Emerging role of echocardiographic strain/strain rate imaging and twist in systolic function evaluation and operative procedure in patients with aortic stenosis

Bin Wang, Haiyan Chen, Xianhong Shu, Tao Hong, Hao Lai, Chunsheng Wang,* and Leilei Cheng,*

Introduction

Aortic stenosis (AS) is one of the common valvular heart diseases, mostly caused by rheumatic fever, valvular degeneration, antiphospholipid syndrome, congenital aortic bicuspid valve and so on. In general, aortic valve replacement (AVR) or valvuloplasty is beneficial for symptomatic patients to improve their haemodynamic and cardiac function. Therefore, cardiac surgeons are somewhat confused with regards to how to select appropriate patients for an aortic valve procedure as well as how to judge the prognosis. Selection criteria for AVR or valvuloplasty includes symptoms, left ventricular ejection fraction (LVEF), size of left ventricle (LV), atrial fibrillation and other indexes. LVEF is the most important parameter, but until now, echocardiographic could not fully ensure its reliability [2], especially in patients with abnormal haemodynamics, left ventricular hypertrophy or ventricular dilatation.

Echocardiographic strain/strain rate (SR) and torsion are emerging parameters on myocardial deformation in one direction normalized to its initial dimension, written as:

\[ S = \frac{L - L_0}{L_0} \]

where \( L \) is the length after deformation and \( L_0 \) is the length before deformation. It can be applied to evaluate the systolic function at longitudinal, circumferential and radial directions (Fig. 1). SR is the rate of deformation within a time unit (1 s), calculated as:

\[ SR = \frac{V_1 - V_2}{\Delta L} \]
where $V_1$ and $V_2$ are velocities at two points on ventricular muscles, and $\Delta L$ is the distance between these two points. It has been demonstrated that strain is a non-dimensional quantity which is independent of wall thickness and motion. This means that myocardial strain will not be affected by cardiac motion, rotation or the function of adjacent segments \[3, 4\].

In addition to local myocardial motion, torsion is a rotatory measurement for the LV in short-axis views. Looking from the apex, counterclockwise rotation is defined as positive and clockwise as negative. Twist is sometimes used simply to mean wringing, while torsion means the basal-to-apex gradient in the rotation angle (Fig. 2) \[5\]. Apical rotation and twist mostly represent synchronous changes, which increase in AS and decrease in myocardial infarction, dilated cardiomyopathy and heart failure \[6\].

To quantify myocardial strain, SR and twist, there are three available echocardiographic imaging modalities: tissue Doppler imaging (TDI), two-dimensional speckle-tracking imaging (2D-STI) and three-dimensional speckle-tracking imaging (3D-STI). By means of these imaging techniques, information on myocardial strain, SR and torsion can be derived (Fig. 3).

### Tissue Doppler imaging

TDI is a Doppler technique that allows quantification of myocardial tissue velocities. By using a high-pass filter (>100 Hz), the high amplitude but low-velocity myocardial velocities can be measured. Through spatial derivation of the derived velocity, the strain and SR can be obtained \[7\].

### Two-dimensional speckle tracking

2D-STI allows frame-by-frame tracking of natural acoustic markers within the myocardium in standard echocardiographic images. Unlike TDI, 2D-STI is not a Doppler-based technique and allows direct derivation of myocardial strain that is angle independent. 2D-STI-derived SR is obtained through temporal derivation of the 2D strain data, and spatial integration of 2D SR results in 2D myocardial velocity \[7\].

### Three-dimensional speckle tracking

With regard to the 3D technique, the speckles are tracked inside the three-dimensional scan volume, and irrespective of their direction, myocardial motion and deformation of the entire LV can be assessed in all three spatial dimensions through the entire cardiac cycle \[7\].

The reproducibility of TDI and 2D-STI is acceptable. However, when radial deformation was measured with TDI, both intra-observer variability (<8%) and interobserver variability (<16%) were significantly higher \[8, 9\]. Meanwhile, the intra- and inter-observer agreement for strain measurement in 3D-STI were more encouraging (both <3%) \[10\].
STRAIN/STRAIN RATE DECREASES AS AORTIC STENOSIS PROGRESSES, WHILE TORSION INDEX INCREASES

As several studies identified, myocardial deformation was impaired due to AS, and the deterioration was related to the severity of AS [11–13]. Ng et al. [12] have found that there is a progressive stepwise impairment in longitudinal/radial/circumferential strain and SR along with the severity of AS progression (all *P* < 0.001). Miyazaki et al. [14] also suggested that global longitudinal strain manifested significant differences among mild/moderate/severe AS groups (*P* = 0.003). A similar outcome was also reported by Delgado et al. [11], showing that multidirectional deformations decreased except radial strain. Moreover, Marechaux et al. [13] conducted research to assess the relationship between valvulo-arterial impedance and global longitudinal strain, and a negative correlation was certified (*r* = −0.41, *P* < 0.0001).

Stress testing (low-dose dobutamine or exercise stress echocardiography) is recommended for asymptomatic patients with severe AS, especially for differentiating true or pseudo-severe AS and detecting contractile reserve (compensation) [15]. Global 2D longitudinal strain as determined by the speckle-tracking method has the potential to provide more precise information on LV function and contractile reserve during stress testing [16]. Donal et al. [17] verified the decrease of longitudinal strain be it at rest or during exercise stress in AS patients. Furthermore, changes in longitudinal strain during exercise in AS patients was also lower than in the normal control. Donal et al. [17] and Lafitte et al. [18] both demonstrated that lower longitudinal strain was detected in AS patients with abnormal exercise testing scores compared with AS patients with normal exercise testing scores.

Furthermore, the elevated LV afterload can induce alteration of torsion. Compared with normal subjects, patients with AS manifested increased apical rotation (13.0 ± 5.8° vs 7.6 ± 2.6°, *P* < 0.001) and twist (19.7 ± 5.7° vs 12.9 ± 3.2°, *P* < 0.001), while basal rotation remained normal [19]. Similar outcomes were obtained by van Dalen et al. [20] and Popescu et al. [21]. They proved that apical rotation (*R*² = 0.34, *P* < 0.001) and twist (*R*² = 0.30, *P* < 0.001) correlated well with aortic valve area indexed by body surface area. In addition, pregnancy, which induces volume overload, generated augmented twist, and in gravidas with AS, twist was prone to a stepwise increase compared with the baseline while longitudinal strain showed little changes [22]. Tammo et al. also demonstrated the elevation of the torsion-to-shortening ratio in AS patients, which was considered as a more sensitive parameter of subendocardial ischaemia [23]. Additionally, AS could induce an increase in the peak apical de-rotation rate and time-to-peak diastolic de-rotation rate [20, 21]. Nevertheless, Laser et al. [24] did not think there was a relationship between the severity of disease and twist.

CIRCUMFERENTIAL STRAIN AND TWIST ARE VALUABLE IN THE IDENTIFICATION OF LEFT VENTRICLE COMPENSATION AND DECOMPENSATION

Cardiac compensation occurs due to altered protein composition and stimulation in the cells and extracellular matrix, which

Figure 2: The waveforms of circumferential S, SR and regional rotation derived from 2D-STI in the short-axis view of the mid-LV. (A) Two-dimensional imaging of the mid-LV, the different colours indicate the different segments; (B) the curves of circumferential S; (C) the curves of circumferential SR and (D) the curves of regional rotation.

Figure 3: Echocardiographic myocardial S and SR can be derived from three fundamentally different ways: (A) TDI, (B) two-dimensional and (C) three-dimensional speckle-tracking imaging.
initially manifests in enhancement of the contractile force and hypertrophy without dilatation. Normal cardiac output is maintained during compensation. But as the impairment persists, cardiac output decreases and cannot afford normal consumption, resulting in symptoms and LV decompensation. LV hypertrophy is a state of pressure-overloaded remodelling, which is characterized by histological fibrosis and myocyte degeneration [25]. It is a deleterious pathology despite being partially reversible after pressure unloading [26]. It is difficult to predict reversibility after AVR for patients with AS. Normal LV deformation could be considered as the compensation which foreshores a fine response to AVR, whereas low deformation could predict a relative high possibility of cardiac events [27]. Carasso et al. [28] performed research on responses of deformation to afterload elevation on patients with severe AS. Accidentally, impact changes of longitudinal and circumferential strain were detected. Thus, it was hypothesized that circumferential strain may increase with myocardial compensation and decrease with decompensation. This hypothesis was verified by the following study. Carasso et al. [29] clearly demonstrated the differential mechanisms between compensation and decompensation of AS using strain imaging. Compensatory LV showed an increased apical rotation angle in patients with 50% > LVEF > 35% and high circumferential strain in patients with preserved LVEF, whereas decompensation showed decreased circumferential strain and an apical rotation angle. Cincirer et al. [30] have demonstrated that TAVI improved longitudinal strain/SR as well as twist, decrease before AVR and partially recover due to surgical procedure. Alterations of circumferential strain/SR are reflected on the status of compensation or decompensation. Anyway, AVR always induces normalization of all directional deformations.

**CHANGES OF STRAIN/STRAIN RATE AFTER TRANSCATHETER AORTIC VALVE IMPLANTATION**

Transcatheter aortic valve implantation (TAVI) is an emerging alternative technique to surgical AVR, which is especially suitable for high-surgical-risk patients with severe symptomatic AS, such as senile patients and those with severe heart failure, coagulation disorder and chronic kidney injury [33]. As reported, the survival rate of high-risk patients who underwent TAVI was 92.9% at 30 days after the procedure, 78.6% at 1 year and 73.7% at 2 years [34]. Table 3 is a summary on the alteration of deformation post-TAVI detected by strain and strain rate.

Bauer et al. [35] have demonstrated that TAVI improved longitudinal deformation in patients with AS just 24 h after the

<table>
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<th>Study</th>
<th>Method</th>
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<th>Follow-up</th>
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<tr>
<td>Iwahashi et al. [30]</td>
<td>DTI</td>
<td>PC3.0, GE</td>
<td>AVR</td>
<td>2 w</td>
<td>Longitudinal S/SR of 18 segments</td>
</tr>
<tr>
<td>Rost et al. [31]</td>
<td>STI</td>
<td>Vivid-7, GE</td>
<td>AVR</td>
<td>1 w, 6 m</td>
<td>Longitudinal/radial S in 18 segments; circumferential peak S in 6 segments</td>
</tr>
<tr>
<td>Carasso et al. [28]</td>
<td>DTI</td>
<td>VVI, Siemens</td>
<td>AVR</td>
<td>1 w, 5 m</td>
<td>Longitudinal S/systolic and early diastolic SR of 18 segments; circumferential S/systolic SR of mid-LV</td>
</tr>
<tr>
<td>Lindqvist et al. [19]</td>
<td>STI</td>
<td>version 8, GE</td>
<td>AVR</td>
<td>6 m</td>
<td>Apical and basal rotation; twist</td>
</tr>
</tbody>
</table>

AS: aortic stenosis; s-AS: severe aortic stenosis; STI: speckle-tracking imaging; DTI: Doppler tissue imaging; AVR: aortic valve replacement; m: month; w: week; LV: left ventricle.
### Table 2: Alterations of strain/SR post-AVR

<table>
<thead>
<tr>
<th>Study</th>
<th>Normal</th>
<th>Pre-AVR</th>
<th>1 week</th>
<th>2 weeks</th>
<th>6 months</th>
<th>17 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal S (%)</td>
<td>-20.3 ± 2.3 (P &lt; 0.0001)</td>
<td>-15.1 ± 3.8 [11]</td>
<td>-11.9 ± 2.6 [30]</td>
<td>-13.8 ± 3.1 (P &lt; 0.01)</td>
<td>-19.7 ± 4.5 (P &lt; 0.001)</td>
<td>-16.9 ± 4.8 (P = 0.026)</td>
</tr>
<tr>
<td>Longitudinal SR (s⁻¹)</td>
<td>-21.4 ± 4.4 (P &lt; 0.005)</td>
<td>-12.8 ± 1.7 [28]</td>
<td>-15.9 ± 2.2 (P &lt; 0.005)</td>
<td>-18.2 ± 1.9 (P &lt; 0.005)</td>
<td>-18.5 ± 1.9 (P &lt; 0.0001)</td>
<td>-18.0 ± 1.9 (P &lt; 0.001)</td>
</tr>
<tr>
<td>Radial S (%)</td>
<td>38.9 ± 6.4 (P &lt; 0.005)</td>
<td>-6.0 ± 0.1 [28]</td>
<td>-0.8 ± 0.1 (P &lt; 0.005)</td>
<td>-0.97 ± 0.19 (P &lt; 0.0001)</td>
<td>-2.1 ± 0.3 (P &lt; 0.005)</td>
<td>-3.1 ± 0.3 (P &lt; 0.005)</td>
</tr>
<tr>
<td>Radial SR (s⁻¹)</td>
<td>2.2 ± 0.6 (P &lt; 0.005)</td>
<td>1.7 ± 0.5 [11]</td>
<td>-1.6 ± 0.5 [31]</td>
<td>-1.5 ± 0.5 (P &lt; 0.0001)</td>
<td>-1.8 ± 0.5 (P &lt; 0.0001)</td>
<td>-1.9 ± 0.5 (P &lt; 0.0001)</td>
</tr>
<tr>
<td>Circumferential S (%)</td>
<td>-21.9 ± 5.2 (P &lt; 0.005)</td>
<td>-27.0 ± 5.1 [28]</td>
<td>-22.3 ± 4.9 (P &lt; 0.005)</td>
<td>-22.5 ± 4.5 (P &lt; 0.005)</td>
<td>-1.3 ± 0.3 (P &lt; 0.005)</td>
<td>-1.3 ± 0.3 (P &lt; 0.005)</td>
</tr>
<tr>
<td>Circumferential SR (s⁻¹)</td>
<td>-1.3 ± 0.3 (P &lt; 0.0001)</td>
<td>-1.0 ± 0.3 [11]</td>
<td>-1.2 ± 0.4 [28]</td>
<td>-1.2 ± 0.4 (P &lt; 0.005)</td>
<td>-1.2 ± 0.4 (P &lt; 0.005)</td>
<td>-1.2 ± 0.4 (P &lt; 0.005)</td>
</tr>
<tr>
<td>Apical rotation (°)</td>
<td>7.6 ± 2.6 (P &lt; 0.0001)</td>
<td>13.0 ± 5.8 [19]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Twist (°)</td>
<td>12.9 ± 3.2 (P &lt; 0.0001)</td>
<td>19.7 ± 5.7 [19]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</table>

AVR: aortic valve replacement; P values in brackets behind numbers are calculated by comparing with numbers of pre-AVR; statistical analysis in these two cells, refer to the 21 patients who completed the whole 6-month follow-up, circumferential S and SR pre-AVR of these 21 patients are 27.5 ± 5.2% and -1.3 ± 0.3 s⁻¹.

<table>
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<tr>
<th>BAURER ET AL.</th>
<th>PARAMETERS INDICATING THE PROGNOSIS</th>
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<tr>
<td>Longitudinal strain (s⁻¹)</td>
<td>36% could achieve further improvement from 1.0 ± 0.3 s⁻¹ (P = 0.02)</td>
</tr>
<tr>
<td>Longitudinal strain (s⁻¹)</td>
<td>1.2 ± 0.4 (P &lt; 0.0001)</td>
</tr>
<tr>
<td>Apical rotation (°)</td>
<td>7.6 ± 2.6 (P &lt; 0.0001)</td>
</tr>
<tr>
<td>Twist (°)</td>
<td>12.9 ± 3.2 (P &lt; 0.0001)</td>
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</table>

Additional parameters indicating the prognosis are also the serial wall and lateral wall.

### STRAIN/SR RATES ARE PROMISING

As also achieved consistency [42], also the AGR [11, 30, 31] and circumferential strain was better correlated with the LV EF in patients with low-low gradient. However, it was also the case that the ventricle responded well to the increase in strain and SR could predict patient prognosis.

### AFTER AVR

Bauer et al. [27] suggested that systolic radial strain/SR of the post-AVR wall with high or bad responses, after AVR, on patients with aortic valve disease. We also say that strain and SR could predict patient prognosis. As also achieved consistency [42]. Bauer et al. [27] demonstrated that systolic radial strain/SR of the post-AVR wall with high or bad responses, after AVR, on patients with aortic valve disease. We also say that strain and SR could predict patient prognosis.

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APPLICATION OF STRAIN AND STRAIN RATE IN LOW-FLOW LOW-GRADIENT AORTIC STENOSIS

LF-LG AS is defined as the combination of an effective orifice area ≤1.0 cm² or ≤0.6 cm²/m² when indexed by the body surface area and a low mean transvalvular gradient (<40 mmHg), accompanied with a persevered or low LVEF. Dobutamine stress echocardiography (DSE) is recommended to test the LV flow reserve (increase in stroke volume >20%), which is useful to estimate operative risk but does not predict recovery of LV function, symptomatic improvement and late survival after operation [43]. Recently, Bartko et al. [42] carried out a research on the relationship between longitudinal strain/SR and survival rate of LF-LG AS, and found that these two parameters measured on DSE were the univariate predictors, and that peak longitudinal SR could add incremental prognostic value.

LIMITATION OF STRAIN/STRAIN RATE IMAGING AND TWIST

S/SR and twist have been certified as valuable tools in the understanding and assessment of myocardial motion, function and mechanics. Owing to lack of substantial research, strain/SR and twist have not been utilized in everyday clinical practice and have remained research tools. LVEF is still the most important parameter on left ventricular function and diagnosis.

Moreover, the three imaging techniques have various limitations. Like all Doppler-derived measurements, TDI is limited by angle dependency (the greater the insonation angle, the lower is the measured velocity); this is the bane of worse reproducibility in the radial direction [8]. Owing to the effect of respiration and tethering effects of the surrounding myocardium, the area of interest moves in and out of the scanning beam during the cardiac cycle and this makes tracking difficult. Furthermore, TDI is susceptible to noise arising from the blood pool [3, 7]. Although there is no angle limitation, 2D-STI is prone to a higher degree of error while motion is perpendicular to the ultrasound beam. Similar to TDI, speckle patterns are not constant in serial frames [44]. 3D-STI has emerged as a further advancement to provide greater insight, but is much less popular than TDI or 2D-STI due to the limited availability of echo systems. In general, 2D-STI is currently used most widely in clinical practice.

CONCLUSION

Systolic strain/SR and twist are emerging parameters developed during this decade. Their challenging roles in coronary artery disease, ventricular disynchrony, chronic heart failure and right ventricular function have been discussed. Their roles in aortic valve disease and surgery (AVR or aortic valve reconstruction or TAVI) also cannot be ignored. These parameters directly delineate the motion of the LV and demonstrate the function of the LV. We express several opinions and desired research directions: (i) strain, SR and torsion, especially longitudinal strain and SR, can reflect the severity of AS and systolic function of the LV; (ii) circumferential strain/SR and twist seem to be promising parameters on differentiating LV compensation or decompensation, which is important for preoperative evaluation. But as the status of compensation or decompensation has no concrete diagnostic criteria, sequential research studies are needed for identification of a cut-off value which could indicate operative mortality and prognosis; however, we can say decreased circumferential strain and SR indicates higher operative risk and a worse prognosis; (iii) deformations of the LV are partly normalized after AVR, be it during compensation or decompensation; however, the length of time needed for deformation recovery is unclear—1 week or 2 weeks? (iv) TAVI is a minimally invasive technique, but whether the occurrence of new conduction abnormalities affects the recovery of LV deformation is still not clear; (v) considering the fuzziness of myocardial imaging and the inaccuracy of ventricular wall recognition, more advanced devices and probes are necessary.

FUNDING

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<table>
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<tr>
<th>Study</th>
<th>n</th>
<th>Technique</th>
<th>Machine</th>
<th>Follow-up</th>
<th>Parameters detected before operation</th>
<th>Changes of parameters pre-/post-TAVI</th>
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<tbody>
<tr>
<td>Bauer et al. [35]</td>
<td>8</td>
<td>DTI</td>
<td>VingMed</td>
<td>24 h</td>
<td>Anterior wall peak systolic strain, Anterior wall peak systolic SR, Posterior wall peak systolic S, Posterior wall peak systolic SR</td>
<td>11 ± 9 vs 18 ± 7%, P = 0.02, 0.8 ± 0.5 vs 1.5 ± 0.3 s⁻¹, P = 0.002, 11 ± 5 vs 17 ± 9%, P = 0.02, 1.0 ± 0.3 vs 1.9 ± 0.7 s⁻¹, P = 0.009</td>
</tr>
<tr>
<td>Tzikas et al. [37]</td>
<td>27</td>
<td>STI</td>
<td>iE33, Philips</td>
<td>6 d</td>
<td>Longitudinal strain, Longitudinal strain of patients without new conduction abnormalities (9 cases), Longitudinal strain of patients with new conduction abnormalities (18 cases)</td>
<td>11 ± 3 vs 12 ± 3%, P = 0.64, 11 ± 3 vs 13 ± 3%, P &lt; 0.05, 11 ± 4 vs 11 ± 2%, P &gt; 0.05</td>
</tr>
<tr>
<td>Grabskaya et al. [38]</td>
<td>36</td>
<td>STI</td>
<td>Vivid7, GE</td>
<td>1 m</td>
<td>Longitudinal strain, Longitudinal SR, Circumferential and radial strain/SR</td>
<td>-15.8 ± 3.6 vs -17.6 ± 3.1%, P &lt; 0.001, -1.03 ± 0.21 vs -1.21 ± 0.19 s⁻¹, P &lt; 0.001, P &gt; 0.05</td>
</tr>
</tbody>
</table>

TAVI: transcatheter aortic valve implantation; DTI: Doppler tissue imaging; STI: speckle-tracking imaging; h: hour; d: day; m: month.
REFERENCES


that a better means of risk stratification of patients with asymptomatic severe AS is required. In patients with asymptomatic severe AS a reduction in left ventricular ejection fraction <50% is associated with a poor prognosis. Indeed the European Society of Cardiology and European Association for Cardio-Thoracic Surgery guidelines grade this as a Class I indication for aortic valve replacement [3]. Left ventricular ejection fraction is an imperfect marker of left ventricular systolic function. Myocardial deformation (strain) is a more sensitive marker of contractile function. In a study of 79 patients with asymptomatic severe AS and preserved ejection fraction, a global longitudinal strain of <15% was an independent predictor of mortality adding incremental prognostic value to other markers of risk i.e aortic valve calcification, valvulo-arterial impedance and STS risk score [4]. Furthermore, reduced preoperative global longitudinal strain in patients with preserved ejection fraction has been shown to predict cardiac mortality and morbidity post aortic valve replacement [5].

In summary, myocardial deformation imaging is able to add incremental prognostic data for evaluation of patients with asymptomatic severe AS and preserved ejection fraction.

Conflict of interest: none declared.

References