Cardiac Imaging

Effect of Preload Reduction by Hemodialysis on Left Ventricular Mechanical Parameters by Three-Dimensional Speckle Tracking Echocardiography

Bao-Tzung Wu, Mei-An Tsai-Pai, Hung-Yi Hsu, Pail-Seung Lin, Ching-Heng Lin and Ying-Tsung Chen

Background: The effect of acute volume change by hemodialysis on contractile characteristics of the left ventricle (LV) is not well known and has never been evaluated by 3-dimensional speckle tracking echocardiography (3D-STE).

Methods: Twenty-three patients on chronic hemodialysis were recruited. 3D-STE was performed immediately before and after hemodialysis in the dialysis room. The strain, displacement, rotation, torsion, and twist of LV were calculated by commercial software for different segments of LV.

Results: Hemodialysis produced significant decreases in body weight, systolic and diastolic blood pressure, end-diastolic and end-systolic volumes, but ejection fraction did not change. The regional torsion increased from 2.1 ± 1.2 to 2.7 ± 1.3 degree/cm (p = 0.012) after dialysis, though the crude global torsion, longitudinal, radial, circumferential, 3D strain, rotation and twist of LV did not change significantly. The regional torsion correlated with the crude global torsion (r = 0.763, p < 0.001). The change of ejection fraction after hemodialysis was significantly correlated with changes of circumferential strain (r = -0.858, p < 0.001), longitudinal strain (r = -0.516, p = 0.012) and LV area (r = -0.883, p < 0.001).

Conclusion: Assessment of LV contractile characteristics by 3D-STE is easy and efficient. The regional torsion, which could only be evaluated by 3D-STE, is more sensitive to reduction in preload possibly due to deformation non-uniformity of myocardium in uremic patients.

Key Words: Echocardiography • Hemodialysis • Speckle tracking • Torsion

INTRODUCTION

Chronic pressure and volume overload can lead to left ventricular (LV) remodeling in uremic patients. About 75% of patients receiving chronic dialysis developed a concentric or eccentric LV geometry and LV hypertrophy. These structural changes of LV are associated with impaired LV perfusion and function.

Contraction of helical myocardial fibers of LV produces torsional deformation of LV. This twisting motion of LV has been shown to be a key factor of normal systolic and diastolic myocardial function in both animals and humans. Assessment of LV torsion deformation assists in the understanding and quantification of LV function. LV torsion can be assessed using several techniques such as implanted radiopaque markers, sonomicrometry, magnetic resonance imaging (MRI), and echocardiography. The radiopaque marker and sono-
micrometry were only used in animal studies. Cardiac MRI can be used in humans and represents an assessment “gold standard.” This technique is only used in a few medical centers in Taiwan. Two-dimensional speckle tracking imaging echocardiography (2D-STE) has provided a new opportunity for the noninvasive evaluation of LV torsional deformation. However, the 2D-STE could only detect a portion of real 3-dimensional myocardial motion in 2-dimensional section plane of echocardiography. Now, three-dimensional speckle tracking echocardiography (3D-STE) can evaluate the LV motion in all directions and can overcome the out-of-plane limitation. The applications of 3D-STE in evaluation of LV function had only been described in a few reports.

Hemodialysis in uremic patients removes a large amount of fluid from the body in a few hours. Change in LV volume during dialysis will alter LV contraction and strain as described by previous studies. The effect of acute volume change by hemodialysis on LV torsion has never been evaluated by 3D-STE. The effect of preload change on LV torsion is controversial. Using different methods and different subjects (animal or human) will generate different results. The aim of this study was to evaluate the LV torsional function in chronic uremic patients, and to compare changes in LV torsional function immediately before and after dialysis by using 3D-STE. There are several methods to describe LV torsion. In this article, we used crude global torsion and regional torsion to measure the LV short axis function. In both the normal and the diseased heart, LV is characterized both morphologically and functionally by a high degree of regional non-uniformity. This deformation non-uniformity of myocardium varies from base to apex (regional torsion). The regional torsion represents the different rotation angle between two LV short axis planes nearby and is expressed as “degree/cm”. It is evident from the literature that the LV deformation is complex and closely related to the variations in transmural fiber orientation, irregular shape of the left ventricle, and local differences in ventricular morphology.

SUBJECTS AND METHODS

Study population
The study group included 23 uremic patients on maintenance hemodialysis. All patients were in sinus rhythm and had received regular hemodialysis three times a week, according to a standard dialysis program, for three months or longer. 3D-STE was performed within 30 minutes before vein puncture for hemodialysis, and after removal of the catheter in all participants.

3D speckle tracking echocardiography
3D-STE was performed from the apical position with PST-25SX probe (Artida system, Toshiba Medical Systems, Tokyo, Japan) by the same experienced technician, using a frame rate of 20-30 Hertz. The apical 2 chamber and 4 chamber views, short axis views at different levels of LV from the base to apex, LV endocardial and epicardial boundaries were automatically reconstructed and tracked in 3D space throughout the whole cardiac cycle (Figure 1). Subsequently, the endocardial surface was manually adjusted when necessary in the five planes that best match the actual endocardial position. The LV was automatically divided into 16 three-dimensional segments, according to American Society of Echocardiographic recommendation. The software automatically tracked the contour on the subsequent frame in different vectors simultaneously. The radial and longitudinal displacement and rotation, torsion, and twist were automatically calculated for each segment.

Strain, displacement, rotation and torsion
Strain was calculated as: strain = (Lf - Lo)/Lo, where Lf is the final segmental length and Lo is the original segment length at the peak of the R wave of QRS complex. Longitudinal strain (Ls) is defined as the percentage change in regional length in the direction of the longitudinal axis of the endocardium. Circumferential strain (Cs) is defined as the percentage change in the regional length in the circumferential direction of the endocardium, and radial strain (Rs) as the percentage change in wall thickness in the direction of the endocardium. 3D strain is a true 3D radial strain measurement, defined as the percentage change in wall thickness in the direction toward the endocardium in three-dimensional spaces (Figure 2). Displacement is the displacement of the endocardial surface (mm) in the direction perpendicular to the endocardial contour. A positive value indicates displacement toward the center. Radial displacement is
calculated from the short axis view and longitudinal displacement from the apical view. 3D displacement is measured in 3D dimensional space. Area tracking is the rate of change in the area of a regional part of the endocardial contour. Rotation is the rotary motion of the myocardium during contraction, while the apex moves counter-clockwise and the base rotates clockwise. Counter-clockwise is defined as plus direction. Twist is the difference in myocardial rotation at any given short axis level relative to the corresponding point at the left ventricular base (Figure 2).

Crude global torsion and regional torsion

Torsion is a measurement of the degree of a point on the LV short axis segment rotated around the long axis, subtracting the rotation of a reference point on the basal short axis plane, and dividing the distance between these two points. Counter-clockwise rotation is expressed in a positive value and clockwise rotation in a negative value. Crude global torsion (so-called basal torsion by the manufacturer), is calculated by net LV rotation angles obtained from basal (clockwise) and apical (counter-clockwise) short axis planes at the

*Figure 1. Three-dimensional speckle tracking echocardiography showed reconstructing imaging respond to the apical 4-chamber (A, upper), the apical 2-chamber (A, lower), and 3 short-axis views at different levels (B); the plastic bag 3-dimentional and segmental strain images of left ventricular (C); and parametric image of regional circumferential strain-time curves (D).*

*Figure 2. Calculation of strain, rotation and twist Strain is calculated as \((L_f - L_o) / L_o \times 100\%\) in longitudinal (A), circumferential (B) and circumferential (C) directions as well as in dimension. (D) In each short-axis plane, rotation (degree) is calculated as the rotatory motion about the center of the left ventricle. Counter clockwise rotation is expressed with positive values. (E) Twists (degrees) calculation: difference in rotation angle between each short axis and basal short axis. ED, end-diastole; ES, end-systole; \(L_f\), final segmental length in each subsequent frame; \(L_o\), original segmental length in starting frame.*
same time point dividing by the long axis length of LV between both planes. Regional torsion is a summation of torsional movement of different segments of LV. The LV is divided into six to seven short-axis planes with a pre-set thickness about 1 cm. The torsion of each segment is calculated by the degree of a point on the LV wall rotating around the long axis relative to a nearby point, and dividing by the distance between these two points. Although every LV long axis distance is different, the values are consistent even though the distances between different points are not the same (Figure 3).

**Intraobserver and interobserver variability**

Intraobserver variability was determined by having an experienced sonographer repeat the measurement of LV torsion in 10 randomly selected subjects. Interobserver variability was determined by having an echocardiography specialist repeat the measuring of these variables after the first sonographer. Intraobserver and interobserver variabilities were calculated as the absolute difference between the corresponding repeated measurements as a percentage of their mean.

**Statistical methods**

Data were expressed as mean ± SD for continuous variables. Values of different groups of patients were compared using the Student t test. Univariate correlation was assessed by Pearson’s correlation coefficients. A p value < .05 was considered statistically significant.

**RESULTS**

A total of 23 patients were enrolled in this study. The mean patient age was 64 years (range 41 to 81 years). Ten patients were men, thirteen patients had hypertension, and twelve patients had diabetes. Table 1 summarizes clinical and echocardiographic characteristics in the 23 patients.

The body weight, systolic blood pressure (BP) and diastolic BP were significantly decreased after hemodialysis (p < 0.001, p = 0.007 and p = 0.003, respectively). Hemodialysis produced significant decreases in end-diastolic volume and end-systolic volume, though LV ejection fraction did not change after hemodialysis.

Hemodialysis did not produce significant changes in longitudinal, radial, circumferential, or 3D strain of LV. The regional LV torsion increased from 2.1 ± 1.2 to 2.7 ± 1.3 degree/cm (p = 0.012) after dialysis. Crude global torsion, rotation, twist and endocardial displacement in all three directions did not change after hemodialysis.

Non-parametric Spearman’s correlation test showed that both end-diastolic volume and end-systolic volume were correlated with systolic BP (r = 0.507, p < 0.001 and r = 0.536, p < 0.001, respectively), diastolic BP (r = 0.435, p < 0.003; r = 0.462, p = 0.001), ejection fraction (r = -0.553, p < 0.001; r = -0.711, p < 0.001), circumferential strain (r = 0.451, p = 0.002; r = 0.600, p < 0.001), longitudinal strain (r = 0.309, p = 0.037; r = 0.427, p = 0.003), radial strain (r = -0.368, p = 0.008; r = -0.359, p = 0.014), and LV area (r = 0.416, p = 0.004; r = 0.582, p < 0.001). LV ejection fraction was significantly correlated with systolic BP (r = -0.442, p = 0.020), diastolic BP (r = -0.350, p = 0.017), circumferential strain (r = -0.822, p < 0.001), longitudinal strain (r = -0.589, p < 0.001), and LV area (r = -0.862, p < 0.001). Circumferential strain was correlated with longitudinal strain (r = 0.525, p < 0.001) and radial strain (r = -0.334, p =
Longitudinal strain was correlated with radial strain \((r = -0.501, p < 0.001)\). Among circumferential, longitudinal and radial strain, only circumferential strain was correlated with LV twist \((r = -0.360, p = 0.014)\), regional torsion \((r = -0.320, p = 0.016)\) and crude global torsion \((r = -0.329, p = 0.025)\). The regional torsion significantly correlated with the crude global torsion \((r = 0.763, p < 0.001)\). However, regional and crude global torsion were not correlated with LV volumes or LV ejection fraction.

Changes of ejection fraction after hemodialysis were significantly correlated with changes of circumferential strain \((r = -0.858, p < 0.001)\), longitudinal strain \((r = -0.516, p = 0.012)\) and LV area \((r = -0.883, p < 0.001)\), but not with those of radial strain, systolic BP, diastolic BP, end-diastolic volume, or end-systolic volume (Figure 4). Change in ejection fraction was not correlated with rotation, torsion or twist of LV.

The intraobserver variability for the LV torsion measurement were \(10 \pm 6\%\), and the interobserver variability were \(12 \pm 8\%\).

## DISCUSSION

### Main findings

In this study, we evaluated the effect of acute preload reduction in uremic patients by newly developed 3D-STE. Hemodialysis produces acute change in intravascular volume status, and gives a good opportunity to examine the changes of cardiac contractile characteristics in relation to acute volume loss. However, few reports demonstrated the changes of contractile parameters of left ventricle in chronic dialysis patients.\(^{23,26}\) The significant decreases in end-diastolic volume and end systolic volume after dialysis were clearly demonstrated by using 3D-STE in our study. The application of 3D-STE in clinical practice is still developing. Our study demonstrated the benefits of 3D-STE in the evaluation and quantification of the cardiac contractile function. Our results could be a basis for future studies.

LV ejection fraction was significantly correlated with systolic BP, diastolic BP, end-diastolic volume, end-systolic volume, circumferential strain, longitudinal

### Table 1. Comparison of contractile properties of left ventricle before and after hemodialysis

<table>
<thead>
<tr>
<th></th>
<th>Before dialysis</th>
<th>After dialysis</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y/o)</td>
<td>61.7 ± 9.1</td>
<td>126.2 ± 22.7</td>
<td>0.007</td>
</tr>
<tr>
<td>Male/Female</td>
<td>13/10</td>
<td></td>
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<tr>
<td>Height (cm)</td>
<td>155.5 ± 8.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic BP (mmHg)</td>
<td>137.4 ± 18.4</td>
<td>74.0 ± 11.9</td>
<td>0.003</td>
</tr>
<tr>
<td>Diastolic BP (mmHg)</td>
<td>82.8 ± 13.1</td>
<td>83.6 ± 15.8</td>
<td>0.426</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>56.1 ± 10.3</td>
<td>53.9 ± 10.2</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Heart rate (beat /min)</td>
<td>84.2 ± 17.2</td>
<td>83.6 ± 15.8</td>
<td>0.426</td>
</tr>
<tr>
<td>Circumferential strain (%)</td>
<td>-24.0 ± 7.5</td>
<td>-23.8 ± 8.2</td>
<td>0.976</td>
</tr>
<tr>
<td>Longitudinal strain (%)</td>
<td>-13.6 ± 4.7</td>
<td>-13.9 ± 4.3</td>
<td>0.411</td>
</tr>
<tr>
<td>Radial strain (%)</td>
<td>22.9 ± 12.3</td>
<td>19.8 ± 13.1</td>
<td>0.260</td>
</tr>
<tr>
<td>Rotation (deg)</td>
<td>2.6 ± 1.8</td>
<td>2.2 ± 2.0</td>
<td>0.121</td>
</tr>
<tr>
<td>Twist (deg)</td>
<td>3.5 ± 3.1</td>
<td>4.3 ± 3.0</td>
<td>0.339</td>
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<tr>
<td>Regional torsion (deg/cm)</td>
<td>2.1 ± 1.2</td>
<td>2.7 ± 1.3</td>
<td>0.012</td>
</tr>
<tr>
<td>Crude global torsion (deg/cm)</td>
<td>1.2 ± 1.1</td>
<td>1.4 ± 1.1</td>
<td>0.858</td>
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<td>3-dimentional strain (%)</td>
<td>26.2 ± 12.3</td>
<td>23.6 ± 12.8</td>
<td>0.287</td>
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<tr>
<td>Radial displacement (mm)</td>
<td>5.0 ± 1.5</td>
<td>4.8 ± 1.5</td>
<td>0.191</td>
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<tr>
<td>Longitudinal displacement (mm)</td>
<td>3.6 ± 1.2</td>
<td>3.5 ± 1.2</td>
<td>0.773</td>
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<tr>
<td>3-dimentional displacement (mm)</td>
<td>7.3 ± 1.1</td>
<td>7.3 ± 1.2</td>
<td>0.726</td>
</tr>
<tr>
<td>Area (%)</td>
<td>-34.9 ± 10.5</td>
<td>-35.1 ± 10.9</td>
<td>0.858</td>
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<tr>
<td>End-diastolic volume</td>
<td>89.7 ± 35.9</td>
<td>79.3 ± 27.5</td>
<td>0.036</td>
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<tr>
<td>End-systolic volume</td>
<td>44.1 ± 25.7</td>
<td>38.0 ± 20.7</td>
<td>0.016</td>
</tr>
<tr>
<td>Ejection fraction (%)</td>
<td>53.1 ± 9.0</td>
<td>54.1 ± 9.5</td>
<td>0.394</td>
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strain, and LV area. In contrast, the changes in ejection fraction after hemodialysis were correlated with the changes in circumferential strain, longitudinal strain and LV area, but not with systolic BP, diastolic BP, end-diastolic volume or end-systolic volume. Although hemodialysis consistently produces acute reduction in intravascular volume, the changes in ejection fraction, strain and torsion of LV after dialysis were quite variable. The hemodialysis which induced changes in ejection fraction, systolic BP and diastolic BP among different patients were not only a result of intravascular volume reduction, but might be affected by the co-existence of myocardial damage, intravascular volume status, and a function of the autonomic nervous system. Chronic dialysis patients may have prominent myocardial interstitial fibrosis. Marked cardiac fibrosis may alter myocardial contractile characteristics, and influence the results of speckle tracking analysis. Therefore, our study did not show consistent changes in most echocardiographic parameters. The changes in cardiac performance after hemodialysis were difficult to judge by simple clinical rule in different patients. 3D-STE could help to evaluate individual responses to hemodialysis and to tailor appropriate dialysis therapy, especially in vulnerable patients suffering hypotension and fainting episodes.

Our results were consistent with Murata et al.’s report that peak systolic strain and ejection were not changed before and after hemodialysis. But the LV functions in the horizontal plane, not only the radial dysynchrony but also the regional torsion, improved after dialysis. Weiner et al. revealed that the LV rotation and torsion increased after normal saline infusion in normal subjects. We further demonstrated that in volume overload uremic patients, decreased preload also increased LV torsion. The changes in LV torsion after hemodialysis were substantial as evaluated by regional torsion, but not by crude global torsion. The regional torsion could be a better parameter to assess changes in LV contractile property, because of the deformation non-uniformity of myocardium.

Previous studies by other imaging techniques

The regional LV torsion increased significantly after hemodialysis in our patients. The increase in LV torsion
Effect of Preload Reduction on 3D Strain and Torsion

could result from decreases in afterload (blood pressure) and preload (end-diastolic volume). The results of changing afterload and preload on LV torsion were controversial in previous animal and human studies, which used cine, MRI, microsonometry and 2D-STE testing techniques. In a human cardiac allografts study, the author used LV mid-wall metallic markers to measure the rotation of LV. After volume loading with normal saline (2000 cc), torsion angles between middle and apex of LV wall did not increase significantly. But in an animal study evaluated by cardiac MRI, LV torsion increased after volume loading. MacGowan et al. studied the canine heart using MRI tagging, and LV torsion was concluded to be afterload and preload dependent. Hansen showed that pressure and volume loading do not affect LV systolic twist or torsion in transplant patients by using cine with titanium marker at the middle wall of the heart.32

The advantages of 3D-STE

3D echocardiography (3D-STE) has been applied to assess traditional echocardiographic parameters such as volume, mass, global and regional wall motion of LV. The myocardial architecture of LV includes layers of helical fibers running in different directions. Left ventricular motion is a complex process consisting of rotation, contraction and shortening. Estimation of components of LV strain and strain rate by using 3D-STE correlated well with those estimated by sonomicrometry and cardiac magnetic resonance, and provided further information about the kinetics of LV. This study used the newly developed 3D speckle tracking technique to trace the speckle spatial motion of myocardium. By calculation and reconstruction of the motion and deformation of the myocardial tissue, the 3D-STE could achieve accurate qualitative and quantitative estimation of motion velocity, strain, strain rate, displacement, and twist and torsion. Torsional motion has been measured by 2D ultrasound speckle tracking image both in animals and humans. In the conventional 2D echocardiography, only the echo speckles in LV short axis view was calculated for LV short axis strain or twist. The longitudinal heart motion during cardiac cycle inevitably causes out of plane error in 2D short axis imaging. But in the real world, the muscle fibers were contractile in an upright or downward oblique way. Using 3D strain technique, we can calculate the strain directly related to fiber orientation. The regional non-uniformity of myocardium, such as regional torsion in this study, could be evaluated easily by 3D-STE, but not 2D echocardiography. In addition, circumferential rotation also contributes 3D wall deformation and affects tracking accuracy. The 3D-STE had the benefit of being less time consuming, with fewer out of plane artifacts and limitations of the Doppler insonation angle, compared with 2D-STE and 2D tissue Doppler. Discordant results between 3D-STE and 2D-STE in previous reports may be explained by the fact that 3D-STE assesses the real motion of the myocardium in the certain three-dimensional volume space, and current 2D-STE ignored the movement out of the ultrasound section plane.

LIMITATIONS

There were some limitations of this study. Three-dimensional echocardiography spatial resolution full volume LV data set for 3D-STE comprised 6 sectors, so the artifact occurring around the border between sectors may affect speckle tracking quality. After hemodialysis, LV volume may still be in fluctuation in these patients, therefore, it is necessary to perform echocardiography at the patients’ dry weight, preferably the day after dialysis due to substantial variability over time in measurement of LV volume and strain. Our study population was small, and there were substantial differences in demographic characteristics among recruited patients.

CONCLUSION

Assessment of LV contractile characteristics by 3D-STE is less laborious, and more time-saving than 2D-STE. The regional torsion is more sensitive to change, as preload changed, than other parameters such as crude global torsion, longitudinal, circumferential and radial strain. This could be due to unevenly distributed interstitial fibrosis in regional myocardium in uremic patients. The changes of 3D-STE parameters in chronic dialysis patients might help the medical community to better understand the physiological and biomechanical alterations of cardiac contraction caused by hemodialysis.
REFERENCES


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