Cardiovascular Ultrasound

REVIEW

Transthoracic echocardiographic assessment of ventricular function in functional single ventricle: a comprehensive review

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Abstract

Background Functional single ventricle represents a complex congenital cardiac malformation where ventricular function directly impacts patients' quality of life and prognosis. Accurate assessment of ventricular function in FSV patients is crucial for treatment planning, surgical intervention, and monitoring therapeutic efficacy.

Main text Echocardiography, as a non-invasive, readily available, and real-time cardiac imaging modality, has emerged as the preferred method for evaluating functional single ventricle ventricular function. With continuous advancement and innovation in echocardiographic technology, methods for evaluating functional single ventricle ventricular function have become increasingly diverse and refined. This review synthesizes recent research developments in echocardiographic assessment of functional single ventricle ventricular function and analyzes the advantages, limitations, and future applications of various techniques.

Conclusion Strain and strain rate derived from two-dimensional speckle tracking imaging have progressively entered clinical application, demonstrating substantial potential as crucial parameters for evaluating single ventricular function. Emerging technologies, including three-dimensional speckle tracking imaging and non-invasive pressure-strain loops, show promise for contributing to multi-dimensional, integrated assessment as research continues to advance.

Keywords Functional single ventricle, Echocardiography, Speckle-tracking imaging, Ventricular function

Introduction

Functional single ventricle (FSV) represents a complex congenital cardiac malformation characterized by one dominant ventricle and an underdeveloped or hypoplastic subsidiary ventricle, with true isolated single ventricle being extremely rare [1]. Despite advances in surgical techniques and perioperative care, FSV patients continue to experience significant mortality [2]. Multiple factors influence clinical outcomes in these patients, including ventricular volume overload, chronic cyanosis, and elevated pulmonary vascular resistance. Previous research has demonstrated that prolonged single ventricle volume overload and persistent cyanosis adversely affect ventricular function, while early intervention to reduce volume overload may improve outcomes [3, 4]. Therefore, timely, accurate, and comprehensive assessment of ventricular function is essential for optimizing therapeutic strategies and surgical planning in FSV patients.

Cardiac catheterization provides important indicators for estimating single ventricular systolic and diastolic function, including the peak rate of isovolumic

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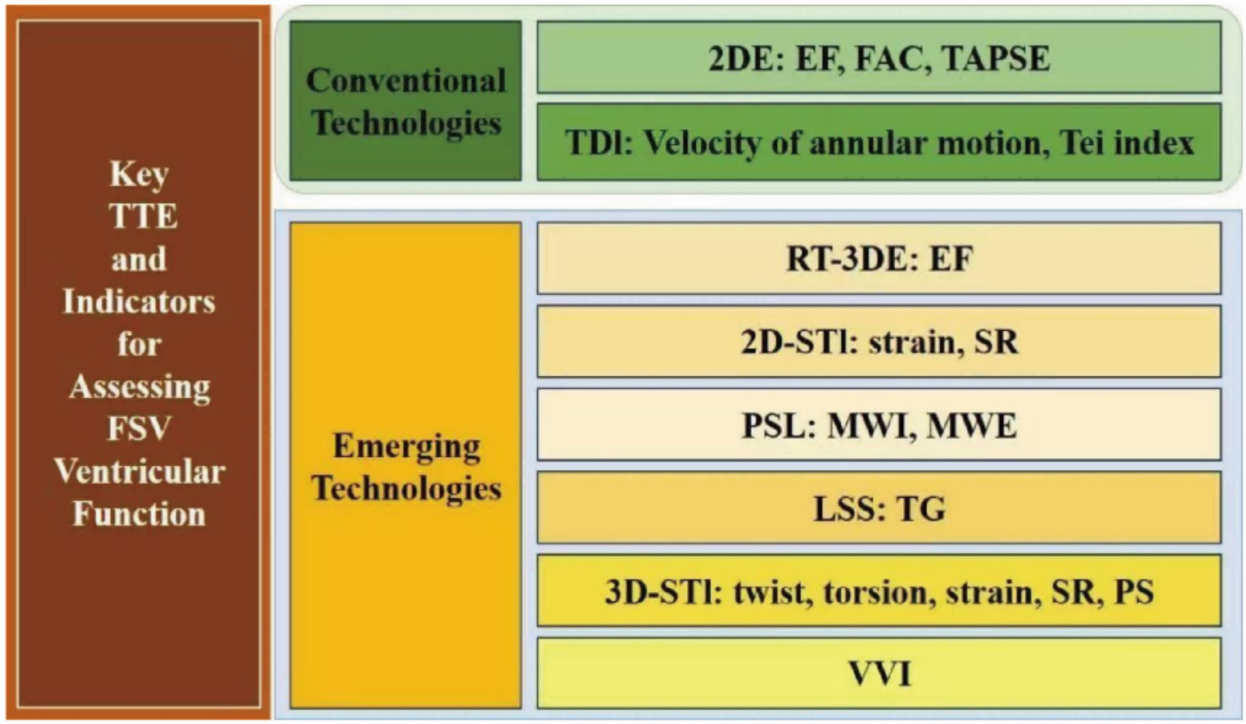
Graphical Abstract



ventricular pressure rise [Max(dp/dt)] and ventricular end-diastolic pressure (VEDP) [2]. However, this invasive approach carries inherent risks and is unsuitable for serial evaluations. While cardiac magnetic resonance (CMR) imaging offers non-invasive assessment independent of ventricular geometry, its clinical utility is limited by lengthy acquisition times, acoustic noise, and frequent requirement for sedation or anesthesia in infants and young children [5]. Consequently, echocardiography has become the principal modality for assessing FSV functional status, offering direct visualization of ventricular morphology, chamber dimensions, myocardial wall thickness, and dynamic motion patterns. This non-invasive technique simultaneously provides comprehensive insights into both systolic-diastolic performance and hemodynamic characteristics, positioning it as an indispensable tool in clinical evaluation.

Traditional echocardiographic parameters for ventricular function assessment are predominantly qualitative or semi-quantitative. Qualitative evaluation relies heavily on observer experience, potentially introducing significant inter-observer variability, while quantitative methods are limited by load dependency and geometric assumptions [6]. These approaches lack reproducibility and standardization, and their sensitivity to preload and afterload changes makes them particularly unsuitable for FSV cases with complex geometric morphology. These limitations have driven the development of more objective and reproducible cardiac function measurement techniques.

The assessment of FSV function presents unique challenges due to several factors: complex and variable anatomical structures, myocardial scarring from multiple staged surgeries, alterations in ventricular loading conditions, and various degrees of ventricular remodeling. These factors lead to changes in myocardial cell composition, structure, and fiber arrangement, affecting ventricular systolic and diastolic motion patterns.

This review systematically consolidates conventional and emerging echocardiographic methodologies for FSV ventricular function assessment, evaluates their clinical applicability and accuracy, and highlights existing knowledge gaps alongside future research priorities. By synthesizing these advancements, this work aims to guide clinicians in tailoring imaging modality selection to individualized patient needs, optimize longitudinal monitoring strategies for single ventricle populations, and ultimately improve quality of life outcomes in this distinct patient cohort.

Conventional imaging techniques

Two-dimensional echocardiography (2DE)

Two-dimensional echocardiography-derived ejection fraction (EF) remains widely utilized for cardiac function evaluation, offering procedural simplicity and established correlation with clinical outcomes across diverse patient populations. However, EF assessment presents several inherent limitations that warrant consideration [7].

The primary limitations of EF include low sensitivity for early dysfunction detection and significant load dependence [8]. Ventricular dysfunction may be present despite preserved EF through compensatory mechanisms, while severe EF reduction typically indicates advanced ventricular impairment [9]. Consequently, EF demonstrates limited utility in detecting subclinical ventricular systolic dysfunction and offers restricted prognostic value. Furthermore, as a global functional parameter, EF inadequately assesses regional myocardial function, compromising its reliability for comprehensive cardiac function evaluation [10].Of particular relevance to FSV patients, EF measurement relies on geometric assumptions that often prove invalid given the diverse ventricular geometries encountered in this population [9].

Conventional metrics such as fractional area change (FAC) and tricuspid annular plane systolic excursion (TAPSE) demonstrate limited clinical utility in FSV functional assessment, with studies revealing no distinct advantages over alternative parameters in this population [11, 12].

Tissue doppler imaging (TDI)

Tissue Doppler imaging employs Doppler principles to quantitatively assess myocardial motion velocity [13]. Available on most contemporary echocardiography platforms, TDI offers a non-invasive approach for monitoring ventricular function in FSV patients.

Notable disparities in tissue Doppler imaging (TDI) parameters exist between FSV patients and healthy controls. Both single left ventricle (SLV) and single right ventricle (SRV) cohorts exhibit marked reductions in systolic peak velocity, early diastolic peak velocity, and late diastolic peak velocity within the ventricular free wall. Concurrently, these patients demonstrate elevated Tei indices, further corroborating impaired ventricular mechanics [14].The Tei index, being a time ratio, provides geometry-independent ventricular function measurements and correlates well with the invasive measurement Max (dp/dt), suggesting its feasibility in evaluating single ventricle function [14, 15].

Post-Fontan FSV patients typically exhibit ventricular diastolic dysfunction, characterized by reduced early diastolic peak velocity at the mitral annulus and decreased ratio of early to late diastolic velocities, even in the presence of preserved systolic ejection fraction [15, 16]. This observation underscores TDI's enhanced sensitivity in detecting and monitoring diastolic dysfunction progression.

Despite its clinical utility, TDI presents inherent limitations. As with all Doppler-based techniques, TDI exhibits angle dependency, capturing only motion vectors parallel to the ultrasound beam. Adjacent myocardial segment interactions may additionally distort velocity measurements through mechanical tethering effects. Furthermore, the Tei index demonstrates load sensitivity and provides solely global functional assessment, lacking the capacity to differentiate isolated systolic or diastolic dysfunction or quantify dysfunction severity. These constraints necessitate cautious interpretation of TDI-derived data.

Advanced echocardiographic technologies

Real-time three-dimensional echocardiography (RT-3DE)

Complex congenital heart diseases, particularly FSV often accompanied by multiple anomalies such as patent ductus arteriosus, atrial septal defect, and great artery transposition, frequently present spatial relationships that exceed the capabilities of 2DE visualization. While three-dimensional echocardiography (3DE) was developed to overcome 2DE limitations, it still relies on high-quality two-dimensional images for three-dimensional reconstruction, making it complex, time-consuming, and susceptible to respiratory interference [17].

RT-3DE enables acquisition of three-dimensional cardiac dynamic images independent of specific timing and orientation constraints, facilitating improved visualization of ventricular spatial relationships and dynamic changes without relying on geometric assumptions [18]. This advancement represents a significant step toward accurate and reliable FSV function assessment.

Studies have shown good correlation between ventricular volumes and ejection fraction measured by RT-3DE and CMR [19]. However, RT-3DE tends to underestimate ventricular volumes and EF in SRV compared to CMR, potentially due to the exclusion of trabeculations from volume calculations. In patients with hypoplastic left heart syndrome (HLHS), RT-3DE has demonstrated good reproducibility for evaluating right ventricular volume and EF, enabling continuous assessment of cardiac function changes [20].

RT-3DE is limited by its suboptimal frame rate, and pre-Fontan functional single ventricles' ventricular overgrowth and eccentric hypertrophy sometimes make the single ventricle too large to be completely contained in one view [21, 22]. These factors limit RT-3DE's use in functional single ventricles.

Speckle tracking imaging (STI)

Two-dimensional speckle tracking imaging (2D-STI)

2D-STI can quantify global and regional cardiac function in FSV(Fig. 1). Its strain parameters have been proven to correlate with catheterization and cardiac magnetic

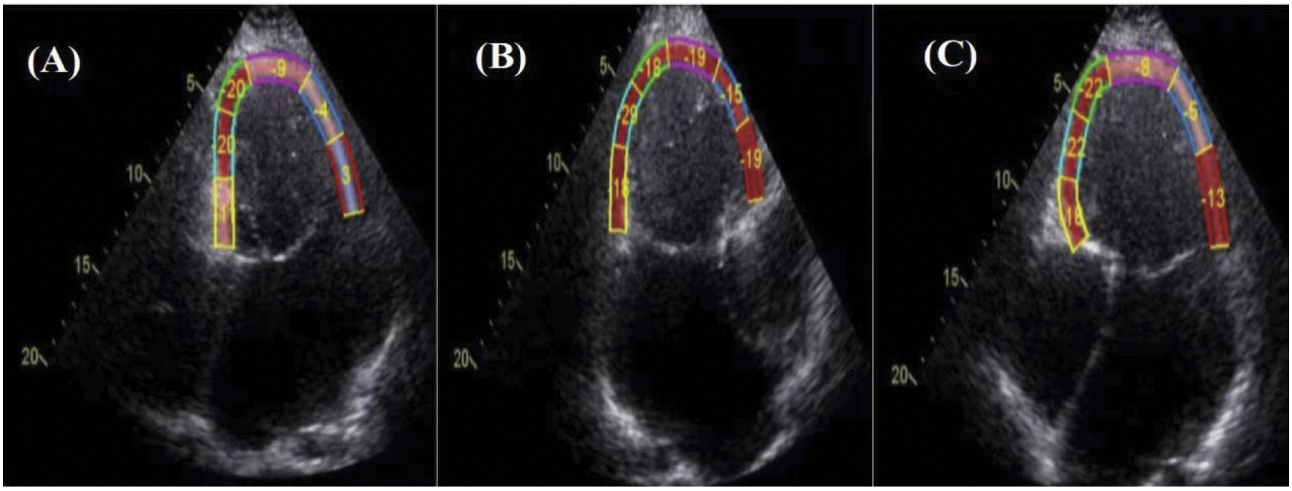


Fig. 1 Images from 2D-STI of FSV. Images for two-dimensional speckle-tracking imaging of the functional single ventricle: (**A**) apical 2-chamber view; (**B**) apical 3-chamber view; (**C**) apical 4-chamber view. Abbreviations: FSV, functional single ventricle;2D-STI, two-dimensional speckle tracking imaging

resonance indices, indicating that 2D-STI can accurately assess ventricular function through non-invasive, more convenient means [23, 24]. Studies have shown that SLV patients have significantly higher circumferential strain and strain rate, longitudinal strain and strain rate compared to SRV patients [25]. Notably, strain indicators demonstrate superior sensitivity to ejection fraction in detecting subclinical myocardial dysfunction, facilitating early intervention before adverse cardiovascular events occur [26].

2D-STI also enables dynamic assessment of single ventricle cardiac function, providing insights into adaptive myocardial structural changes and ventricular functional impairment. Comparative studies of SRV and SLV patients across different palliative surgical stages have revealed progressive decline in longitudinal and circumferential function in SRV patients, potentially reflecting inherent ventricular functional deficits that deteriorate with age [27]. Additionally, between the first and second stages of palliative surgery, SRV patients demonstrate a transition from predominantly longitudinal to predominantly circumferential contraction, suggesting adaptive myocardial structural changes as the right ventricle adapts to systemic circulation demands [28].

Global circumferential strain (GCS) in post-Fontan patients shows strong correlation with transplant-free survival rates and demonstrates predictive value for post-Fontan outcomes [29]. Recent research has identified decreased longitudinal strain in HLHS patients as a predictor of increased risk for death or cardiac transplantation, establishing strain parameters as valuable tools for risk stratification in FSV patients [30].

The indicators measured by 2D-STI in FSV patients appear to have broad development prospects due to their good accuracy, reproducibility, and role in predicting adverse outcomes in functional single ventricles. We have summarized the characteristics of these indicators in Table 1.

Non-invasive pressure-strain loops (PSL)

PSL analysis integrates non-invasive brachial artery pressure measurements with 2D-STI data to provide novel quantification of myocardial work [35]. Specifically, systolic pressure measured via brachial artery cuff is correlated with cardiac event timing (including isovolumic contraction period, ejection period, and isovolumic relaxation period) to generate ventricular pressure curves. These are then integrated with longitudinal strain data obtained through 2D-STI to generate pressure-strain loops, enabling quantification of myocardial work(Fig. 2).

Myocardial work index (MWI) may be a sensitive indicator of myocardial damage and can predict exercise capacity.In post-Fontan FSV patients, even those with preserved ejection fraction may show significantly reduced MWI. Furthermore, Fontan patients with normal right ventricular function demonstrate significantly lower global work efficiency (GWE) compared to those with normal left ventricular function [36]. However, current PSL research in FSV remains limited, necessitating additional studies to establish its clinical utility. A notable limitation is that myocardial work analysis exclusively utilizes longitudinal myocardial deformation, disregarding work associated with radial and circumferential mechanics, which also contribute to ventricular systolic function. This warrants further investigation into the relationship between multi-directional myocardial deformation and overall myocardial work in future research.

Table 1 Summary of indicators measured by 2D-STI

	Indicators measured by 2D-STI	
	SLV	SRV
Consistency	◆ GCS in good agreement with CMR-measured GCS[26]. ◆ GLS in good agreement with CMR-measured GLS[26, 31].	
Correlation	• Longitudinal Early Diastolic Strain Rate was correlated with the isovolumic relaxation time constant measured by PVL[24].	• SR strongly correlates with VEDP measured by cardiac catheterization[32]. • GSR correlates with parameters measured by PVL[12]. • CS and CSR are related to Ea/Ees measured by PVL[24].
	• GLS shows a significant correlation with CMR-derived EF[23].	
Reproducibility	◆ Good repeatability of GLS[11, 23].	
Control	• Parameters measured by 2D-STI provide a more sensitive indication of differences in cardiac function between normal subjects and patients with SV[33]. • CS in SRV correlates better with indicators of PVL, whereas LS in SLV correlates better with indicators of PVL[24].	
Prognosis		◆ LS has value in predicting the prognosis of SRV[30].
	◆ CS correlates with prognosis in patients with SV after Fontan procedure[34].	

Abbreviations:2D-STI, two-dimensional speckle tracking imaging; SLV, single left ventricle; SRV, single right ventricle; GCS, global circumferential strain; GLS, global longitudinal strain; PVL, pressure-volume loop; SR, strain rate; VEDP, ventricular end-diastolic pressure; GSR, global strain rate; EF, ejection fraction; SV, single ventricle; CS, circumferential strain; LS, longitudinal strain; CSR, circumferential strain rate; Ea/Ees, the ratio of arterial elasticity to end-systolic elasticity

Layer-specific strain (LSS)

LSS is a method that utilizes 2D-STI to make separate strain measurements at different layers of the myocardium.This approach is founded on the anatomical principle that myocardial fibers exhibit layer-specific distribution patterns: endocardial fibers are predominantly oriented longitudinally, while epicardial fibers follow a more circumferential arrangement. These architectural differences result in distinct strain characteristics during cardiac cycles across the different myocardial layers.

Contemporary studies have shown that in healthy individuals, myocardial strain shows a gradual decrease from the endocardial to the epicardial layers [37].Previous investigations predominantly focused on average ventricular strain, potentially overlooking crucial information about layer-specific dysfunction and the differential impact of pathological conditions on specific myocardial layers.

State-of-the-art 2D strain software now incorporates LSS measurement capabilities. Compared to conventional monolayer global longitudinal strain, this technology provides comprehensive deformation data across different myocardial levels, enabling more nuanced assessment of myocardial function. Specifically, layer-specific strain analysis utilizes frame-by-frame tracking of inherent speckle patterns within the myocardial layers on two-dimensional grayscale imaging to quantify myocardial deformation during both systolic contraction and diastolic relaxation.

The derived parameter transmural strain gradient (TG), representing the difference between subendocardial and subepicardial strain, has demonstrated utility in evaluating functional single ventricle contractile reserve. Exercise TG shows negative correlation with CMR-measured EF [38]. However, the irregular morphology and multiple associated anomalies in FSV cases present technical challenges for TG measurement, necessitating further research to optimize its clinical application.

Three-dimensional speckle tracking imaging (3D-STI)

Twist and torsion Cardiac twist motion is closely related to myocardial fiber spiral arrangement, with subepicardial fibers arranged in a left-handed spiral, subendocardial fibers in a right-handed spiral, and middle layer circumferentially. This complex arrangement leads to cardiac twist during contraction, actively pumping blood in and out of the heart. During ventricular contraction, basal and apical segments rotate in opposite directions. The difference between these opposing rotations is expressed as twist value. Dividing twist value by ventricular long-axis length yields torsion value.

Given that twist motion occurs in three-dimensional space, 2D-STI is limited by through-plane motion loss. 3D-STI overcomes this limitation by enabling precise tracking of myocardial speckle movement throughout the three-dimensional cardiac volume, potentially offering more accurate assessment of cardiac twist mechanics. In SLV patients, twist parameters measured by 3D-STI show good reproducibility [39].

Anatomical abnormalities in FSV cases compound twist motion abnormalities.Compared to normal

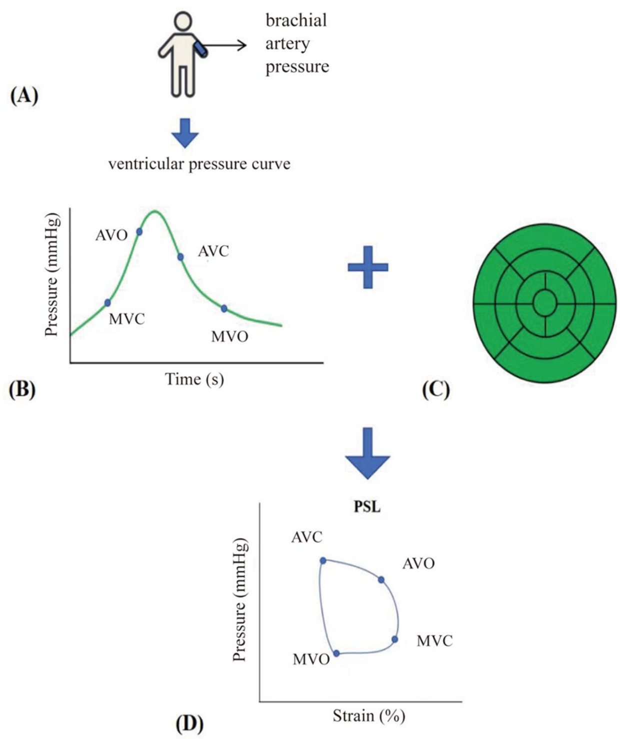


Fig. 2 Schematic representation of PSL acquisition process. (**A**) Brachial artery pressure measurement as a surrogate for ventricular pressure (**B**) Integration of pressure measurements with cardiac event timing to generate ventricular pressure curves. The x-axis represents time, and the y-axis represents ventricular pressure. (**C**) Bull's eye plot generated through two-dimensional speckle tracking imaging (**D**) Pressure-strain loop analysis. The x-axis represents strain, and the y-axis represents ventricular pressure. Abbreviations: FSV, functional single ventricle;2D-STI, two-dimensional speckle tracking imaging

biventricular hearts, structural differences and adaptive ventricular remodeling in response to altered loading conditions may result in compromised twist mechanics, with more pronounced torsion abnormalities observed in SRV cases [40]. Assessment of cardiac function using 3D-STI in post-Fontan SLV children has revealed decreased apical rotation angle, basal rotation angle, and ventricular twist angle compared to controls [39]. These findings may reflect the impact of post-Fontan low preload-induced remodeling, altered ventricular geometry, and reduced compliance.

Both twist and torsion are common parameters for evaluating cardiac twist motion. Torsion better assesses ventricular systolic function than twist angle because it is not affected by age. Decreased twist and torsion may indicate impaired ventricular contractility, and accurate assessment of ventricular twist might be a new method for quantifying ventricular function.

Principal strain (PS) While STI offers numerous advantages in evaluating functional single ventricle cardiac function, several challenges persist in clinical application. A primary consideration is determining which directional strain measurement (longitudinal, circumferential, or radial) most accurately reflects ventricular function in FSV patients. Although preliminary evidence suggests circumferential strain may be most relevant for SRV and longitudinal strain for SLV assessment, these findings require validation in larger cohort studies [24].

Principal strain (PS), measured via 3D-STE, presents a potential solution to these directional challenges. Originally developed in materials mechanics, PS has recently been adapted for cardiac assessment. While longitudinal strain (LS), circumferential strain (CS), and radial strain (RS) demonstrate axial dependence, with nine strains in 3D models (three normal strains and six shear strains), principal strain remains independent of axis-dependent directions. PS represents deformation along the direction of maximum contraction, characterized by negligible shear strain in the principal strain direction [41].

In HLHS patients, principal strain demonstrates strong correlation with 3D-STE-measured ejection fraction, suggesting its potential utility as a key indicator for right ventricular function assessment [42]. PS provides comprehensive characterization of not only contraction magnitude but also contraction angle, offering more detailed insights into FSV cardiac mechanics [43].

Velocity vector imaging (VVI)

Velocity vector imaging represents a non-invasive, angle-independent technique capable of detecting global and regional myocardial function changes during subclinical cardiac dysfunction, demonstrating potential value in early disease detection [44]. VVI provides novel approaches to measuring cardiac twist motion, strain, and strain rate, exhibiting high sensitivity and specificity in myocardial function assessment [45].

Yu-Rong Wu et al. found that SRV patients exhibit longitudinal systolic dysfunction that can be accurately quantified through VVI [46]. The technology also enables detailed evaluation of regional function in FSV. Studies utilizing VVI to assess segmental ventricular function in post-cavopulmonary anastomosis SRV children have revealed significantly reduced strain and strain rate across all six analyzed segments compared to controls, validating VVI's utility in segmental ventricular function assessment [47].

However, velocity vector imaging technology has some limitations. First, it is not completely independent of ventricular preload and afterload, which must be considered. Second, the influence of age changes on various parameters is unknown. Additionally, underdeveloped residual chambers in functional single ventricle children affect local ventricular contraction function, potentially leading to result bias.

Reproducibility of emerging echocardiographic parameters

In emerging echocardiographic techniques, global longitudinal strain and strain rate measured by 2D-STI, as well as global longitudinal strain, circumferential strain, twist, torsion, and principal strain measured by 3D-STI, along with EF measured by RT-3DE, all demonstrate good to excellent reproducibility (Table 2).

Limitations and future perspectives

Existing imaging modalities and indices for FSV evaluation each carry unique strengths and limitations (Table 3). A multimodal approach combining complementary techniques and parameters could mitigate individual method shortcomings.

These echocardiographic techniques face specific limitations and challenges in clinical applications. First, unique characteristics of the study population pose challenges: (1)Anatomical disparities between functionally single ventricles (FSV) and normal ventricles render standard reference values derived from healthy populations potentially inapplicable to FSV patients.(2)Complex hemodynamic alterations during staged palliative procedures complicate longitudinal functional assessments. (3)The low prevalence of FSV results in predominantly small-sample studies, limiting statistical power and generalizability of findings.Second, technical limitations inherent to echocardiography require attention: (1) Inter-device variability in measurement protocols and proprietary software algorithms across manufacturers hinders data integration in multicenter research.(2)Advanced echocardiographic modalities demand high-resolution imaging for accurate quantification, where suboptimal image quality may critically compromise measurement accuracy.

Future investigations should prioritize the following (Fig. 3): First, establishing multicenter collaborations to expand sample sizes is recommended to ensure robust statistical power and enhance the reliability of research findings. Second, comprehensive exploration is needed regarding changes in various ultrasound indicators and their impact on patients, including prognosis, exercise capacity, and quality of life. While novel indices like principal strain and myocardial work index show potential, their clinical utility requires validation in larger FSV cohorts. FSV patients require staged surgical treatment, allowing comparison of indicator changes before and after each stage to identify optimal indicators for evaluating surgical outcomes. Considering changes in ventricular loading conditions before and after surgery, attention should perhaps focus on load-independent indicators. Subtype-specific validation remains essential, as SLV and SRV exhibit distinct structural and functional adaptations. Importantly, extending research to aging FSV populations addresses a critical knowledge gap created by improved long-term survival in this cohort.

Artificial intelligence (AI) applications in echocardiography

AI applications in cardiac function assessment continue to evolve.Traditional echocardiographic techniques predominantly depend on manual or semi-automated delineation of endocardial borders, coupled with model-derived computations [54]. This approach introduces significant variability, as the accuracy of results is highly contingent on the operator's skill and experience.Recent

Table 2 Overview of reproducibility of emerging echocardiographic parameters

Study	Parameters	Intraobserver variability			Interobserver variability		
		n	ICC	Categorization[a]	*n*	ICC	Categorization[a]
Wilkinson et al[48].	2D-GLS	40	0.93	excellent	40	0.88	good
Tham et al[12].	2D-GLS	20	0.81	good	52	0.83	good
	2D-GLSR		0.81	good		0.93	excellent
Colquitt et al[30].	2D-GLS	10	0.91	excellent	10	0.85	good
	2D-GLSR		0.80	good		0.78	good
Sato et al[49].	3D-PS	25	0.86	good	25	0.81	good
Sato et al[50].	3D-PS	14	0.95	excellent	14	0.79	good
Chen et al[51].	3D-GLS	45	0.76	good	45	0.83	good
	3D-GCS		0.84	good		0.80	good
	Twist		0.88	good		0.87	good
	Torsion		0.80	good		0.83	good
Bell et al[52].	RT3DE-EF	28	0.92	excellent	28	0.83	good
Soriano et al[53].	RT3DE-EF	7	0.86	good	27	0.75	good

a. Indicator repeatability classification criteria: ICC < 0.5: poor repeatability, 0.5 ≤ ICC < 0.75: moderate repeatability, 0.75 ≤ ICC < 0.9: good repeatability, ICC ≥ 0.9: excellent repeatability [53]

Abbreviations: ICC, intraclass correlation coefficient;2D-GLS, global longitudinal strain measured by two-dimensional speckle tracking imaging;2D-GLSR, global longitudinal strain rate measured by two-dimensional speckle tracking imaging;3D-PS, principal strains measured by three-dimensional speckle tracking imaging; 3D-GLS, global longitudinal strain measured by three-dimensional speckle tracking imaging;3D-GCS, global circumferential strain measured by three-dimensional speckle tracking imaging; RT3DE-EF, ejection fraction measured by real-time three-dimensional echocardiography

Table 3 Major advantages and disadvantages of various echocardiographic techniques for assessing SV cardiac function

	Major advantages	**Major disadvantages**
2DE	Wide range of applications Easy acces	Dependent on geometric assumptions Susceptible to load Low sensitivity Used more to assess overall rather than local cardiac function
TDI	Parameters Moderately Correlated with VEDP Measured by Cardiac Catheterization	There was no statistically significant correlation between EF measured by CMR and Tei index Angle dependence
RT-3DE	Provides a full range of 3D images of the heart Real-time observation Parameters correlate well with CMR-EF	Highly dependent on image quality Large SV cannot be included in a single view Sensitive to changes in position, respiration, and heart rate RT-3DE tends to underestimate right ventricular volume in children with SRV
2D-STI	2D-STI-Measured strain rates closely correlate with VEDP measured by cardiac catheterization 2D-STI measured strain in good agreement with CMR	Depends on image quality Cross-plane motion loss tracking phenomenon
PSL	MWI may be a more sensitive indicator of myocardial damage than ejection fraction and may predict exercise capacity	Few studies have been done on the subject Role is uncertain
3D-STI	Torsion measured with 3D-STI has good reproducibility and is age-independent	Highly dependent on image quality Complex post-processing and expensive equipment
VVI	Provides multidirectional myocardial motion information Strain rate measured by VVI closely correlates with Max (dp/ dt) measured by cardiac catheterization	Few relevant studies

Abbreviations: TTE, transthoracic chocardiographic;2DE, two-dimensional echocardiography; TDI, tissue doppler imaging; VEDP, ventricular end-diastolic pressure; CMR, cardiac magnetic resonance; EF, ejection fraction; RT-3DE, real-time 3-dimensional echocardiography;2D-STI, two-dimensional speckle tracking imaging; SRV, single right ventricle; PSL, Pressure-strain loops; MWI, myocardial work index;3D-STI, three-dimensional speckle tracking imaging; VVI, velocity vector imaging

developments in AI technology have enabled nearly fully automated detection of endocardial boundaries, potentially enhancing precision in cardiac function assessment [55].

Ruotsalainen et al. reported that in FSV patients, automated fractional area change (FAC) measurements exhibited stronger correlation with cardiac magnetic resonance (CMR)-derived ejection fraction (EF) values while significantly enhancing measurement reproducibility [56].The three-dimensional knowledge-based reconstruction is an AI-driven method that utilizes predefined anatomical landmarks and proprietary algorithms.By cross-referencing 2D image data against an extensive online database of lesion-specific templates, this method generates precise 3D ventricular reconstructions. Wheeler et al. validated its clinical utility, demonstrating improved accuracy in right ventricular (RV) volumetric and functional assessments, particularly in complex congenital heart disease (CHD) cases [57].Furthermore, Pouch et al. developed an automated image segmentation and modeling system for tricuspid valve analysis in FSV patients, enabling efficient and accurate morphological evaluation [58].This technological advancement provides valuable insights into valvular dysfunction mechanisms in this patient population.

Summary

In conclusion, echocardiographic evaluation of FSV ventricular function is inherently challenging due to the complex anatomical and physiological characteristics of this unique patient population. Although conventional techniques and parameters continue to serve as the cornerstone of clinical assessment, their limitations necessitate the exploration of more advanced methodologies. This comprehensive review synthesizes recent developments in echocardiographic assessment of FSV, emphasizing the critical need for the integration of multimodal imaging data to refine clinical decision-making and enhance patient outcomes.The integration of artificial intelligence into echocardiographic workflows offers transformative potential, enabling automated parameter quantification, minimizing operator-dependent variability, improving reproducibility, and lowering the operational threshold.

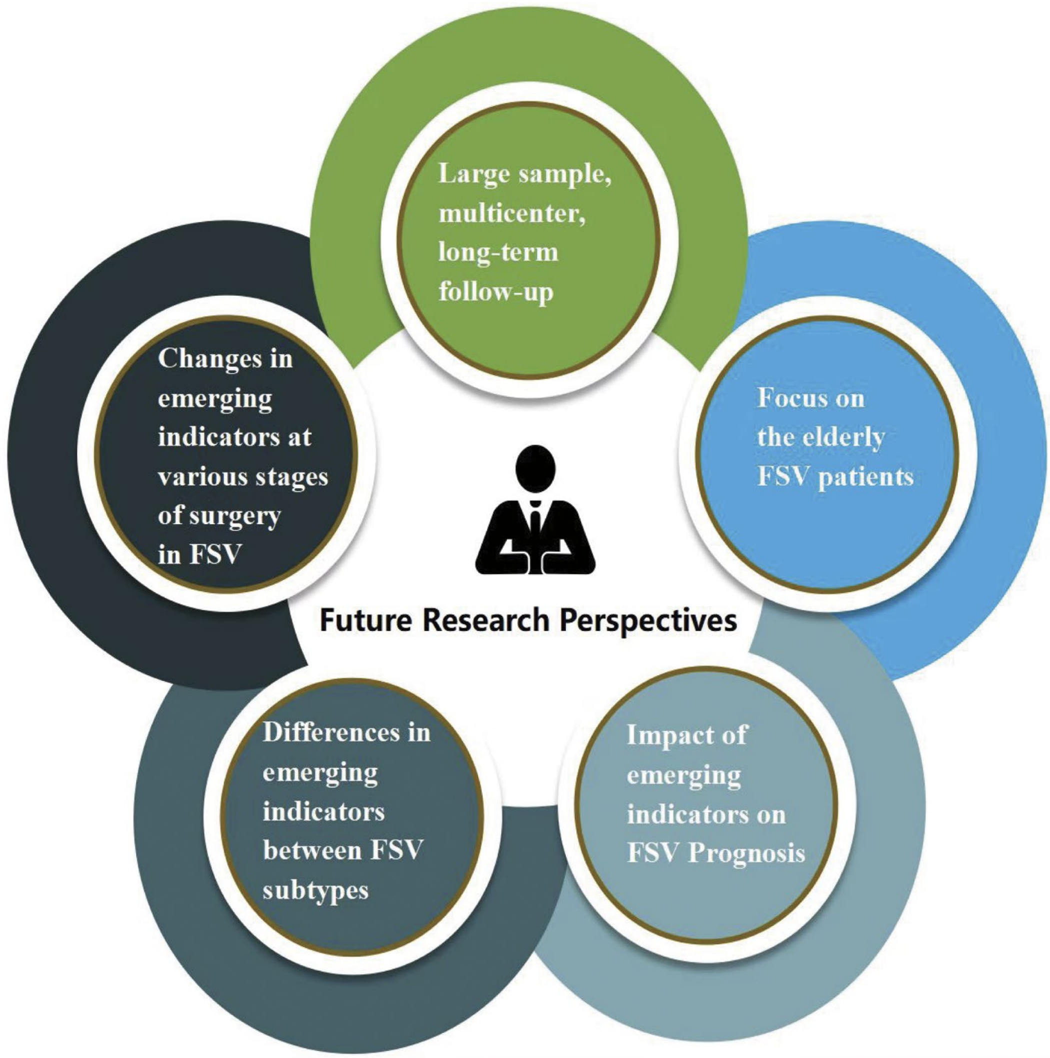


Fig. 3 Future research perspectives on TTE assessment of FSV ventricular function. A few suggestions for future research directions. Abbreviations: TTE, transthoracic chocardiographic; FSV, functional single ventricle

Abbreviations

FSV	Functional Single Ventricle
SV	Single Ventricle
SLV	Single Left Ventricle
SRV	Single Right Ventricle
EF	Ejection Fraction
FAC	Fraction Area Change
TAPSE	Tricuspid Annular Plane Systolic Excursion
Max(dp/dt)	The peak rate of isovolumic ventricular pressure rise
CMR	Cardiac Magnetic Resonance
2DE	Two-Dimensional Echocardiography
TDI	Tissue Doppler Imaging
VEDP	Ventricular End-Diastolic Pressure
TTEs	Transthoracic Echocardiograms
RT-3DE	Real-Time 3-Dimensional Echocardiography
3DE	three-Dimensional Echocardiography
STI	Speckle Tracking Imaging
SR	Strain Rate
2D-STI	Two-Dimensional Speckle Tracking Imaging
HLHS	Hypoplastic Left Heart Syndrome
PSL	Pressure-Strain Loops
MVC	Mitral Valve Closure
AVO	Aortic Valve Opening
AVC	Aortic Valve Closure
MVO	Mitral Valve Opening
MWI	Myocardial Work Index
GWE	Global Work Efficiency
LSS	Layer-Specific Strain
TG	Transmural Strain Gradient
3D-STI	Three-Dimensional Speckle Tracking Imaging
PS	Principal Strain
VVI	Velocity Vector Imaging
ICC	Intraclass Correlation Coefficient
2D-GLS	Global Longitudinal Strain measured by two-dimensional speckle tracking imaging
2D-GLSR	Global Longitudinal Strain Rate measured by two-dimensional speckle tracking imaging
3D-PS	Principal Strains measured by three-dimensional speckle tracking imaging
3D-GLS	Global Longitudinal Strain measured by three-dimensional speckle tracking imaging
3D-GCS	Global Circumferential Strain measured by three-dimensional speckle tracking imaging
RT3DE-EF	Ejection Fraction Measured by real-time three-dimensional echocardiography
TTE	Transthoracic Chocardiographic
GLS	Global Longitudinal Strain
GCS	Global Circumferential Strain

LS	Longitudinal Strain
CS	Circumferential Strain
RS	Radial Strain
AI	Artificial Intelligence

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Competing interests
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