Three-Dimensional Speckle Tracking Echocardiography
– A Promising Tool for Cardiac Functional Analysis –

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Speckle tracking echocardiography (STE) was popularized in the first decade of this century. Analysis of cardiac mechanics has been the focus of ultrasonics, and the breakthrough came with STE. Beyond analysis solely of left ventricular ejection fraction, STE allows the assessment of various pathophysioligies, including myocardial layer-specific myocardial function, twist and rotation, and dysynchrony. Recent developments in the technology have resulted in commercially available 3-dimensional (D)-STE systems. Through experimental studies and clinical investigations, the reliability and feasibility of 3D-STE-derived data have been validated, and the advantages of 3D-STE over 2D-STE have been revealed. In addition, because of the 3D nature of the technology, 3D-STE provides novel deformation parameters (ie, 3D-strain and area change ratio) that have the potential for more accurate assessment of overall and regional myocardial function. Recently, various preliminary studies using 3D-STE have reported on myocardial characteristics, novel mechanics in the left ventricle, prediction of therapeutic effects, observations of cardiac function through interventions, and challenges for left atrial and right ventricular functions. In this review, we focus on the features of the methodology, validation, and clinical application of 3D-ST. (Circ J 2014; 78: 1290–1301)

Key Words: Cardiac function; Speckle tracking; Three-dimensional echocardiography

Left ventricular (LV) ejection fraction (EF) has been the gold standard for assessing the function of this chamber, but has several limitations; of particular importance is that LVEF is obtained from end-systolic and end-diastolic volumes with tracing endocardial borders of the LV in each phase, and is not equal to the intrinsic myocardial function. Therefore, further methodological developments were expected, and the first clinical breakthrough came with speckle tracking echocardiography (STE), which allows for the clinical assessment of myocardial function through analysis of myocardial deformation. This was followed by the introduction of commercially available 3-dimensional (D)-STE systems. In this review, we focus on the features of methodology, validation, and clinical applications of 3D-STE.

From 2D to 3D STE

‘Speckles’ are natural acoustic markers that move together with the tissue. In addition, speckled structures are temporally stable and do not change their pattern significantly between adjacent frames of the ultrasound tissue image. Accordingly, ‘speckle tracking’ is a method of estimating the location and vector of regional myocardium on sequential B-mode images. However, tracking of a specific speckled pattern incurs a risk of tracking error, and the block-matching method has been used to improve tracking accuracy. In this way, 2D-STE has been used widely in assessing myocardial tissue tracking. However, 2D imaging has several limitations. First, full LV segmental data are obtained from multiple planes in different cardiac cycles. Because of this non-simultaneous data acquisition, myocardial function may be altered beat by beat during unstable cardiac conditions. Second, the whole heart moves through the 2D plane of interest. Therefore, the 2D plane of interest disappears through a cardiac cycle, which is well known as the ‘through-plane’ or ‘out-of-plane phenomenon’. 3D full-volume LV data acquisitions have the potential to overcome the limitation of plane-dependency of 2D imaging, the details of which are discussed later.

Wall Motion Tracking Method

Several methods have been used for 3D-STE. First, the block-matching method has been widely used in the clinical setting (Figure 1). The motion vector between consecutive volume frames is detected by a cubic matching technique. The most similar point in the next volume is searched for by comparing a template volume in the next volume. Finally, interpolation of the motion vectors is performed with a 3D interpolation algorithm. After these steps, arbitrary points of interest on the cardiac wall can be tracked by integrating the interpolated motions over all frames during 1 cardiac cycle. Second is the elastic or non-rigid image registration method. Image-warping techniques

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Analysis of 3D wall motion of the LV requires the acquisition of a full-volume dataset from the cardiac apex. To obtain the 3D dataset, multiple sectors are scanned and automatically integrated into a wide-angle pyramidal data image covering the entire LV.\textsuperscript{4} In the current systems, the volume rate of each sector image is set at approximately 30Hz or more. The 3D datasets are displayed as multiplanar reconstruction images, which generally correspond to apical 2- and 4-chamber views and 3 short-axis levels (Figure 2). Next, both the endocardial and epicardial borders are identified by tracing. There are several

**Figure 1.** Speckle tracking echocardiography. (A) Block-matching method. \textbf{Left panel:} tracking is performed by searching the region (white arrows and red dashed line squares) in the next frame (t\(_1\)), which is the most similar to the region of interest (ROI; solid red square) in the baseline frame (t\(_0\)). Tracking the specific ROI is vulnerable to tracking error. Thus, tracking is performed using a block around the ROI (orange area). \textbf{Right panel:} motion of the ROI between frames can be quantified as a vector (black arrow). (B) Similarly, images of speckle tracking on the 2-dimensional B-mode images are modeled after those in (A). (C) The 3-dimensional speckle tracking method of the volume of interest (red line cubic template) from one volume (starting volume) to the next volume (white dashed line cubic template).
Figure 2. Parametric images of multiplanar reconstruction, strain-time curves, and 3-dimensional (D) and polar map images. Three types of parametric images are obtained by different vendor systems in a representative normal control subject. (A) Multiplanar reconstruction (MPR) images, global longitudinal strain-time curve, left ventricular (LV) 3D image, and a polar map are shown. In this vendor system, the borders in the MPR images were fully manually traced. (B) MPR images, regional and global longitudinal strain–time curves, and a polar map are shown. In this vendor system, after the points at the mitral annular level and endocardial apex were manually chosen, sequential tracings were automatically performed. (C) MPR images, global longitudinal strain-time curve of 2 cardiac cycles, 3D LV images, and a polar map are shown. In this vendor system, the 3D datasets were obtained from a single cardiac cycle, and the borders were traced fully automatically. The percentage shown in each panel is the peak global longitudinal strain value. Note the differences in strain data values between the different vendors.
3D-STE for Cardiac Function Analysis

Advantages of Assessing Myocardial Deformation

STE can measure a length between tracking points frame by frame and allows for the calculation of LV global and regional myocardial deformation. This deformation is known as ‘strain’, which is a measure of deformation representing shortening or expansion of an object and is defined as follows: strain = (L_t - L_0) / L_0, where L_0 is initial length and L_t is length at time t. Unlike velocity or displacement, strain is unaffected by the motion of the entire heart and therefore is more suitable for regional wall motion analysis.

The advantage of 3D-STE is the simultaneous computation of various wall motion parameters, in particular, the 3 orthogonal strain values (radial strain (RS), longitudinal strain (LS), and circumferential strain (CS)) in the entire LV myocardium. It is important to know that each strain reflects abnormality of a different myocardial layer. In the subendocardium, the myofibers are oriented longitudinally. The angle of the myofibers toward the horizontal axis continuously decreases toward the mid-wall, where the myofibers are oriented in the circumferential direction, and decreases further to change to an opposite oblique orientation in the subepicardium. Accordingly, longitudinal contraction depends on the subendocardial layer. However, transmural involvement of myocardial injury leads to a reduction in LV circumferential and torsional deformation and results in a decreased EF. Therefore, the combination of multiple deformation indices provides insight into the pathophysiologic mechanics of LV dysfunction.

To recognize additional detail of LV myocardial deformation, types of border tracing: full automatic tracing of both the endocardial and epicardial borders, manual tracing of the endocardial border and automatic tracing of the epicardial border based on the endocardial border trace, and full manual tracing. Even if automatic tracking is performed, verification and manual adjustment need to be performed when necessary on the basis of the 2D cross-sectional planes. The software further automatically divides the LV into 16 or 17 segments for the assessment of magnitude and timing of regional myocardial deformation.

Figure 3. Deformation parameters. (A) Three-dimensional (D) left ventricular images, in which the blue mesh corresponds to the epicardial border and the white to the endocardial border. (B) Myocardial block at end-diastole. R_0 = baseline length between endo- and epicardium, L_0 = baseline longitudinal length at the endocardium, C_0 = baseline circumferential length at the endocardium. (C) Myocardial block at end-systole, which has moved toward the apex (La). R_t, C_t, and L_t are the lengths at end-systole between the tracked points by the 3D-speckle tracking method. Although R_t1 and C_t are the estimated lengths at the same level as in end-diastole, which correspond to the lengths in the 2D strain calculations. Therefore, the principle strains are calculated as follows: 3D-RS: (R_t-R_0)/R_0, 3D-CS: (C_t-C_0)/C_0, 3D-LS: (L_t-L_0)/L_0. 2D-RS: (R'_t-R_0)/R_0, 2D-CS: (C'_t-C_0)/C_0. (D) Block with deformation including shear strain. If the shear α degree is between the radial and longitudinal directions, the shear β degree is between the radial and circumferential directions, and without shear is between the circumferential and longitudinal directions, the length between the estimated endo- and epicardial points at end-systole is R_3D. The novel parameter 3D-strain is calculated as (R_3D-R_0)/R_0, so 3D-strain is greater than 3D-RS because R_3D is longer than R_t. (E,F) Endocardial surface at end-diastole and -systole, respectively. An area A_0 is relocated and deformed to an area A_t by various wall motions including apical translation, regional rotation that causes shear strain, and longitudinal and circumferential contractions. The area change ratio is calculated as (A_t-A_0)/A_0.
Spatial distribution of torsion values. The parameter of regional torsion is measurable and represents the distance between the planes. Therefore, the novel parameter the ‘ACR’, because the strain principally indicates changes of a unit length, not an area. The ACR of the endocardial layer of the myocardium. The white double arrow shows longitudinal deformation in the endocardial, the yellow one is the mid-cardium, and the blue one is the epicardium. The white double arrow shows longitudinal deformation in the endocardium, and the yellow one shows circumferential deformation in the mid-cardium.

Validation of the Reliability of 3D-STI Measures

In our experimental study of the block-matching method, strong correlations between strain measurements by 3D-STI and sonomicrometry were observed (LS: $r=0.89$, RS: $r=0.84$, CS: $r=0.90$). Of these correlations, CS and LS showed better accuracy for estimation of regional deformation than did RS. In the validated system, LS and CS are calculated at the endocardial border, whereas RS is estimated by tracking of both the endocardial and epicardial borders, which may increase the tracking errors. In addition, because the fundamental length for RS calculation is shorter than those of LS and CS, RS is more vulnerable to tracking errors.

ACR also was validated in a similar experimental study, and its measurement by 3D-STI was found to strongly correlate with that by sonomicrometry ($r=0.87$). ACR was more sensitive to changes in regional deformation compared with LS and CS. The sensitivity of ACR may be created by combining the deformation data in 2 orthogonal directions, because ACR can be expressed as a total sum of the product of LS and CS and the sum of them as follows: $\text{ACR}=\text{LS} \cdot \text{CS}+\text{RL} \cdot \text{LS}+\text{CS}$. In practice, ACR shows significant relations with both LS and CS (LS: $r=0.73$, CS: $r=0.79$). Additionally, combining the data for 2 directional deformations can reduce the tracking error because of higher signal-noise ratio compared with that of LS and CS. Further, the endocardial site is more sensitive to myocardial ischemia than the epicardial site because of the myocardial ischemic cascade. Thus, ACR may be a reliable parameter of myocardial deformation.

As for rotation measurements, a validation study using pig hearts mounted on a 2-axis linear/rotary system reported that both 3D- and 2D-STI showed the degree of rotation; however, the biases of overestimation by 3D-STI were smaller than those by 2D-STI.

Clinical Issues Associated With 3D-STI

B-Mode Image Quality

The accuracy of STE measurements strongly depends on the B-mode image quality. Because 3D datasets are acquired from the cardiac apex, image quality in the anterior regions is poorer than in other regions, which affects the reliability of the strain data. Accordingly, caution needs to be taken when interpreting strain data in a segment with poor B-mode image quality.

Because full-volume LV datasets comprise multiple sectors, the artifact occurring around the border between sectors, primarily caused by breathing, may affect the reliability of speckle tracking. In addition, the system is not suitable for use in patients with beat-to-beat variability, mainly atrial fibrillation. To overcome this limitation, recent advanced systems allow the entire 3D dataset to be obtained from a single beat (Figure 2).

System-Related Issues

3D-STI has a limitation of temporal resolution. Although an optimal volume rate has not yet been recommended, the strain value may be underestimated in conditions of inappropriate lower volume rate because the tracking points to obtain accurate maximum and minimum myocardial lengths may be lost. However, compared with earlier systems the latest systems have a relatively higher volume rate of more than 50 volume/s, but a higher than necessary volume rate degrades the image quality, which causes tracking errors. Yodwut et al studied the effect of volume rate on strain data and concluded that 3D-STI allowed quantification similar to that of 2D-STI at a relatively lower volume rate (18 with 4-beat or 25 with 6-beat 3D datasets). This may be attributed to the ability of 3D imaging to acquire complex ventricular systolic mechanics without the limitations imposed by through-plane motion.

Another important issue is the vendor-dependent variability of deformation data (Figure 2). Gayat et al emphasized that as with 2D-STI, the high vendor dependence of 3D-STI data means that inter-vendor discordance of data must be taken into account when interpreting 3D deformation data.
Figure 5. Effects of longitudinal displacements for 2-dimensional (D)- and 3D-circumferential strain (CS). (A) Correlation between longitudinal displacement and the absolute difference between 2D- and 3D-CS. DCM, idiopathic dilated cardiomyopathy. (B) Left ventricular (LV) segmental comparisons of longitudinal displacement between controls (blue dots) and DCM patients (pink dots). (C) LV segmental comparisons of correlation between longitudinal displacement and absolute difference in CS.
Figure 6. Correlations of deformation parameters with left ventricular ejection fraction (LVEF). Each left panel shows the correlation in total subjects, each center panel shows the correlation in the subgroup with LVEF <50%, and each right panel shows the correlation in the subgroup with LVEF ≥50%. Circumferential strain, longitudinal strain, and area change ratio are plotted as absolute values.
Reproducibility
Intra- or inter-observer variability occurs to some extent in strain measurements. As confirmed in our experimental studies, the variability is greater for RS values than for other parameters. In clinical studies also, reproducibility of RS is lower than for LS, CS, and ACR. In almost all of the clinical studies, which are discussed later, the absolute differences of RS between 2 repeated measurements were greater than 10%. In contrast, intra-observer variabilities of LS, CS, and ACR were less than 10%, and inter-observer variabilities were approximately 10%. Among them, the best reproducibility was revealed for ACR measurements. All studies reported that both intra- and inter-observer variabilities were ≤8%. In addition, the intra- and inter-observer variabilities of 3D-STE are equal to or better than that of 2D-STE, despite the complex computations of 3D-STE. This may be related to the full-volume data acquisitions and automatic or semi-automatic measurement.

Differences Between 2D- and 3D-STE Clinical Data
Previous studies compared global 2D- and 3D-STE-derived strain values in normal control subjects and patients with heart disease. The common finding was that absolute CS values by 3D-STE are significantly higher than those by 2D-STE. In contrast, LS values do not differ between 3D- and 2D-STE. Recently, Wu et al showed that through-plane motion produced discrepancies in CS measurements, especially at the LV basal level. In addition, LV twisting affects the LS values: larger twisting is a major determinant of differences between 2D and 3D LS values. In our study also, the absolute differences between 3D and 2D CS correlated significantly with the magnitude of longitudinal displacement (Figures 3C, 5). In normal subjects, the differences between 3D and 2D LS were more significant in the free wall, in which longitudinal displacements were larger than those in the septum. In contrast, the discrepancy was not present in patients with dilated cardiomyopathy, in which longitudinal displacements were much less than those in the normal control subjects. These findings suggest that 3D-STE can overcome LV translation and rotation effects for quantification of ventricular contraction.

Clinical Implications
LV Volume Measurements
Because 3D-STE tracks the LV endocardial boundaries, it can directly measure LV volume throughout a cardiac cycle. Kawamura et al reported that compared with cardiac magnetic resonance imaging (MRI), 3D-STE showed a tendency to underestimate LV volume measurements but not significantly (end-diastolic volume: bias=−18±37 ml; end-systolic volume: bias=−10±34 ml), and measurements correlated well with those by cardiac MRI (end-diastolic volume: r=0.80, end-diastolic volume: r=0.86).

LV Global Function
LV global strain has received attention as a parameter of global LV function. In our study (n=97, EF range: 13–78%), CS showed better correlation with LVEF than LS and RS (CS: r=0.92, LS: r=0.87, RS: r=0.73, P<0.001) (Figure 6). In the lower range of EF (<50%), LV contraction depends on the systolic strain of circumferential direction because LS changes in a relatively narrow range (CS: r=0.83, P<0.001; LS: r=0.63, P=0.001; RS: r=0.47, P=0.01). In patients with preserved EF (≥50%) also, CS showed a moderate but better correlation with LVEF than did LS and RS (CS: r=0.65, P=0.001; LS: r=0.50, P<0.001; RS: NS, P=0.08). We should note the weaker correlation of LS with LVEF. LS might be associated with intrinsic myocardial function, particularly in patients with preserved LVEF. ACR is an equal or more reliable surrogate of LVEF (r=0.93) compared with the principle strains (Figure 6). Recent reports also found that ACR is the most reliable surrogate of LVEF.

Recently, Kaku et al reported age-related differences associated with LV strain and torsion in healthy subjects. In particular, global LS showed age dependency, which was significantly reduced in adulthood compared with childhood. In addition, there are small maturational changes in global LS and global CS even in children from birth to 18 years. The differences may reflect myocardial maturation and aging.

LV Regional Function
Judgments of regional wall motion abnormalities are the most common assessment made, but are not an easy matter in the clinical setting. 3D-STE has the potential to more accurately detect wall motion abnormalities compared with ‘eyeball’ judgments or 2D-STE. Kleijn et al reported disagreement (55%) between ACR and visual assessment in assessing hypokinesia compared with high agreements in 94% of normal and 91% of akinetic segments. The lower percentage of agreement for hypokinetic segments may be attributable to subjective judgments, because agreement between 2 observers for visual assessments was low (57%). Therefore, ACR allows more accurate differentiation between normokinesia and regional wall motion abnormalities compared with visual assessments.

Hayat et al reported the usefulness of 3D-STE to identify the transmural extent of scar on late enhancement images by MRI in patients with ischemic heart disease. 3D LS, but not 2D LS, and ACR could distinguish the segments with subendocardial infarction from those with more extensive infarction. In contrast, 3D strain and 3D RS were significantly lower in segments with transmural infarction only, despite there being no differences between normal and non-transmural infarction. The findings sought to depend on the wall thickening mechanism; the epicardial layer may contribute more to wall thickening in the non-transmural infarction compared with normal thickening. Those studies suggest that analysis of regional deformation with 3D-STE is feasible by objectively assessing regional wall motion abnormalities and the extent of myocardial scar.

Dyssynchrony
Ever since cardiac resynchronization therapy (CRT) was established as therapy for advanced heart failure patients with LV dyssynchrony, assessment of LV mechanical dyssynchrony has been a focal issue. Compared with 2D-STE, 3D-STE provides more accessible images for the analysis of LV dyssynchronous wall motion by showing temporal changes of strain distribution over the entire LV chamber. In patients with left bundle branch block, who have the most typical indication for CRT, the initial contraction is observed in the mid to apical septum; next, the contraction propagates to the basal lateral wall, turning at the apex. This propagation pattern has been confirmed as the typical dyssynchrony pattern of left bundle branch block in a previous study using an electrical 3D mapping system. Recently, we developed a novel 3D-STE system to visualize mechanical activation, called ‘activation imaging’ (Figure 7A). The concept of activation imaging is to visualize the onset of regional mechanical activation modeled after that of electrical mapping systems. The activation imaging quantifies a time from the onset of the QRS to the onset of regional deformation in 16 LV segments. This imaging allows identification at a glance...
Figure 7. Representative cases from clinical studies. (A) Dyssynchrony images with activation imaging. Upper figures were obtained at baseline, and lower ones after cardiac resynchronization therapy (CRT). The color bar in each figure is the activation time from QRS onset. Left-hand images are from the septum, and blue areas are the earliest activation sites. Right-hand images are from the free wall, and yellow or orange areas are the latest activation sites. Note the blue area on the image after CRT, which corresponds to the left ventricular pacing site and equates to resynchronization. (B) Right ventricular (RV) multiplanar reconstruction (MPR) 3-dimensional-STE images using mesh imaging, and time-area change ratio curves in a healthy subject. Lower left panel shows the RV-STE at end-diastole, the center panel at mid-systole, and the right panel at end-systole. (C) The end-diastolic (Left) and end-systolic (Right) images from a 75-year-old women with sepsis at the onset of takotsubo cardiomyopathy (Upper) and 1 month after (Lower) (our case). (D) Left atrial tracking images in a 45-year-old man with paroxysmal atrial fibrillation (our case). Lower left panel shows the LA-STE at pre-atrial kick, the center panel at end-atrial kick shows the smallest volume, and the right panel at end-systole shows the largest volume.
of the earliest and latest segments on the images, which is helpful to determine the optimal LV lead position, as well as quantifying the LV dysynchrony. In addition, various propagation patterns of LV activation deserve special attention for predicting CRT response. To date, evidence for the role of echocardiography in predicting CRT response has accumulated from various standpoints, including myocardial viability in the segment for lead replacements, severity of mitral regurgitation, LV filling abnormality, except for intraventricular dysynchrony quantification. Therefore, 3D-STE may be a breakthrough in resolving these persistent issues.

Right ventricular (RV) Function Analysis

RV function is a particular concern in patients with left heart failure.43–46 Accurate calculations of RV volume and function are difficult because of the fundamentally complex geometry of the RV chamber. However, we reported a preliminary study of RV 3D-STE using a modified system for the LV (Figure 7B).46 Interestingly, there were intraventricular differences in the systolic ACR values and in contraction timing, even in normal control subjects. In the comparison of RV dysfunction and control subjects, ACR was significantly lower in patients with RV dysfunction. Similarly, Yu et al reported that RV ACR was impaired in association with RV dysynchrony, volume overloading, and reduced EF in adults after tetralogy of Fallot repair.47 The use of 3D-STE for RV wall motion analysis is still challenging. However, 3D wall motion analysis will be especially useful, precisely because of the complex nature of the RV.

Novel Insights From Clinical Studies

The superiority of 3D-STE has been reported for assessing both the pathophysiology of various cardiac diseases and the changes in cardiac performance following treatments. Baccouche et al reported a case of takotsubo cardiomyopathy and noted that 3D-STE was a quick and feasible tool for assessing the extent of the wall motion abnormality and for follow-up (Figure 7C).48 This is the advantage of 3D speckle tracking imaging. Hypertension is a common risk factor of heart failure, and LV functional abnormalities have been revealed with 3D-STE in patients with subclinical hypertension.49,50 In addition Wen et al showed that the ACR differed between normal controls and early stage heart failure patients.32 In addition, the ACR was reduced even in patients with aortic valve diseases and NYHA class I or II.51 Thus, subclinical intrinsic myocardial dysfuncation may be detectable by 3D-STE, and the ACR is a sensitive parameter of early and subtle LV systolic dysfunction. Miyoshi et al reported a clinically important study of chemotherapy-induced LV deformation abnormalities.52 They demonstrated that a reduced ACR was associated with the use of anthracycline, even in patients with preserved LVEF, and recommended this modality as an advisory tool for the oncologist. Urbano-Moral et al reported that 3D-STE-derived, but not 2D-derived, global LS was independently associated with NYHA functional class in heart transplant recipients, which suggests a clinically relevant relation between functional status and 3D myocardial mechanics in heart transplant recipients.53 In primary or secondary cardiomyopathies, late gadolinium-enhanced MRI has been widely used to identify myocardial characteristics, but 3D-STE also has the potential to provide additional information on myocardial characteristics. Matsumoto et al reported novel insights of the LV mechanics of dilated cardiomyopathy.54 In addition, they studied the relations between prognosis and contractile reserve in dilated cardiomyopathy with dobutamine stress echocardiography and revealed that an increase in the 3D global CS under dobutamine infusion was the best predictor of cardiovascular events.55 Baccouche et al found differences in the RS gradient patterns from base to apex between cardiac amyloidosis and hypertrophic cardiomyopathy.56 In cardiac amyloidosis, the apical RS was greater than the basal RS; in contrast, apical RS in hypertrophic cardiomyopathy was smaller than either mid or basal RS. Changes in LV mechanics after operations have been assessed by 3D-STE. Li et al reported the usefulness of 3D-STE in the comprehensive evaluation of LV mechanics in repaired tetralogy of Fallot patients both before and after pulmonary valve replacement.58 Schuete et al demonstrated a significant correlation between functional LV improvement determined with 3D-STE and the clinical course in patients after transcatheter aortic valve implantation.59 Left atrial function analysis may provide additional information over that of left atrial volume calculations to identify patients at high risk of atrial fibrillation (Figure 7D). Mochizuki et al revealed the ability of 3D-STE in the left atrium for identifying patients with paroxysmal atrial fibrillation compared with using 2D-STE parameters.58 Finally, in this era of multimodality imaging, 3D-STE has the potential to merge with other types of 3D imaging, which may provide a breakthrough for 3D echocardiography.59

Conclusions

For the past decade, experimental and clinical studies have validated the reliability of 3D-STE and found various advantages specific to the nature of 3D imaging. Combined with current technological advancements, 3D-STE holds great promise as a reliable and feasible tool for evaluating both overall and regional myocardial function. Beyond the cardiac function assessments solely provided by the LVEF, clinical investigations using 3D-STE are only just beginning.

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