, and systolic rotation at the basal and apical levels in 15 randomly selected subjects using intraclass correlation coefficients and Bland-Altman plot.

**Results**

The demographic, clinical, and conventional echocardiographic data of AR patients and healthy controls are shown in Table 1. There were no significant differences in age, gender, heart rate, and diastolic blood pressure during the study comparing the groups. Systolic blood pressure was higher in the patients with severe AR. All the patients with moderate AR were free of heart failure symptoms, whereas only 6 patients with severe AR were asymptomatic. The proportion of patients with moderate mitral regurgitation was greater in the severe AR group than moderate AR group. LV end-diastolic

and end-systolic diameter, end-diastolic and end-systolic length, and end-diastolic volume were significantly greater in both the groups of patients with AR. LV end-systolic volume was significantly greater and LV ejection fraction was significantly lower in the patients with severe AR compared with the control group and patients with moderate AR. No significant differences in early diastolic transmitral flow velocity (E) and its ratio (E/A) with atrial systolic velocity (A) were documented comparing the groups, while early diastolic mitral annular velocity (E') was significantly lower in the patients with moderate and severe AR than the healthy subjects.

A significant reduction in the systolic longitudinal strain was documented in the patients with moderate and severe AR as compared with the control group ( $P<0.05$  and  $P=0.003$ , respectively) (Table 2). Systolic and diastolic longitudinal strain rates were reduced in both AR groups as well. Systolic radial strain was significantly lower in the patients with severe AR compared with the control patients and patients with moderate AR. There were no significant

Table 1. Demographic, Clinical, and Conventional Echocardiographic Data of the Study Population

Characteristic	Control Patients (n=28)	Patients With Moderate AR (n=26)	Patients With Severe AR (n=34)
Age, years	43.9 (11.5)	43.5 (12.5)	50.35 (12.2)
Gender, F/M, n	8/20	6/20	7/27
Heart rate, bpm	65.3 (8.3)	68.0 (9.9)	67.3 (12.6)
History of arterial hypertension, n	0	12*	16*
Systolic blood pressure, mm Hg	127.5 (8.9)	131.9 (11.9)	134.5 (13.5)*
Diastolic blood pressure, mm Hg	77.1 (7.1)	75.9 (10.2)	72.9 (13.5)
Antihypertensive treatment, n	0	12*	15*
NYHA functional class, n (%)			
I	0	26 (100)	6 (17.6)‡
II	0	0	20 (58.8)‡
III	0	0	8 (23.5)
Mitral regurgitation, n (%)			
Mild	20 (71.4)	23 (88.5)	23 (67.6)
Moderate	0	3 (11.5)	9 (26.5)‡
Severe	0	0	2 (5.9)
LV diastolic diameter, mm	47.6 (4.4)	53.6 (5.4)*	62.0 (9.1)*†
LV systolic diameter, mm	30.8 (4.5)	38.0 (6.0)*	45.5 (10.8)*†
LV diastolic length, mm	83.3 (7.8)	89.8 (7.2)*	97.8 (9.8)*†
LV systolic length, mm	67.6 (7.8)	78.5 (7.0)*	86.1 (10.9)*†
LV diastolic volume, mL	82.9 (19.1)	111.7 (25.8)*	181.3 (70.4)*†
LV systolic volume, mL	33.9 (9.10)	47.8 (13.8)	91.8 (51.8)*†
LV ejection fraction, %	59.4 (3.7)	57.1 (5.6)	51.7 (8.9)*†
Left atrial diameter, mm	36.0 (4.1)	39.6 (6.2)	43.3 (6.3)*†
E, cm/s	72.5 (12.7)	66.45 (18.7)	75.85 (25.2)
E/A ratio	1.38 (0.37)	1.16 (0.37)	1.28 (0.55)
E'	10.9 (3.68)	8.88 (3.2)*	7.68 (2.57)*
E/E'	6.79 (2.04)	7.46 (2.44)	10.71 (3.85)*†

Values are mean (standard deviation) unless otherwise indicated.

AR, aortic regurgitation; LV, left ventricle; E, early diastolic transmitral flow velocity; E/A, early diastolic transmitral flow velocity (E) and atrial systolic velocity (A) ratio, E', early diastolic mitral annular velocity.

\* $P<0.05$ , compared with the control patients; † $P<0.05$ , compared with the moderate AR group; ‡ $P<0.05$ , compared with the moderate AR group using chi-square test.

differences in the systolic radial strain rate comparing all the groups, while the diastolic strain rate was lower in the patients with moderate and severe AR than the control group. The systolic basal rotation was found to be reduced in the patients with severe AR ( $P=0.008$ ), but the rotation at the apical level in the patients with moderate AR was greater than in the control group ( $P=0.02$ ). Respectively, reduced systolic and diastolic basal rotation rates in the severe AR group and increased systolic apical rotation rate in the moderate AR group were found as compared with the control group. There were no significant differences in the LV twist and torsion comparing the groups. Summarized differences in the LV deformation and rotation comparing the groups are shown in Fig. 1.

In the control group, volumetric and diastolic LV function parameters predominantly correlated with rotational indices (Table 3). Contrarily, in the patients with AR, volumetric LV parameters and LV ejection fraction additionally correlated with longitudinal and radial strain, and E/E' had a relationship with systolic and diastolic longitudinal strain indices. Correlation analysis showed that greater volumetric LV parameters and E/E' ratio, and lower LV ejection fraction had a relationship with less expressed mechanical parameters. Fig. 2 depicts moderate-to-strong correlations between LV ejection fraction and LV longitudinal strain, radial strain, and basal rotation in severe AR.

Multiple forward regression analysis identified

Table 2. Comparison of Left Ventricular Systolic Longitudinal, Radial Strain, and Rotation by Groups

Parameter	Control Patients	Patients With Moderate AR	Patients With Severe AR
Longitudinal strain			
Systolic longitudinal S, %	-21.0 (2.52)	-18.3 (2.18)*	-16.8 (3.96)*
Systolic longitudinal Sr, s <sup>-1</sup>	-1.27 (0.15)	-1.08 (0.13)*	-1.04 (0.20)*
Diastolic longitudinal Sr, s <sup>-1</sup>	1.70 (0.27)	1.43 (0.27)*	1.23 (0.32)*
Radial strain			
Systolic radial S, %	48.4 (11.8)	44.9 (10.3)	37.6 (9.77)*†
Systolic radial Sr, s <sup>-1</sup>	2.24 (0.44)	2.13 (0.55)	2.16 (0.49)
Diastolic radial Sr, s <sup>-1</sup>	-2.51 (0.61)	-2.09 (0.61)*	-1.86 (0.52)*
Rotation			
Systolic basal R, °	-6.99 (2.25)	-6.1 (2.96)	-5.22 (1.88)*
Systolic basal Rr, °/s	-71.19 (23.62)	-66.69 (18.20)	-59.75 (20.47)*
Diastolic basal Rr, °/s	84.35 (24.86)	75.54 (22.80)	65.83 (21.56)*
Systolic apical R, °	8.30 (4.34)	11.3 (4.99)*	10.5 (4.59)
Systolic apical Rr, °/s	71.00 (28.04)	82.72 (28.24)*	78.39 (25.80)
Diastolic apical Rr, °/s	-85.42 (34.43)	-87.56 (29.11)	-83.05 (40.36)
Left ventricular twist, °	15.2 (4.91)	17.8 (6.41)	15.6 (5.03)
Left ventricular torsion, °/cm	1.84 (0.64)	2.01 (0.8)	1.63 (0.58)

Values are mean (standard deviation). S, strain; Sr, strain rate; R, rotation; Rr, rotation rate; AR, aortic regurgitation.

\* $P<0.05$ , compared with control patients; † $P<0.05$ , compared with patients with moderate AR.

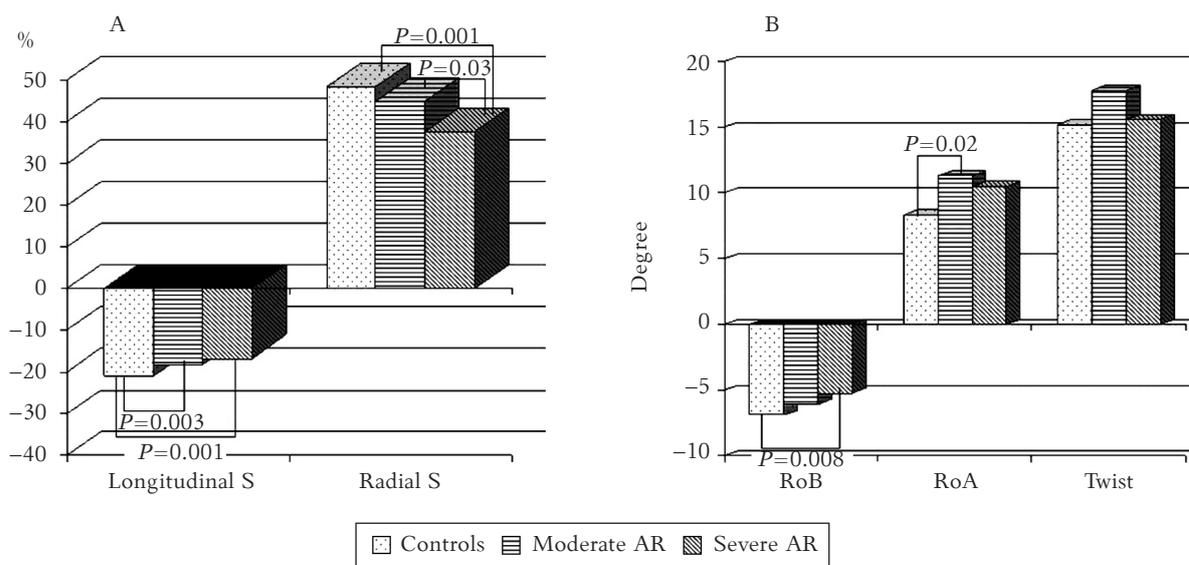


Fig. 1. Differences in left ventricular deformation, rotation, and twist in healthy subjects and patients with aortic regurgitation

Longitudinal and radial strain changes (A) and rotation at the left ventricular basal and apical levels (B). AR, aortic regurgitation; S, strain; RoB, basal rotation; RoA, apical rotation.

Table 3. Correlations Between Longitudinal, Radial Strain, Rotation and Left Ventricular Volume, Ejection Fraction and Diastolic Function Parameters in Controls and AR Patients

Parameter	EDV		EF		E/E'	
	Control Patients	Patients With AR	Control Patients	Patients With AR	Control Patients	Patients With AR
Longitudinal S	0.12	0.60*	-0.1	-0.74*	-0.1	0.55*
Radial S	-0.14	-0.43*	0.1	0.55*	-0.1	-0.11
Basal rotation	0.2	0.30*	-0.1	-0.39*	-0.61*	0.1
Apical rotation	-0.17	-0.18	0.32*	0.24	0.11	-0.15
Left ventricular twist	-0.21	-0.28	0.28	0.32*	0.3	-0.18
Left ventricular torsion	-0.37*	-0.44*	0.24	0.39*	0.42*	-0.21
Systolic basal Rr	0.46*	0.41*	0.1	-0.32*	-0.51*	0.1
Systolic apical Rr	-0.1	-0.22	0.19	0.16	0.22	-0.14
Diastolic basal Rr	-0.1	-0.49*	0.13	0.29*	0.12	-0.2
Diastolic apical Rr	0.49*	0.31*	-0.1	-0.22	-0.21	0.12
Systolic radial Sr	-0.18	-0.26	0.1	0.23	-0.17	-0.1
Diastolic radial Sr	0.14	0.36*	-0.15	-0.34*	0.15	0.11
Systolic longitudinal Sr	0.54*	0.53*	-0.12	0.60*	-0.1	0.4*
Diastolic longitudinal Sr	-0.21	-0.5*	0.49*	0.45*	-0.26	-0.48*

S, strain; EDV, end-diastolic volume; EF, ejection fraction; E/E', early diastolic transmitral flow velocity and early diastolic mitral annular velocity ratio; AR, aortic regurgitation; S, strain; Sr, strain rate; Rr, rotational rate.  
\*P<0.05.

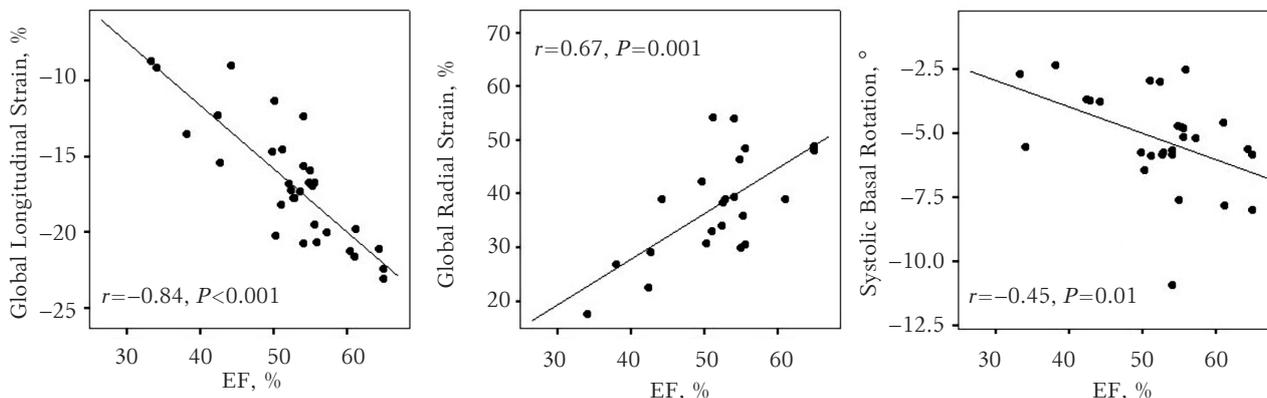


Fig. 2. Scatterplots demonstrating the relationship of left ventricular ejection fraction with longitudinal, radial strain, and basal rotation in patients with severe aortic regurgitation  
EF, ejection fraction.

Table 4. Multiple Regression Analysis to Determine the Best Predictor of Left Ventricular Ejection Fraction in Aortic Regurgitation

Predictor	All Patients With AR (R <sup>2</sup> =0.77)		Patients With Severe AR (R <sup>2</sup> =0.85)	
	β	P	β	P
Global longitudinal strain	-0.38	0.001	-0.37	0.02
Global radial strain	0.260	0.007	0.25	0.02
LV end-systolic diameter	-0.42	0.001	-0.422	0.02
Systolic basal rotation	-0.1	NS	0.1	NS
Systolic apical rotation	0.01	NS	-0.01	NS

Left ventricular end-systolic diameter, systolic basal and apical rotation, and systolic longitudinal and radial strain were included into analysis.

AR, aortic regurgitation; LV, left ventricular.

the global longitudinal and radial strain, and LV end-systolic diameter as independent predictors of LV ejection fraction in all patients with AR and patients with severe AR (R<sup>2</sup>=0.77 and R<sup>2</sup>=0.85, respectively) (Table 4). The systolic apical rotation rate was an independent predictor of E/A ratio for

the control patients (R<sup>2</sup>=0.26); early diastolic longitudinal strain rate, for the patients with moderate AR (R<sup>2</sup>=0.55); and left atrium diameter, diastolic longitudinal strain rate, diastolic apical rotation rate, and systolic basal rotation rate, for the patients with severe AR (R<sup>2</sup>=0.86) (Table 5). The systolic basal

Table 5. Multiple Regression Analysis to Determine Predictors of Left Ventricular Diastolic Dysfunction

Predictor	E/A		
	Control patients ( $R^2=0.26$ )	Patients With Moderate AR ( $R^2=0.55$ )	Patients With Severe AR ( $R^2=0.86$ )
	$\beta$ values		
Systolic apical rotation rate	-0.51*	NS	NS
Systolic basal rotation rate	NS	NS	-0.29*
Diastolic apical rotation rate	NS	NS	0.52*
Diastolic longitudinal strain rate	NS	0.74*	0.48*
Left atrium diameter	NS	NS	0.97†

Left ventricular end-diastolic diameter, left atrium anteroposterior diameter, myocardial mass, systolic basal and apical rotation, systolic longitudinal and radial strain, left ventricular twist and torsion, systolic and early diastolic rates of basal and apical rotation, and radial and longitudinal strain were included into analysis.

AR, aortic regurgitation; E/A, early diastolic transmitral flow velocity (E) and atrial systolic velocity (A) ratio; NS, not significant.

\* $P<0.05$ ; † $P<0.001$ .

Table 6. Multiple Regression Analysis to Determine Predictors of Left Ventricular Diastolic Dysfunction

Predictor	E'			E/E'		
	Control Patients ( $R^2=0.38$ )	Patients With Moderate AR ( $R^2=0.39$ )	Patients With Severe AR ( $R^2=0.33$ )	Control Patients ( $R^2=0.32$ )	Patients With Moderate AR ( $R^2=0.32$ )	Patients With Severe AR ( $R^2=0.35$ )
	$\beta$ values					
Systolic basal rotation	0.62*	NS	NS	-0.60*	NS	NS
Diastolic longitudinal strain rate	NS	0.63*	0.57*	NS	-0.57*	NS
Systolic longitudinal strain	NS	NS	NS	NS	NS	0.60*

Left ventricular end-diastolic diameter, left atrium anteroposterior diameter, myocardial mass, systolic basal rotation, left ventricular torsion, systolic longitudinal strain, systolic basal rotation rate, and systolic and early diastolic longitudinal strain rates were included into analysis.

AR, aortic regurgitation; E', early diastolic mitral annular velocity; E/E', early diastolic transmitral flow and early diastolic mitral annular velocity ratio; NS, not significant.

\* $P<0.05$ .

rotation in the control patients and early diastolic longitudinal strain rate in the patients with moderate and severe AR were independent predictors of E' ( $R^2=0.38$ ,  $R^2=0.39$ , and  $R^2=0.33$ , respectively) (Table 6). The E/E' ratio was predicted by the systolic basal rotation in the control patients, by the early diastolic longitudinal strain rate in the patients with moderate AR, and by the systolic longitudinal strain in the patients with severe AR ( $R^2=0.32$ ,  $R^2=0.32$ , and  $R^2=0.35$ , respectively).

**Reproducibility.** For intraobserver variability, LV endocardium was retraced for analysis in a different cardiac cycle.

Using a two-way random-effect model for absolute agreement, strong intraobserver correlations were documented for the measurements of systolic longitudinal strain (ICC, 0.85; 95% CI, 0.72–0.92), systolic radial strain (ICC, 0.94; 95% CI, 0.88–0.97), systolic apical rotation (ICC, 0.87; 95% CI, 0.68–0.95), and systolic basal rotation (ICC, 0.72; 95% CI, 0.38–0.89).

Bland-Altman analysis showed that the 95% limits of agreement for the intraobserver variation were the best for longitudinal strain measurements (-3.6% to 2.3%) and the worst for radial strain measurements (-12.7% to 11.8%)

## Discussion

The main finding of our study is that LV long-axis systolic dysfunction in moderate asymptomatic AR patients with normal LV ejection fraction and without severe LV dilation and was found to be associated with increased systolic apical rotation. The systolic basal rotation and systolic radial LV function were significantly reduced in severe AR with reduced LV ejection fraction. Signs of diastolic LV dysfunction and its relationship with LV mechanics in systole were observed in moderate AR with good LV ejection fraction.

Subendocardial LV myocardial fibers are aligned longitudinally and connected with the mitral annulus (16). This layer of myocardium is more sensitive to ischemia, which is common in chronic volume overload in AR; thus, long-axis function of the LV may be abnormal in patients with AR without clinical symptoms (11). Our study showed reduced LV longitudinal axis function assessed by speckle-tracking echocardiography in moderate AR with preserved LV ejection fraction.

LV remodeling occurring in chronic volume overload is characterized by eccentric hypertrophy, LV chamber dilatation, and initially normal contractile function. LV systolic function may remain rela-

tively unaffected due to preserved radial, circumferential, and rotational LV function in systole (13, 17). According to our data, asymptomatic patients with moderate AR showed an increased apical rotation without significant changes in the radial deformation. This shows that LV rotation and radial LV contraction may play a compensatory role in maintaining the normal LV ejection fraction in the presence of incipient long-axis dysfunction in moderate AR. Only in more advanced severe AR, a significant radial dysfunction was observed as well as a significant deterioration of rotational function at the basal LV level and a significantly reduced LV ejection fraction. Physiologically, preload with higher end-diastolic volumes produces higher LV twist (18). According to our data, the LV twist increased minimally in moderate AR due to a more markedly increased apical rotation and a slightly reduced basal LV rotation. This may be related to progressive LV dilatation and increased wall stress previously at the basal LV level. Whereas in more advanced disease stage, during which the ventricle develops a progressive chamber enlargement and more spherical geometry, basal systolic rotation becomes reduced more without a further increase in apical rotation, resulting in LV twist reduction.

In AR, the majority of LV deformation and rotational parameters significantly correlated with standard echocardiographic LV dimensions. Our data confirmed that LV dilation caused the reduction of longitudinal, radial LV deformation, and basal LV rotation, whereas global longitudinal and radial strain, and LV systolic diameter were the independent predictors of LV ejection fraction. Our study showed that LV twist and torsion were inversely associated with LV size in the control patients, and in diastole, a higher excursion of systolic basal rotation and LV torsion were associated with greater E/E' ratio. As previously reported in the literature, systolic apical and basal rotations accumulate additional potential energy that is released for improving diastolic suction (19, 20), and the increased LV torsion in systole is associated with mild diastolic dysfunction. Interestingly, our data showed that diastolic function in healthy persons was associated with LV rotation function, but in the patients with AR, signs of diastolic dysfunction were associated additionally with longitudinal LV dysfunction. Our results showed that E/A ratio did not differ significantly between the groups, but E/E' ratio was significantly increased in severe AR. This might indicate that diastolic function in severe AR tends to

pseudonormalization, when E/A ratio is predicted by systolic basal rotation rate, diastolic apical rotation rate, diastolic longitudinal strain rate, and left atrium size. Systolic longitudinal strain is most reduced in severe AR and can be associated with more severe diastolic dysfunction. The parameter of long-axis dysfunction – longitudinal deformation – was found to be an independent predictor to E/E' ratio in severe AR and could be one of the indices of increasing LV filling pressure.

**Clinical Implications.** Patients with severe AR and symptoms have a poor prognosis (21–23). Patients at risk of future symptoms, death, or LV dysfunction should be identified based on noninvasive testing (24). Early detection of LV systolic dysfunction, assessment of diastolic function, and later observation for the reduction of the compensatory mechanisms in patients with chronic AR could be taken into account for further patients' care and clinical decision-making.

**Limitations.** About 20% of all investigated persons were not included into the study due to a poor acoustic window. In the cases of inadequate quality of echocardiographic images, the software cannot perform speckle-tracking analysis properly. This reason reduces the ability to perform analysis in all patients. The accuracy of rotation assessment by 2-dimensional speckle-tracking echocardiography may be limited by the ability to image the most apical and basal planes (25).

## Conclusions

Reduced left ventricular systolic longitudinal strain with an increased apical rotation and preserved radial function derived by speckle-tracking analysis were present in asymptomatic patients with moderate aortic regurgitation. A significant reduction in left ventricular systolic radial strain and lower basal systolic rotation as well as reduced longitudinal strain were found to be associated with severe aortic regurgitation. Left ventricular diastolic filling depended on diastolic and systolic left ventricular strain and rotation components in patients with aortic regurgitation.

## Acknowledgments

Part of the study was funded by a grant from the Lithuanian Science Council (grant No. LIG-10009).

## Statement of Conflict of Interest

The authors state no conflict of interest.

## References

1. Vandembossche JL, Massie BM, Schiller NB, Kaliner JS. Relation of left ventricular shape to volume and mass relation with minimally symptomatic chronic aortic regurgitation. *Am Heart J* 1988;116:1022-7.
2. Ohi H, Uchida M, Sato H, Yamaguchi H, Kawai S, Okada R. Differences in left ventricular shape between aortic and mitral regurgitation: an echocardiographic study. *J Cardiol* 1889;19:823-30.

3. Hiro T, Katayama K, Miura T, Kohno M, Fujii T, Hiro J, et al. Stroke volume generation of the left ventricle and its relation to chamber shape in normal subjects and patients with mitral or aortic regurgitation. *Jpn Circ J* 1996;60:216-27.
4. Geyer H, Caracciolo G, Abe H, Wilansky S, Carerj S, Gentile F, et al. Assessment of myocardial mechanics using speckle tracking echocardiography: fundamentals and clinical applications. *J Am Soc Echocardiogr* 2010;23(4):351-69.
5. Greenbaum RA, Ho SY, Gibson DG, Becker AE, Anderson RH. Left ventricular fibre architecture in man. *Br Heart J* 1981;45:248-63.
6. Jones CJH, Raposo L, Gibson DG. Functional importance of the long axis dynamics of the human left ventricle. *Br Heart J* 1990;63:215-20.
7. Isaz K, Munoz-del-Romeral L, Lee E, Schiller NB. Quantitation of the motion of the cardiac base in normal subjects by Doppler echocardiography. *J Am Soc Echocardiogr* 1993;6:166-76.
8. Gulati VK, Katz WE, Follansbee WP, Gorscsan J. Mitral annular descent velocity by tissue Doppler echocardiography as an index of global left ventricular function. *Am J Cardiol* 1996;77:979-84.
9. Gorscsan J, Gulati VK, Mandarino WA, Katz WE. Color-coded measures of myocardial velocity throughout the cardiac cycle by tissue Doppler imaging to quantify regional left ventricular function. *Am Heart J* 1996;131:1203-13.
10. Paraskevaidis IA, Tsiapras D, Kyrzopoulos S, Cokkinos P, Iliodromitis EK, Parissis J, et al. The role of left ventricular long-axis contraction in patients with asymptomatic aortic regurgitation. *J Am Soc Echocardiogr* 2006;19:249-54.
11. Marciniak A, Sutherland GR, Marciniak M, Claus P, Bijmens B, Jahangiri M. Myocardial deformation abnormalities in patients with aortic regurgitation: a strain rate imaging study. *Eur J Echocardiogr* 2009;10:112-9.
12. Souterland GR, Di Salvo G, Claus P, D'Hooghe J, Bijmens B. Strain and strain rate imaging: a new clinical approach to quantifying regional myocardial function. *J Am Soc Echocardiogr* 2004;17:788-802.
13. Perk G, Tunick PA, Kronzon I. Non-Doppler two-dimensional strain imaging by echocardiography – from technical considerations to clinical applications. *J Am Soc Echocardiogr* 2007;20(3):234-43.
14. Zoghbi WA, Enriquez-Sarano M, Foster E, Grayburn PA, Kraft CD, Levine RA, et al. Recommendations for evaluation of the severity of native valvular regurgitation with two-dimensional and Doppler echocardiography. *J Am Soc Echocardiogr* 2003;16:777-802.
15. Lang RM, Bierig M, Devereux RB, Flachskampf FA, Foster E, Pellikka PA, et al. Recommendations for chamber quantification: a report from the American Society of Echocardiography's Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. *J Am Soc Echocardiogr* 2005;18:1440-63.
16. Vinereanu D, Ionescu AA, Fraser AG. Assessment of left ventricular long axis contraction can detect early myocardial dysfunction in asymptomatic patients with severe aortic regurgitation. *Heart* 2001;85:30-6.
17. Sengupta PP, Korinek J, Belohlavek M, Narula J, Vannan MA, Jahangir A, et al. Left ventricular structure and function: basic science for cardiac imaging. *J Am Coll Cardiol* 2006;48:1988-2001.
18. Dong SJ, Hees PS, Huang WM, Buffer SA, Weiss JL, Shapiro EP. Independent effects of preload, afterload, and contractility on left ventricular torsion. *Am J Physiol* 1999;277:H1053-60.
19. Sengupta PP, Tajik AJ, Chandrasekaran K, Khandheria BK. Twist mechanics of the left ventricle. *J Am Coll Cardiol* 2008;1:366-76.
20. Park SJ, Miyazaki C, Bruce CJ, Ommen S, Miller FA, Oh JK. Left ventricular torsion by two-dimensional speckle tracking echocardiography in patients with diastolic dysfunction and normal ejection fraction. *J Am Soc Echocardiogr* 2008;21:1129-37.
21. Borer JS, Hochreiter C, Herrold EM, Supino P, Aschermann M, Wencker D, et al. Prediction of indications for valve replacement among asymptomatic or minimally symptomatic patients with chronic aortic regurgitation and normal left ventricular performance. *Circulation* 1998;97:525-34.
22. Tarasoutchi F, Grinberg M, Spina GS, Sampaio RO, Cardoso LF, Rossi EG, et al. Ten-year laboratory follow up after application of a symptom-based therapeutic strategy to patients with severe chronic aortic regurgitation of predominant rheumatic etiology. *J Am Coll Cardiol* 2003;41:1316-24.
23. Scognamiglio R, Negut C, Palisi M, Fasoli G, Dalla-Volta S. Long-term survival and functional results after aortic valve replacement in asymptomatic patients with chronic severe aortic regurgitation and left ventricular dysfunction. *J Am Coll Cardiol* 2005;45:1025-30.
24. Vahanian A, Baumgartner H, Bax J, Butchart E, Dion R, Filippatos G, et al. Guidelines on the management of valvular heart disease: The Task Force on the Management of Valvular Heart Disease of the European Society of Cardiology. *Eur Heart J* 2007;28(2):230-68.
25. Goffinet C, Chenot F, Robert A, Pouleur AC, le Polain de Waroux JB, Vancraynest D, et al. Assessment of subendocardial vs. subepicardial left ventricular rotation and twist using two-dimensional speckle tracking echocardiography: comparison with tagged cardiac magnetic resonance. *Eur Heart J* 2009;30(5):608-17.

*Received 15 March 2011, accepted 29 January 2011*