

Quantitative Assessment of Right Ventricular Size and Function with Multiple Parameters from Artificial Intelligence-Based Three-Dimensional Echocardiography: A Comparative Study with Cardiac Magnetic Resonance

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Abstract

Abstract Aims: This study aimed to explore the validation and the diagnostic value of multiple right ventricle (RV) volumes and functional parameters derived from a novel artificial intelligence (AI)-based three-dimensional echocardiography (3DE) algorithm compared to cardiac magnetic resonance (CMR). **Methods and Results:** 51 patients with a broad spectrum of clinical diagnoses were finally included in this study. AI-based RV 3DE was performed in a single-beat HeartModel mode within 24 hours after CMR. Whether in the entire population or the patients with moderate and poor image quality, RV volumes and right ventricular ejection fraction (RVEF) measured by AI-based 3DE showed a statistically significant correlation with the corresponding CMR analysis ($P < 0.05$ for all). The Bland-Altman plots indicated that these parameters were slightly underestimated by AI-based 3DE. Based on CMR derived $RVEF < 45\%$ as RV dysfunction, end-systolic volume (ESV), end-systolic volume index (EDVi), stroke volume (SV), and RVEF showed great diagnostic performance in identifying RV dysfunction, as well as some non-volumetric parameters, including tricuspid annular systolic excursion (TAPSE), fractional area change (FAC), RV septum and free-wall longitudinal strains (LS) ($P < 0.05$ for all). The cutoff value was 43% for RVEF with a sensitivity of 94% and specificity of 67%. **Conclusion:** AI-based 3DE provide rapid and accurate quantitation of the RV volumes and function with multiple parameters. Both volumetric and non-volumetric measurements derived from AI-based 3DE contributed to the identification of the RV dysfunction, even in the patients without excellent image quality of RV 3DE. **Keywords:** artificial intelligence, three-dimensional echocardiography, right ventricle, multiple parameters

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Type of manuscript: Original contribution

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Methods and Results: 51 patients with a broad spectrum of clinical diagnoses were finally included in this study. AI-based RV 3DE was performed in a single-beat HeartModel mode within 24 hours after CMR. Whether in the entire population or the patients with moderate and poor image quality, RV volumes and right ventricular ejection fraction (RVEF) measured by AI-based 3DE showed a statistically significant correlation with the corresponding CMR analysis ($P < 0.05$ for all). The Bland-Altman plots indicated that these parameters were slightly underestimated by AI-based 3DE. Based on CMR derived RVEF $< 45\%$ as RV dysfunction, end-systolic volume (ESV), end-systolic volume index (EDVi), stroke volume (SV), and RVEF showed great diagnostic performance in identifying RV dysfunction, as well as some non-volumetric parameters, including tricuspid annular systolic excursion (TAPSE), fractional area change (FAC), RV septum and free-wall longitudinal strains (LS) ($P < 0.05$ for all). The cutoff value was 43% for RVEF with a sensitivity of 94% and specificity of 67%.

Conclusion: AI-based 3DE provide rapid and accurate quantitation of the RV volumes and function with multiple parameters. Both volumetric and non-volumetric measurements derived from AI-based 3DE contributed to the identification of the RV dysfunction, even in the patients without excellent image quality of RV 3DE.

Keywords: artificial intelligence, three-dimensional echocardiography, right ventricle, multiple parameters

Introduction

Rapid and accurate assessment of the right ventricle (RV) is a great challenge because of its complex anatomy and mechanics [1-2]. Although the role of the RV was often underestimated, many studies demonstrated the RV dysfunction could independently predict the worse outcomes in various cardiac conditions, such as pulmonary arterial hypertension (PAH), heart failure, and congenital heart disease [2-4]. There is also growing evidence that RV size and function are critical determinants in the treatment decision-making and perioperative complications for patients undergoing cardiac or noncardiac surgeries [4-6].

Currently, cardiac magnetic resonance (CMR) is regarded as the gold standard for quantifying RV volume and function because of its excellent spatial resolution and three-dimensional volume rendering [2,7]. However, limited availability, high cost, and long image acquisition time hampered its wide use in different clinical settings. Besides, its performance would be reduced seriously in patients with arrhythmia or critically ill patients who cannot hold breath during image acquisition[2,7]. Echocardiography is the most commonly used imaging technique to assess cardiac function. However, the conventional linear and area measurements by two-dimensional echocardiography (2DE) often failed to give accurate estimates of RV volume [2,8-9]. It is not recommended to calculate the right ventricular ejection fraction (RVEF) derived from RV volumes on 2DE [9].

Previous studies have confirmed that RV volumes and RVEF from three-dimensional echocardiography (3DE) were accurate and reproducible compared to CMR [10-12]. However, conventional 3DE software still requires manual analysis and is time-consuming and skill demanding, and therefore, it is unacceptable in a busy

echocardiographic laboratory [10-12]. A novel artificial intelligence (AI)-based 3DE algorithm, named 3D Auto RV, holds the promise to provide an ideal solution for fast and convenient quantification of RV volume and function [13]. A recent study verified this algorithm with CMR in RV volumes and EF measurements [13]. However, the diagnostic ability of AI-based 3DE in the identification of RV systolic dysfunction was not elucidated. This study performed a comprehensive assessment of RV size and function with multiple volumetric and non-volumetric parameters using the new AI-based 3DE algorithm. We also analyzed the diagnostic value of these measurements regarding their sensitivity and specificity in detecting patients with impaired RV function (CMR-derived EF < 45%).

Materials and Methods

Study Population

From January 2021 to February 2021, 54 consecutive patients (31 men and 23 women, median age [range]: 52[34–59] y) referred for a clinically indicated CMR were recruited in this study. RV volumes and function were measured using the AI-based 3DE software within 24 hours after CMR. Reliable CMR analysis was not completed in 3 critically ill patients due to motion artifact. A total of 51 patients were finally included in this study. The Ethics Committee approved this study, and informed consent was obtained from all patients before the study.

RV 3DE Image Acquisition

Transthoracic echocardiography was performed by two experienced doctors using an EPIQ CVx system (Philips Healthcare, Andover, MA), equipped with an X5-1 transducer. RV 2DE was imaged on apical RV focused four-chamber view according to the guidelines from the American Society of Echocardiography (ASE) [9]. Then, RV 3DE were acquired in a single-beat HeartModel mode. Imaging depth and sector width was controlled to obtain the optimized 3DE frame rate. The entire RV and left ventricle (LV) chambers should be encompassed during the imaging acquisition. All three-dimensional (3D) data was stored digitally and analyzed with the machine built-in software.

AI-based RV 3DE Analysis

Before the image analysis, image quality was evaluated on two-dimensional (2D) apical four-chamber, inflow-outflow, and short-axis views extracted from RV 3DE data. The right ventricular wall was divided into 17 segments, five on the short axis view, six on the four-chamber view, and six on the inflow-outflow tract view [13-14]. Image quality was graded as poor (defined as RV endocardial border were invisible in >2 continuous segments on at least one view), moderate (between the poor and the good images), or good (full RV endocardial visualization on three views) in each patient.

All measurements were automatically obtained using the machine built-in software (3D Auto RV, QLAB, version 13, Philips Healthcare). After selecting RV 3DE data in HeartModel mode, it continuously identifies and traces the RV endocardium throughout the cardiac cycle in multiple tomographic views. Then 3D RV end-diastolic volume (EDV), end-diastolic volume index (EDVi), end-systolic volume (ESV), and end-systolic volume index (ESVi), stroke volume (SV) and RVEF were automatically calculated (Fig. 1a). The conventional 2D RV non-volumetric parameters, including tricuspid annular plane systolic excursion (TAPSE), fraction area change (FAC), and RV longitudinal strain (LS), were also presented side by side (Fig. 1b). This software permits manual editing of the RV endocardial border when some parts of the RV wall did not track adequately. All the RV volumes and functional measurements were recorded for each patient.

CMR Imaging and RV Quantification Analysis

All subjects underwent CMR examination on a 3.0T scanner (Skyra, Siemens, Healthineers, Erlangen, Germany) using an 18-channel cardiac coil, head-first in a supine position. The dynamic imaging protocol included the RV short-axis cine (from apex to tricuspid annulus) and four-chamber cine with electrocardiograph gating during breath-hold.

CMR images were analyzed offline using commercial software CVI42 (Circle Cardiovascular Imaging, Inc.), performed by an experienced radiologist blinded to all 3DE information. During the analysis process, 6 to 12 short-axis slices on steady-state free precession (SSFP) images from the tricuspid valve insertion point to the apex to encompass the entire RV were obtained. In every slice, the endocardial contours were manually traced at end-diastole (the image phase with the largest cavity area) and end-systole (the image phase with the smallest cavity area). The disk summation was used to calculate RV volume indices, including EDV, EDVi, ESV, and ESVi. RVEF was calculated using the standard formula: $EF = (EDV-ESV)/EDV$. The measurements were repeated three times for each patient, and the final measurements were defined as the average value of three repeated measurements.

Reproducibility

To assess the reproducibility and accuracy of the research results, we randomly selected 20 patients' 3DE images. The images were analyzed by two experienced independent researchers who were blinded to the patients' information and CMR results. The inter-observer and intra-observer variabilities for all the RV measurements were analyzed using the intra-class correlation coefficient (ICC).

Statistical analysis

Statistical analysis was accomplished using the SPSS software package (version 22.0; SPSS, Chicago, III). Categorical variables were expressed as percentages and were statistically analyzed by the chi-square test or Fisher's exact test. The Shapiro-Wilk test was used to verify whether continuous variables met the normal distribution. If continuous variables obeyed a normal distribution, the paired *t*-test was used to compare the two groups' parameters. Continuous values that did not obey the normal distribution were analyzed using the Mann-Whitney U test and are presented as median (50th) values and interquartile ranges (25th and 75th). Spearman linear correlation and Bland-Altman analysis were performed to compare the RV measurements derived from AI-based 3DE with CMR. Receiver operating characteristic (ROC) curve analysis was performed to investigate the diagnostic value of RV parameters from 3DE in identifying RV dysfunction. Comparison of areas under the curve (AUC) was performed using the method of DeLong in MedCalc. All results were considered statistically significantly different at $P < 0.05$.

Results

Clinical Characteristics of Study Population

A total of 51 patients with sinus rhythm were finally included in this study. Table 1 showed the clinical characteristics of the study population. Since the unselected patients referred for CMR were enrolled, this study encompassed a broad spectrum of cardiac diagnoses.

Image Quality Assessment of RV 3DE

Of the 18 patients with good image quality, the fully automated analysis was completed in 12 (66.7%) patients. For 27 patients with moderate image quality, the fully automated analysis was completed in 7 (25.9%) patients, and manual editing was needed in 20 patients. The fully automated analysis failed in the 6 patients with poor images, and a more manual correction was required during the analysis procession.

The analysis time for AI-based 3DE RV quantification was significantly dependent on image quality. A fully automated analysis was finished in 19 patients in 15 ± 1 seconds. With manual editing performed when needed, AI-based 3DE RV analysis was completed in 100 ± 12 seconds in patients with good quality images, 105 ± 6 seconds with moderate, and 162 ± 3 seconds with poor quality images ($P < 0.05$ for any two groups). The comprehensive RV volumes and RVEF analysis for CMR imaging were generally completed in 448 ± 25 seconds.

Table 2 and Fig. 2 showed the comparisons of RV Volumes and RVEF between AI-based 3DE and CMR. All the measurements from both modalities showed statistically significant correlations in the whole study population ($P < 0.05$ for all). Although the AI-based 3DE algorithm slightly underestimated RV volumes and RVEF compared with CMR, the Bland-Altman plots indicated that the differences obtained by the two

modalities distributed around the mean of the difference (Fig. 2). It's worth noting statistically significant correlations between the two modalities were also found for all the RV measurements in the moderate and poor image quality group ($P < 0.05$ for all). However, compared with the good image group, a lower correlation value and greater limits of agreement (LOA) for the measurements except EDVi were found in the moderate and poor image quality group (Table 2).

Identifying RV Dysfunction Using AI-based 3DE Quantitative Parameters in comparison with CMR

Based on CMR as the gold standard, RV dysfunction was defined as CMR-derived $RVEF < 45\%$ [10]. Table 3 summarized the clinical characteristics and the quantitative parameters derived from AI-based 3DE in patients with CMR-derived $RVEF \geq 45\%$ and $< 45\%$.

In the entire study population, significant differences were found in ESV, ESVi, SV, EF, TAPSE, FAC, RV septum LS, and RV free-wall LS between the normal and the reduced RV function groups ($P < 0.05$ for all) (Table 3). As shown in Figure 3 and Table 4, most of the volumetric and non-volumetric parameters from AI-based 3DE showed good diagnostic performance in identifying RV dysfunction with CMR-derived $RVEF \geq 45\%$ ($P < 0.05$ for all). Of these multiple quantitative indices, RVEF from AI-based 3DE was superior to the others at a value of 43% diagnosed RV dysfunction with 94% sensitivity and 67% specificity whereas there was no statistical significance ($P > 0.05$). Even in patients with moderate and poor RV 3DE images, ESVi, RVEF, FAC, and RV septum LS can be used to distinguish normal from abnormal RV function with acceptable sensitivity and specificity ($P < 0.05$ for all) (Table 4).

Reproducibility

In a random sample of 20 people, all RV volumes and functional parameters exhibited excellent intra- and interobserver reproducibility. The detailed ICCs for interobserver and intraobserver variability were presented in Table 5.

Discussion

This study performed an automatic assessment of RV size and function with multiple quantitative parameters using AI-based 3DE. Our findings indicated that the analysis process for AI-based 3DE was significantly dependent on image quality. On the whole, RV volumes and RVEF measured by AI-based 3DE showed a good correlation with CMR, with a slight underestimation. Based on CMR-derived $RVEF < 45\%$ as RV dysfunction, RVEF showed an excellent performance in identifying the reduced RV function at a cut value of 43% with 94% sensitivity and 67% specificity (AUC = 0.854, $p < 0.001$). Some non-volumetric parameters, such as FAC and RVLS, can also be used to distinguish normal from abnormal RV function, even in patients without excellent RV 3DE images.

For a long time, the importance of RV in cardiac performance was often neglected in comparison to the left ventricle [1]. With the development of non-invasive imaging modalities, accumulating evidence indicated the crucial role of RV in determining functional status and prognosis in universal clinical conditions [3-7, 15-16]. In patients with pulmonary embolism, PAH, and arrhythmogenic RV dysplasia, the dilated RV was a strong predictor of morbidity and mortality [3,15-16]. A single-center study by Chou et al. pointed out RV dysfunction was associated independently with a higher incidence of postoperative major cardiovascular events and more extended hospital stays [6]. Therefore, the precise and reliable quantitative assessment of RV size and function is widely required to diagnose and manage cardiovascular disease in different clinical settings, such as emergency room, intraoperative and perioperative care.

CMR is currently regarded as the gold standard for accurate assessment of RV volumes and function [2]. Still, its high cost, time-consuming and limited availability preclude its wide application as a routine method of choice. Echocardiography is the most commonly used cardiac imaging modalities in clinical practice. With the improvement of 3DE, a large of previous studies confirmed that 3DE could overcome the challenges related to the complex RV geometry and was superior to 2DE in RV analysis [12, 17-20]. Although 3DE was recommended by ASE guidelines as the primary method for quantifying RV volumes and EF [9], this

effective technique has not been widely used in clinical practice until now. The main limiting factor is the cumbersome manual tracing of the RV endocardial, which is time-consuming, skill demanding, and relatively poor reproducibility [13].

Artificial intelligence (AI) has the potential to improve the analysis and interpretation of medical images to a new stage compared with previous algorithms [21]. A novel AI-based 3DE algorithm has achieved significant success in fast measuring the dynamic left ventricle and atrium volumes and accurately analyzing ejection/filling parameters [22]. Recently, the machine-learning algorithm was also developed for automated RV quantitative analysis on 3DE [13, 23]. Consistent with Genovese et al.'s results[13], the present study confirmed that fully automatic RV analysis could be accurately realized in 37% of unselected patients in nearly 15 seconds. After manual correction for unsatisfying RV endocardial tracing, all the volumetric parameters and EF derived from AI-based 3DE showed an excellent correlation with CMR reference values. It's worth noting that the accuracy of AI-based 3DE algorithms depended on the 3DE image quality to some extent, and decreased image quality is often associated with a lower correlation and greater LOA for the measurements.

Compared with previous 3DE studies, a significant advantage of AI-based 3DE is the improved reproducibility of RV measurements [13,23]. In theory, a fully automated analysis was 100% reproducible. Even with manual correction in AI-based 3DE, excellent reproducibility was also found, as reflected by the coefficient of Variation (CoV) < 7% and ICC >0.95 for all the measurements in Genovese et al.'s study [13]. As for AI-based 3DE, image data was acquired in single-beat and high frame rate HeartModel mode. It is different from the full-volume image acquisition with a multiple-beat approach for conventional 3DE, which requires regular heart rhythm, stable probe position, and good breath-holding capability to avoid stitching artifacts [10-11]. In a study by Park et al., single-beat 3DE was confirmed to determine RV volume and systolic function with good accuracy and reproducibility, regardless of the rhythm status [10].

Along with previous RV volume studies on 3DE, the AI-based 3DE also inevitably underestimated the RV volumes, even in the patients with satisfying image quality [10-11, 13]. We believed that the lower spatial resolution of 3DE could be the main reason for the unclear identification of the endocardial border, resulting in the smaller cavity contouring. With contrast-enhanced echocardiography, more accurate and reproducible 3D echocardiographic measurements of RV volumes can be obtained through improving the visualization of RV endocardial borders [24-25]. This approach may be beneficial in patients with suboptimal image quality.

In a broad spectrum of cardiovascular diseases, RVEF is related to future cardiovascular events and or all causes of death [6, 7, 20, 23]. In our study, RVEF obtained from AI-based showed an excellent performance in identifying the reduced RV function at a cut value of 43% with 94% sensitivity and 67% specificity (AUC = 0.854, $p < 0.001$). Another study found that RVEF from AI-based 3DE was significantly associated with outcomes, providing accurate information regarding RV function and risk for adverse outcomes [23]. In addition to RVEF, some non-volumetric parameters, including RV FAC, TAPSE, and RV longitudinal strain, have also been proposed for RV functional assessment in recent years [7, 26]. A recent study developed a machine learning-based algorithm that could detect low RV function based on clinical and 2D echocardiographic parameters, including RVEF, TAPSE, S', and FAC [27]. With an AI-based algorithm, Liu et al. confirmed the feasibility of RV global longitudinal strain (GLS) on 2DE to assess intraoperative RV function [28]. In addition to the 3D volumetric parameters, AI-based 3DE could quickly provide the non-volumetric parameters of RV based on 2D four-chamber view automatically extracted from 3D data. As far as we know, our study firstly explored the diagnostic value of non-volumetric parameters from AI-based 3DE in determining RV dysfunction with a good sensitivity and specificity in comparison with CMR. Even in the patients with moderate and poor image quality, in whom RV free wall was often missing due to the location behind the thoracic cage and the shielding of pulmonary air, FAC and RV septum LS could identify RV dysfunction, but not the TAPSE and RV free-wall LS. **Limitations**

Several limitations in this study should be considered. First, the number of subjects in this study is still small. As for the unscreened patients referred for CMR, a wide range of RV volumes and RVEF were presented. Therefore, all the measurements obtained from AI-based 3DE and CMR did not obey the normal

distribution. That might be why the weak correlation value of RVEF between AI-based 3DE and CMR, in which spearman linear correlation analysis was performed. Second, we did not compare the measurement differences among various experienced doctors based on AI-based 3DE algorithm. Third, the RV septum and free-wall LS, but not global RVLS was provided by the AI-based 3DE. Some studies indicated that the global RVLS could be more clinically relevant. Also, although contrast enhancement echocardiography contributes to improve the visualization of RV endocardial borders, especially in patients with suboptimal image quality, it was unavailable in the current AI-based 3DE algorithm.

Conclusion

This novel AI-based algorithm holds the promise to provide an ideal solution for fast and reliable quantification of the RV size and function with multiple RV volumetric and non-volumetric indices.

Supplementary Data

Table 1 showed the clinical characteristics of the study population. The detailed ICCs for interobserver and intraobserver variability in a random sample of 20 people, were presented in Table 5.

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Table 1. Clinic Characteristics of the Study Population

Variable	Patients (n=51)
Age, median (range) years	53 (34-60)
Male, n(%)	29 (56.9)
Height, cm	165.5±8.5

Variable	Patients (n=51)
Weight, Kg	64.9±11.5
BSA, m ²	1.7±0.2
SBP, mmHg	123±19.3
DBP, mmHg	77.1±10.3
HR, beats/min	
During 3DE	75.7±11.3
During CMR	76.2±10.1
Frame rate	20 (16-21)
Disease Classification	
Ischemic heart disease, n (%)	13 (25.5)
Hypertrophic cardiomyopathy, n (%)	12 (23.5)
Dilated cardiomyopathy, n (%)	2 (3.9)
Myocarditis, n (%)	2 (3.9)
Normal heart, n (%)	14 (27.5)
Others, n (%)	8 (15.7)

Categorical variables are expressed as number (%). Continuous variables that obey the normal distribution are expressed as mean±SD. Continuous variables that did not obey the normal distribution are expressed as median (50th) values and interquartile ranges (25th and 75th).

BSA, Body surface area; DBP, diastolic blood pressure; SBP; systolic blood pressure; HR, heart rate; 3DE, three dimensional echocardiography; CMR, cardiac magnetic resonance.

Table 2. Comparisons of RV volumes and RVEF between AI-based 3DE and CMR

Group	Parameter	AI-3DE	CMR	P ₁ Value	Bias	LOA mL	r	P ₂ Value
ALL (n=51)	EDV, ml	98.7 (90.5- 128.)	115.4 (92.6- 130.2)	0.089	-11.12	-62.7- 40.5	0.61	¡0.001
	EDVi, ml/m2	67.5 (55.9- 76.4)	68.9 (55.9- 78.4)	0.053	-6.155	-37.6- 25.3	0.52	¡0.001
	ESV, ml	55.8 (46.5- 69.3)	59.8 (45.2- 72.3)	0.051	-3.499	-40.0- 33.0	0.55	¡0.001
	ESVi, ml/m2	31.8 (26.6- 38.5)	34.0 (25.5- 42.3)	0.572	-1.285	-25.2- 22.7	0.45	0.001
	SV, ml	47.5(37.3- 58.6)	54.6 (46.2- 66.3)	0.010	-7.63	-29.2- 13.9	0.70	¡0.001
	RVEF %	47 (43-50)	51 (44-54)	0.077	-2.167	-16.8- 12.4	0.38	0.005
Good n=18)	EDV, ml	96.6 (84.1- 116.5)	110.0 (98.0- 128.8)	0.074	-15.09	-46.5- 16.3	0.72	0.001
	EDVi, ml/m2	57.4 (50.8- 65.4)	67.2 (59.8- 72.1)	0.034	-8.90	-28.4- 10.6	0.49	0.040

Group	Parameter	AI-3DE	CMR	P ₁ Value	Bias	LOA mL	r	P ₂ Value
Moderate+Poc (n=33)	ESV, ml	49.6 (44.0-59.2)	59.2 (44.4-65.4)	0.239	-7.63	-33.7-18.4	0.65	0.003
	ESVi, ml/m2	30.7 (25.2-33.5)	32.5 (27.6-39.8)	1.000	-3.07	-25.4-19.2	0.47	0.052
	SV, ml	46.9 (40.1-56.7)	55.3 (47.6-63.8)	0.055	-7.47	-23.8-8.84	0.74	<0.001
	RVEF %	49 (47-54)	52 (45-55)	0.606	-0.32	-13.6-13.0	0.61	0.008
	EDV, ml	104.1 (92.3-136)	118.3 (86.1-146.9)	0.349	-8.961	-68.8-50.9	0.60	0.001
	EDVi, ml/m2	62.0 (52.0-74.2)	69.6 (47.9-78.2)	0.346	-4.657	-40.9-50.9	0.52	0.002
	ESV, ml	57.7 (47.6-77.5)	63.4 (42.7-73.1)	0.964	-1.247	-42.0-39.6	0.53	0.001
	ESVi, ml/m2	34.7 (28.7-41.4)	36.6 (24.7-44.8)	0.959	-0.314	-25.2-24.6	0.43	0.013
	SV, ml	48.3 (37.1-59)	52.6 (45.7-67.8)	0.074	-7.719	-31.9-16.5	0.69	0.001
	RVEF %	45 (42-49)	50 (43-53)	0.066	-3.176	-18.3-11.9	0.36	0.038

Continuous variables that did not obey the normal distribution are expressed as median (50th) values and interquartile ranges (25th - 75th).

RV, right ventricle; RVEF, right ventricular ejection fraction; AI, artificial intelligence; 3DE, three-dimensional echocardiography; CMR: Cardiovascular magnetic resonance; EDV, end-diastolic volume; EDVi, RV end-diastolic volume index; ESV, end-systolic volume; ESVi: RV end-systolic volume index; SV, stroke volume; LOA, limits of agreement.

P1 value for AI-3DE versus CMR; P2 value for correlation between AI-3DE and CMR

Table 3. Comparing Volumetric and Non-volumetric Parameters from AI-based 3DE in Identifying CMR-derived RVEF < 45%

Variables	CMR-derived RVEF [?]45% (n=36)	CMR-derived RVEF;45% (n=15)	P Value
Age, median (range) years	54 (35-61)	38 (29-60)	0.29
Male, n(%)	24(66.7)	5(33.3)	0.02
Height, cm	166.9±8.5	163.3±7.8	0.13
Weight, Kg	65.1±12.1	64.4±10.6	0.80
BSA, m ²	1.7±0.2	1.7±0.2	0.53
CMR-derived RVEF, %	49 (50-55)	40 (27-43)	<0.001

Volumetric Parameters

Variables	CMR-derived RVEF [?]45% (n=36)	CMR-derived RVEF;45% (n=15)	P Value
EDV, ml	98.7(88.0-126.5)	101.3(91.4-141.1)	0.773
EDVi, ml/m2	59.3(50.3-67.3)	62.0(55.3-80.8)	0.154
ESV, ml	50.9(45.9-60.5)	65.8(51.7-82.5)*	0.023
ESVi, ml/m2	30.7(25.8-36.6)	38.8(31.6-53.4)*	0.006
SV, ml	50.1(40.0-65.3)	43.9(31.6-50.3)*	0.019
RVEF, %	49(45-52)	40(27-46)*	0.006
Non-volumetric Parameters			
RVDd base, mm	36.0(34.3-39.1)	39.3(35.0-43.6)	0.166
RVDd mid, mm	31.1(28.5-34.8)	30.9(27.1-39.7)	0.683
RVLd, mm	83.3(76.9-86.1)	76.9(71.5-80.1)	0.073
TAPSE, mm	19.8(17.0-23.2)	15(12.5-18.6)*	0.004
FAC, %	45.7(40.9-50.1)	37.5(27.3-43.7)*	0.003
RVLS Septum, -%	19.1(22.5-14.9)	12.5(15.7-9.1)*	0.003
RVLS Freewall, -%	27.0(30.07-21.75)	22.8(26.4-14.4)*	0.023

Categorical variables are expressed as number (%). Continuous variables that obey the normal distribution are expressed as mean±SD. Continuous variables that did not obey the normal distribution are expressed as median (50th) values and interquartile ranges (25th - 75th).

AI, artificial intelligence; 3DE, three-dimensional echocardiography; CMR: cardiovascular magnetic resonance; EDV, end-diastolic volume; EDVi, RV end-diastolic volume index; ESV, end-systolic volume; ESVi: RV end-systolic volume index; SV, stroke volume; RVEF: right ventricular ejection fraction; TAPSE, tricuspid annular systolic excursion; FAC, fractional area change; RVLS, right ventricle longitudinal strain. P value for RVEF [?]45% versus RVEF ;45%.

Table 4. ROC analysis of Multiple Parameters from AI-based 3DE in Diagnosing RV Dysfunction (CMR-derived RVEF;45%)

Group	Parameter	AUC	95%CI	P Value	Cutoff value	Sensitivity	Specificity
ALL (n=51)	ESV, ml	0.706	0.540-0.872	0.022	59.9	77.8%	60%
	ESVi, ml/m2	0.747	0.594-0.900	0.006	38.5	75%	60%
	SV, ml	0.706	0.576-0.865	0.021	45.9	63.9%	67.6%
	RVEF, %	0.854	0.728-0.970	0.001	43	94.4%	66.6%
	TAPSE, mm	0.757	0.589-0.926	0.004	16.3	88.9%	66.0%
	FAC, %	0.779	0.627-0.930	0.002	39.6	91.7%	60%
	RVLS Septum, -%	0.751	0.582-0.920	0.005	-26.6	69.4%	53.3%
	RVLS Freewall, -%	0.708	0.544-0.873	0.020	-21.6	50%	53.3%
Moderate+Poor (n=33)	ESV, ml	0.682	0.486-0.878	0.093	—	—	—

Group	Parameter	AUC	95%CI	P Value	Cutoff value	Sensitivity	Specificity
	ESVi, ml/m ²	0.742	0.560-0.924	0.025	44.1	68.2%	63.6%
	SV, ml	0.669	0.480-0.859	0.117	—	—	—
	RVEF, %	0.835	0.665-0.941	0.002	43	90.9%	72.7%
	TAPSE, mm	0.702	0.465-0.940	0.061	—	—	—
	FAC, %	0.731	0.534-0.929	0.032	38.1%	95.5%	54.5%
	RVLS Septum, -% - %sepSeptum, -%	0.767	0.573-0.960	0.014	-22.6	77.3%	54.5%
	RVLS Freewall, -%	0.667	0.459-0.876	0.122	—	—	—

ROC, receiver operating curve; AI, artificial intelligence; 3DE, three-dimensional echocardiography; RV, right ventricle; ESV, end-systolic volume; ESVi: indexed RV end-systolic volume; SV, stroke volume; EF: ejection fraction; TAPSE, tricuspid annular systolic excursion; FAC, fractional area change; RVLS, right ventricle longitudinal strain

Table 5. Inter- and Intra-observer Variability of RV Quantitative Parameters from AI-based 3DE (n=20)

Characteristics	Inter-observer variability			Intra-observer variability
	ICC	95% Confidence Interval	P value	
Volumetric Parameters				
EDV, ml	0.866	0.693-0.945	¡0.001	0.984
EDVi, ml/m ²	0.768	0.502-0.901	¡0.001	0.872
ESV, ml	0.840	0.736-0.906	¡0.001	0.803
ESVi, ml/m ²	0.801	0.676-0.881	¡0.001	0.829
SV, ml	0.864	0.688-0.944	¡0.001	0.796
RVEF, %	0.812	0.693-0.888	¡0.001	0.814
Non-volumetric Parameters				
RVDd base, mm	0.848	0.657-0.937	¡0.001	0.870
RVDd mid, mm	0.831	0.621-0.929	¡0.001	0.859
RVLd, mm	0.827	0.613-0.928	¡0.001	0.838
TAPS, mm	0.824	0.608-0.926	¡0.001	0.870
FAC, %	0.875	0.792-0.927	¡0.001	0.808
RVLS Septum, -%	0.926	0.822-0.970	¡0.001	0.947
RVLS Freewall, -%	0.824	0.711-0.896	¡0.001	0.886

AI, artificial intelligence; 3DE, three-dimensional echocardiography; EDV, end-diastolic volume; EDVi, indexed sum of RV end-diastolic volume; ESV, end-systolic volume; ESVi: indexed RV end-systolic volume;

SV, stroke volume; EF: ejection fraction; TAPSE, tricuspid annular systolic excursion; FAC, fractional area change; RVLS, right ventricle longitudinal strain

Figure Legends

Figure 1. Representative fully automated analysis of RV size and function by AI-based 3DE. (a) RV volumetric parameters, including EDV, EDVi, ESV, ESVi, SV and RVEF were automatically calculated after tracing the RV endocardium throughout the cardiac cycle in multiple tomographic views; (b) the conventional 2D RV non-volumetric parameters, including TAPSE, FAC, RV septum LS, and RV free-wall LS were presented automatically side by side.

AI-based 3DE: artificial intelligence-based three-dimensional echocardiography; RV: right ventricle; EDV: end-diastolic volume; EDVi: end-diastolic volume index; ESV: end-systolic volume; ESVi: end-systolic volume index; SV: stroke volume; RVEF: right ventricular ejection fraction; 2D: two dimension; TAPSE: tricuspid annular systolic excursion; FAC: fraction area change; LS: longitudinal strain.

Figure 2. Comparison between AI-based 3DE and CMR measurements of RV volumes and EF: linear regression (a) and Bland-Altman analysis (b) for EDV (a1 and b1), EDVi (a2 and b2), ESV (a3 and b3), ESVi (a4 and b4), SV (a5 and b5) and EF (a6 and b6). On the Figure a, the black solid lines represent the regression lines of all measurements, and the black dotted lines indicate $Y = X$. On the Figure b, the red dashed lines indicate the Bias, and the black dotted lines indicate the 95% LOA.

AI-based 3DE: artificial intelligence-based three-dimensional echocardiography; CMR, cardiac magnetic resonance; RV: right ventricle; EDV: end-diastolic volume; EDVi: end-diastolic volume index; ESV: end-systolic volume; ESVi: end-systolic volume index; SV: stroke volume; EF: ejection fraction; LOA: On the left panels

Figure 3. Receiver operator curves (ROCs) representing univariate analysis of multiple parameters from AI-based 3DE in diagnosing RV Dysfunction (CMR-RVEF;45%). Odds ratios and area under the curve (AUC) values were calculated for each of the variables of interest, along with 95% CIs.

AI-based 3DE: artificial intelligence-based three-dimensional echocardiography; CMR, cardiac magnetic resonance; RV: right ventricle; ESVi: end-systolic volume index; FAC, fractional area change; EF: ejection fraction; LS: longitudinal strain.





