

Three-dimensional Wall Motion Tracking: A Novel Echocardiographic Method for the Assessment of Ventricular Volumes, Strain and Dyssynchrony

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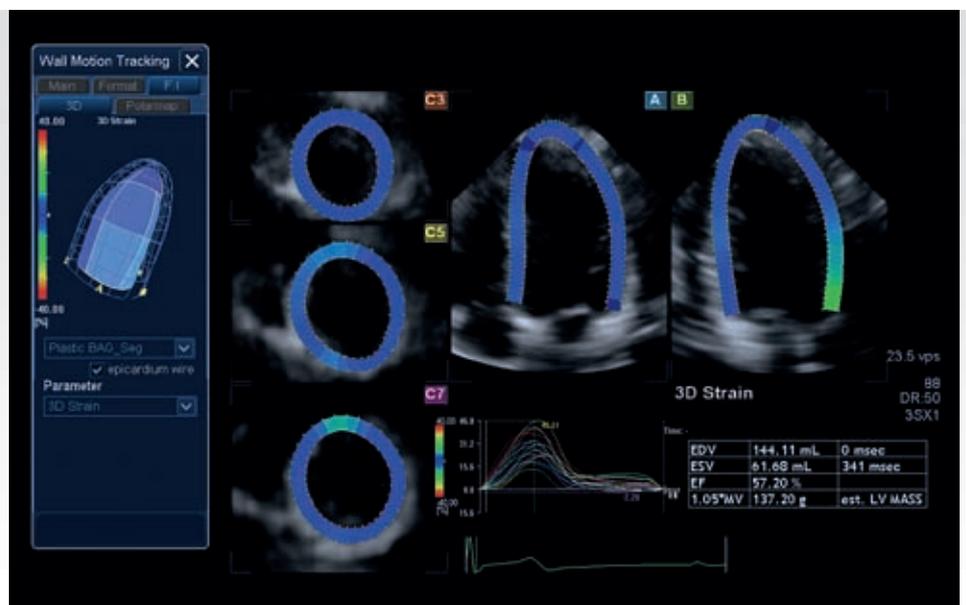
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Echocardiography plays an important role for the assessment of ventricular function in patients with heart failure symptoms. Recent advancements in echocardiography permit measurement of myocardial mechanics through the use of strain imaging. Current techniques are either Doppler based or rely on speckle tracking in two dimensions, but each has limitations. Accordingly, three-dimensional wall motion tracking (3D-WMT) offers rapid acquisition of ventricular volumes and strains, and can potentially overcome the limitations of tissue Doppler based or two-dimensional techniques.

It is well known that congestive heart failure (CHF) is common, with an estimated 500,000 new diagnoses per year in the US, and is associated with significant morbidity and mortality [1]. Heart failure is primarily a disease of the elderly; approximately 6% to 10% of people older than 65 years have

CHF, and approximately 80% of patients hospitalized with CHF are more than 65 years old. Clinical symptoms in patients with heart failure include dyspnea, fatigue and edema and are associated with lower quality of life (QoL) scores.

It has been observed that patients with CHF due to left ventricular (LV) systolic dysfunction have a high prevalence of intraventricular conduction abnormalities, i.e., left bundle branch block or non-specific intraventricular delay, seen on 12-lead electrocardiography (ECG). Among these patients, the prevalence of intraventricular conduction abnormalities increases significantly as LV ejection fraction (EF) declines and ECG-QRS duration increases (> 120 msec). Intraventricular conduction abnormality can lead to dyssynchronous electrical activation and abnormal contraction of the various LV wall segments. Abnormal electromechanical



function may contribute to atrio-ventricular dyssynchrony, increased mitral regurgitation and LV volumes and reduced EF (Fig. 1). Recent investigations involving selected patients with systolic heart failure and prolonged QRS duration have shown efforts to better synchronize ventricular contraction with the use of a biventricular pacemaker or cardiac resynchronization therapy (CRT). Such biventricular pacing has been associated with improvements in heart failure symptoms, exercise capacity, QoL, and hospitalization rates for heart failure and mortality compared to standard medical therapy [2]. However, in clinical trials, approximately 30% of heart failure patients selected for CRT on the basis of a prolonged QRS duration (> 120 msec), do not demonstrate improvement in status [2], leading to the desire to refine selection criteria for this invasive

and expensive technology. Echocardiographic determination of ventricular volumes and dyssynchrony in selected patients may predict better CRT outcomes compared to standard criteria [3, 4]. The most common echocardiographic techniques used for measurement of ventricular dyssynchrony include traditional color tissue Doppler imaging (TDI) [3] and newly developed, two-dimensional (2D) “speckle” strain imaging (SI) [4]. Color TDI is a Doppler method and is therefore limited by insonation angle dependency, allowing evaluation of strains primarily from the longitudinal axis (apical views); SI, although considered angle independent, is limited by foreshortened images and the assumption that ultrasound speckles can be tracked from frame to frame, despite their “out of plane” motion. 3D-WMT, a next-generation strain and volumetric analysis, has

recently been validated with cardiac MRI (Fig. 2) and demonstrates better correlation of ventricular volumes compared with SI [5]. The application of 3D-WMT has been reported to have faster acquisition and analysis time for the assessment of strain, function and volumes compared to SI [6]. Examples of 3D-WMT can be seen in Fig. 3. In addition, time to peak strain can be measured to determine the extent of ventricular dyssynchrony (Fig. 4), which is important prior to CRT implantation as the degree of dyssynchrony may determine response to CRT [3,4]. Three-dimensional wall motion tracking allows for parametric (polar-mapping) imaging of the LV by displaying color overlay from the 16 segment model simultaneously. As seen in Fig. 4A, a color is assigned to each myocardial segment, displaying the direction each segment is moving throughout

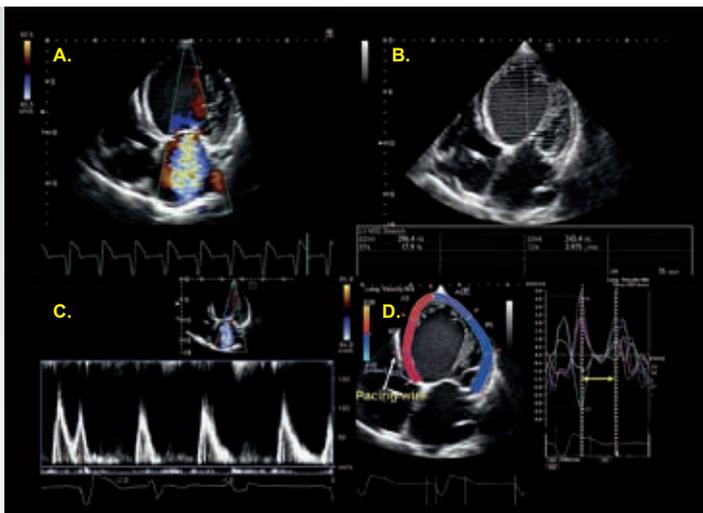


Fig. 1: These images were taken from the study of a patient with CHF and severe mitral regurgitation in the apical four chamber view (A); severely reduced LV function (EF = 17.8%) with significantly increased end-diastolic (296.4 ml) and end-systolic (243.4 ml) volumes (B); atrioventricular dysfunction of the mitral inflow (C); and significant ventricular longitudinal dyssynchrony. The septal to lateral wall delay was 260 ms (D).

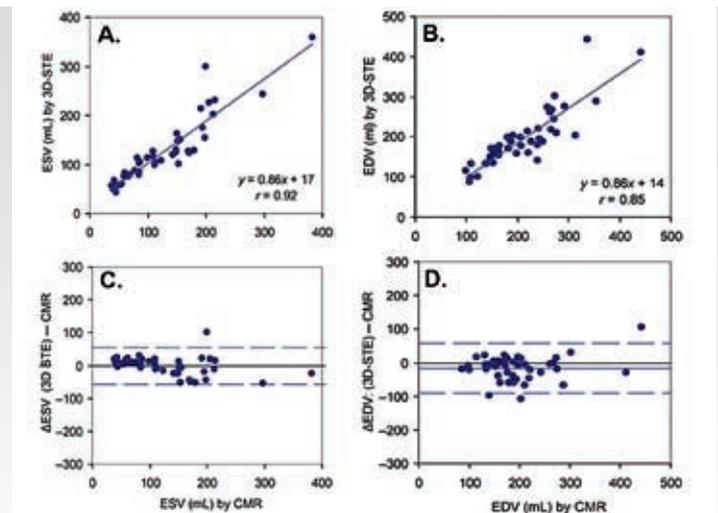


Fig. 2: Above, linear regression correlation between 3D speckle tracking end-systolic volumes (A), end-diastolic volumes (B) and CMR. Below, Bland-Altman agreement between 3D speckle tracking end-systolic volumes (C), end-diastolic volumes (D) and CMR. Note the excellent correlation and agreement between the two methods: STE, speckle tracking echocardiography of ESV, end-systolic volumes, and EDV, end-diastolic volumes compared with CMR, cardiac magnetic resonance imaging [5].

the cardiac cycle. In a normal patient, the strain polar map has a homogeneous display throughout the cardiac cycle. This indicates that the extent of myocardial systolic thickening (radial strain) or shortening (circumferential/longitudinal strain) from each segment, peaks normally and in the same direction at end systole. Conversely, with LV dysfunction and dyssynchrony, the extent of myocardial thickening or shortening is non-uniform with a heterogeneous display within the polar map and peak strains occurring both early and late throughout the cardiac cycle (Fig. 4B). The polar-mapping application can be extended to Dyssynchrony Imaging or DI. This technique permits rapid evaluation of LV mechanical delay with the use of displacement imaging based on a parametric timing sequence. Unlike strain, which calculates the percent thick-

ening or shortening of a specific region, displacement imaging calculates the time (milliseconds) and distance (millimeters) each myocardial segment is traveling throughout the cardiac cycle. Because displacement is not corrected for the absolute length of the contracting segment from which it was measured, a gradient from the base of the heart to apex is seen (i.e., highest displacement occurring at the base, lowest displacement occurring at the apex). In a patient with normal LV function and contraction sequence, segments within the polar map are color-coded green throughout the cardiac cycle, indicating no significant delay in time to peak longitudinal displacement, up to 50 ms after aortic valve closure, between each segment (Fig. 5A). Color-coding of yellow, orange or red within a segment during the diastolic phase of the cardiac

cycle is suggestive of mild, moderate or severe delay. In Fig. 5B there is significant heterogeneity (yellow and red) within the polar map, with red at the apex occurring in early diastole, rapidly identifying delayed segments and dyssynchrony.

Patient History

A 40-year-old male with a history of nonischemic cardiomyopathy was referred to the Cardiac Resynchronization Therapy Clinic for clinical evaluation and implantable cardiac defibrillator (ICD) upgrade. History included alcohol and drug abuse, atrial fibrillation and ventricular tachycardia. Because of ventricular arrhythmias, an ICD was implanted. Physical exam demonstrated dyspnea, NYHA class IV heart failure with an EKG QRS duration = 158 ms.

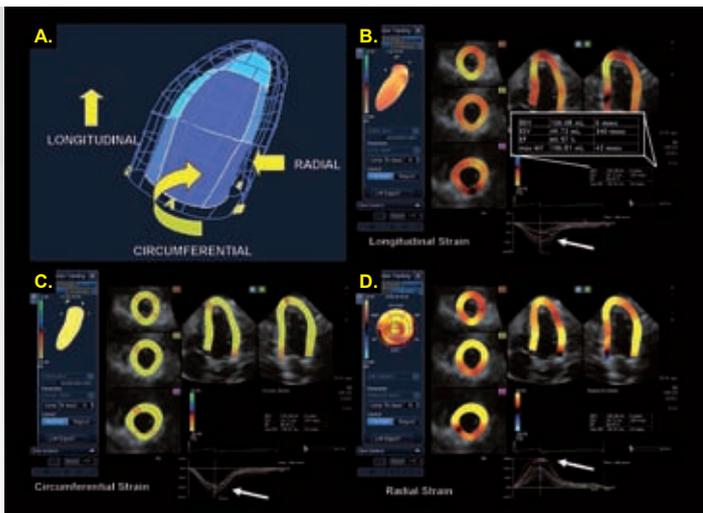


Fig. 3: Normal patterns of 3D-WMT strains. 3D image cast representing the three vectors of myocardial deformation; longitudinal (long axis), circumferential and radial (short axis) (A), longitudinal strains (B), circumferential strains (C), radial strains (D). Both longitudinal and circumferential (shortening) waveforms are negative and displayed below the baseline; radial (thickening) waveforms are positive and displayed above the baseline. Note also that ventricular volumes and EF are reported from the 3D data set (panel B) permitting complete assessment of size and function.

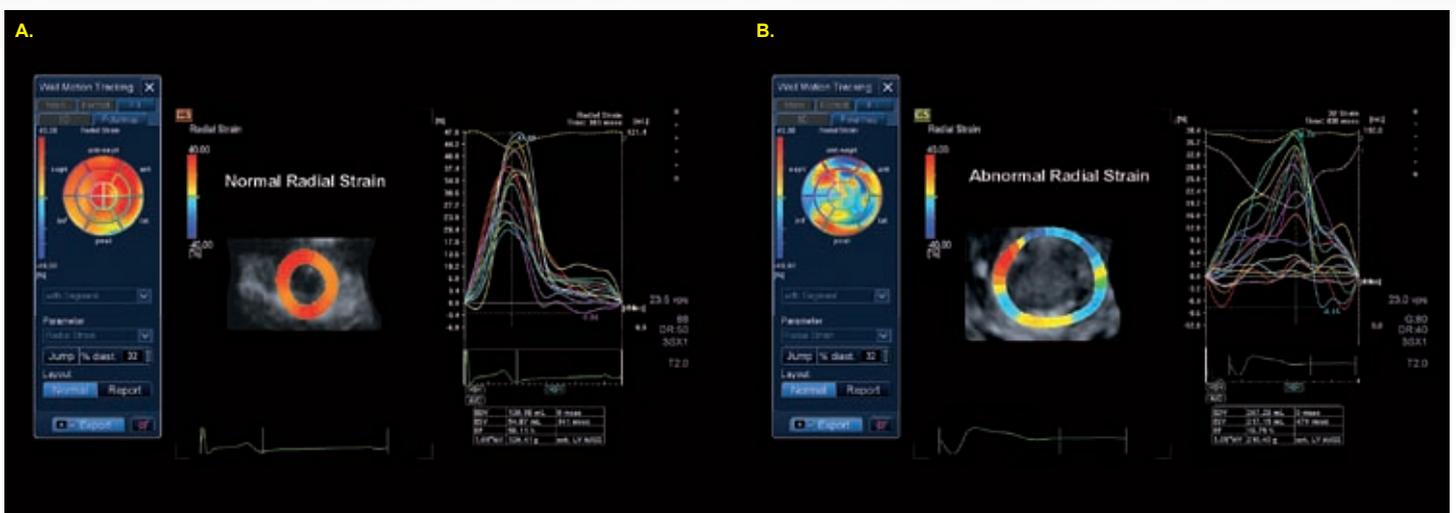


Fig. 4: 3D-WMT radial strain imaging in a normal patient (A). The polar-mapping has a homogeneous display indicating myocardial systolic thickening (radial strain) is normal, occurring at or near end-systole (the end of the T wave on ECG). To the right are the corresponding radial strain waveforms with the alignment of the peaks occurring at or near end-systole. 3D-WMT radial strain imaging in an abnormal patient with LV dysfunction and dyssynchrony (B). Myocardial thickening is non-uniform with heterogeneity within the polar map. Peak strains occur both early and late throughout the cardiac cycle. This pattern of dyssynchrony is typical in a patient with LV dysfunction and wide QRS complex.

Pre-implant Echocardiographic Evaluation

The echocardiogram showed a severely dilated LV with severe global hypokinesis. The 3D EF was 17.6% and the LV end-systolic and end-diastolic volumes were severely increased (ESV = 550.8 ml, EDV = 668.5 ml). There was moderate to severe mitral regurgitation with a restrictive transmitral filling pattern, consistent with highly elevated LV filling pressures. Right heart chamber dimensions were normal with low-normal right ventricular systolic function. There was mild tricuspid regurgitation and severe pulmonary hypertension with a PASP of 66 mmHg.

3D Strain Imaging

Three-dimensional radial strain imaging showed significant heterogeneity throughout the polar

map (Fig. 6A). Although dyssynchronous, the majority of the strain waveforms are positive (thickening) and displayed above the baseline. There was significant reduction in peak radial strains with the latest site activation occurring in the inferior, septal and apical walls (arrow).

3D Dyssynchrony Imaging

Dyssynchrony Imaging showed severe delay (red) occurring in the septal and inferior segments (Fig. 7A). The corresponding displacement waveforms showed severe post systolic displacement occurring well beyond mechanical systole, i.e., after aortic valve closures, (arrow). Although dyssynchronous, the majority of the displacement waveforms are displayed above the baseline and the segments are moving in the same direction.

Based on clinical and echocardiographic criteria (QRS duration ≥ 120 msec, EF $\leq 35\%$, drug refractory CHF), a decision to upgrade his ICD to a biventricular pacemaker was made.

One Month Follow-up

Device interrogation showed an episode of ventricular fibrillation and frequent runs of nonsustained ventricular tachycardia. Physical findings were consistent with acute decompensated heart failure. This patient was therefore considered to be a CRT-nonresponder.

Post-implantation Echocardiography

The 3D end-systolic volumes increased from 558.8 ml to 589.1 ml, with time to peak systolic volumes increasing from 423 ms to 501 ms



Fig. 5: 3D Dyssynchrony Imaging (DI) in a normal patient (A). The polar map display is color coded with green indicating no significant delay within the 16 segment model. Below are the corresponding displacement waveforms demonstrating a decrease from base to apex normally (arrow). Panel B shows DI in a patient with a recent inferior myocardial infarction. The majority of the segments in the inferior/inferolateral regions occurred late (yellow color coding), with the latest site of activation occurring in inferior apex (red color coding) (double arrows). This example offers a rapid visual clue to dyssynchrony. The apical displacement curves in panel B are displayed in the opposite direction, indicating post systolic expansion consistent with dyssynchrony (arrow). Note also that the peak displacement values decrease from the mid to apical level in the normal patient.

respectively. The 3D LVEF decreased significantly from 17.6% to 12.8% (Fig. 6A, B). The degree of MR and PASP were unchanged. However, the LV appeared more dyssynchronous, visually.

3D Strain Imaging

Three-dimensional radial strain imaging showed increased heterogeneity within the polar map compared to baseline (Fig. 6B). The corresponding strain waveforms showed severe, atypical dyssynchrony, bi-directional strains (see Fig. legend), with evidence of worsening dyssynchrony.

3D Dyssynchrony Imaging

DI showed a significant change in the parametric imaging and polar map compared to baseline (Fig. 7B). The corresponding displacement waveforms

showed bi-directional motion consistent with worsening dyssynchrony.

Six Month Follow-up

As noted above, this patient is considered to be a non-responder to CRT and is now being evaluated for a heart transplant.

Conclusion

In this patient, worsening heart failure following CRT paralleled a decrease in LV systolic function and worsening dyssynchrony. As CRT is an invasive and expensive therapy, a means to more fully characterize dyssynchrony prior to implantation would be desirable. 3D-WMT has the potential to be a reliable tool for the screening, selection, and follow-up of patients receiving CRT therapy.

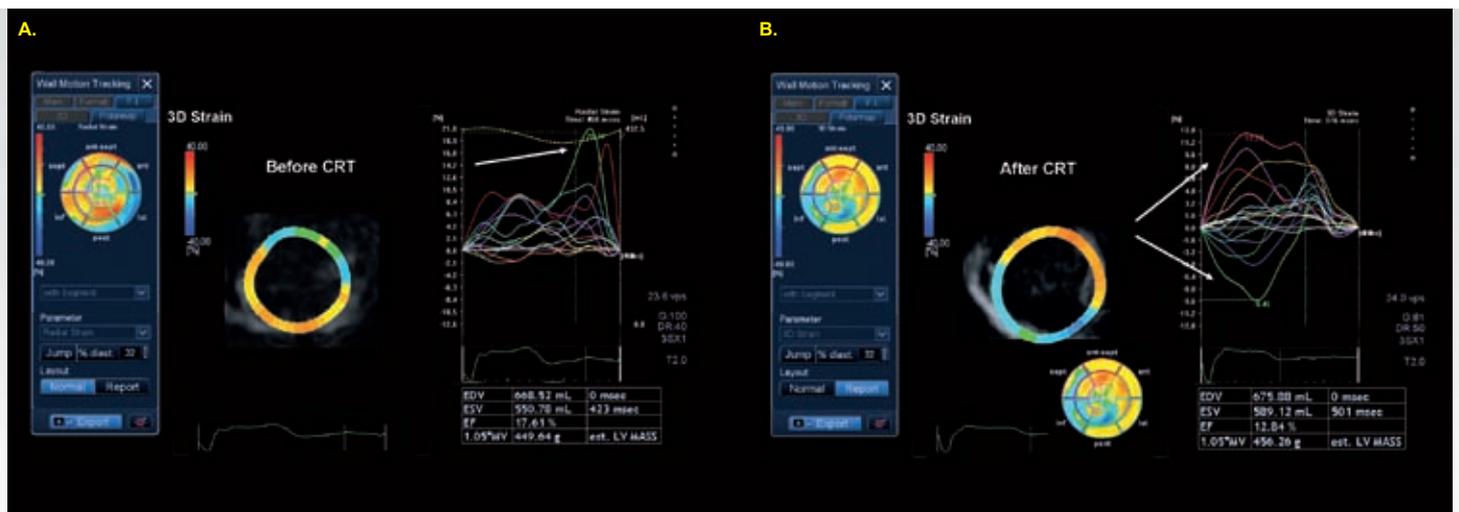


Fig. 6: 3D strain imaging before and after CRT. Although these curves indicate dyssynchrony, majority of the strain waveforms are positive, displayed above the baseline (A). Following CRT, in panel B the EF decreased from 17.6% to 12.8%, end-systolic volumes increased from 550 ml to 589 ml. The strain waveforms are bi-directional with increased “thinning” consistent with worsening dyssynchrony (arrows). The pattern of dyssynchrony in contrast to what was shown in Fig. 4B is less common.

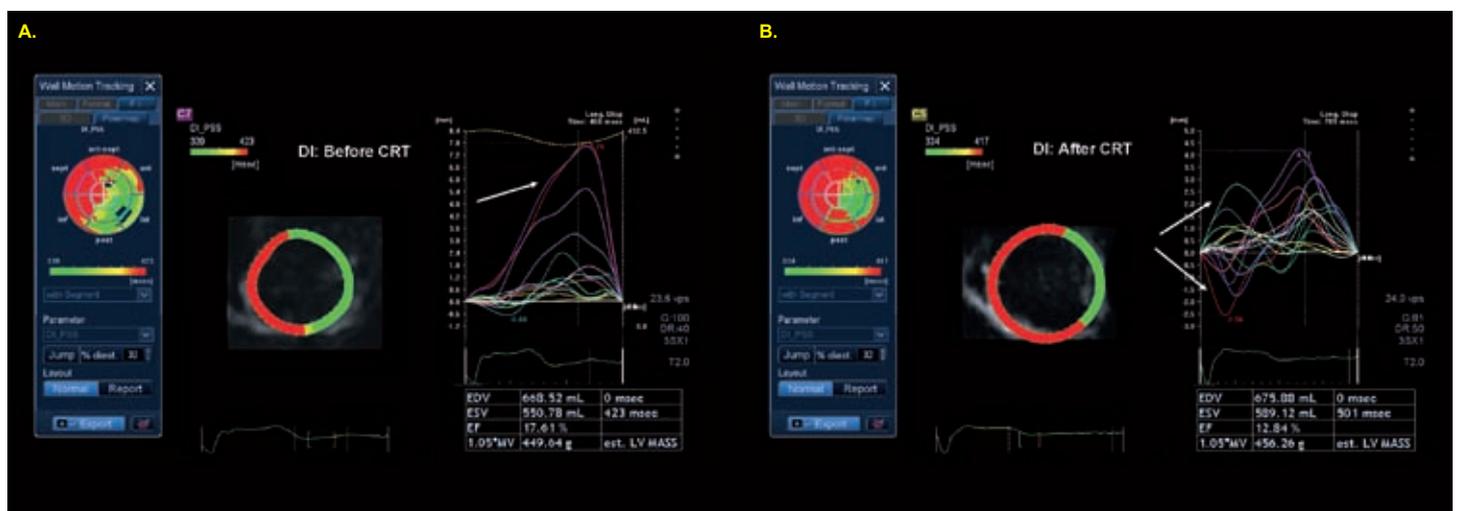


Fig. 7: 3D Dyssynchrony Imaging before and after CRT. There was an increase in red (B) within the polar map compared to baseline (A). Panel B shows the corresponding displacement waveforms. This patient had bi-directional motion consistent with worsening dyssynchrony (arrows).

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