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Vena contracta area measurement by three-dimensional echocardiography for assessing mitral regurgitation severity using a novel, fast, and reliable method

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Abstract

Background Echocardiography is the standard tool for the evaluation of mitral regurgitation (MR). Although Two-dimensional echocardiography is the most recommended tool, it has some limitations. Three-dimensional echocardiography (3DE) is suggested to overcome these limitations, however, it is more time-consuming. Introducing a simplified and accurate 3-D method could be helpful in this regard.

Methods Patients diagnosed with significant MR who were referred to Shahid Madani heart center, Tabriz, Iran for evaluation of MR severity were entered in this study. Patients with prior MR surgery, poor image quality, and without self-consent for participation in the study were excluded. Two-dimensional transthoracic echocardiography (TTE) and 3D transesophageal echocardiography (TEE) were performed in all patients. MR severity was compared between these two methods and between direct planimetry (DP) of the vena contracta area (VCA) and 3D directed multiplanar reconstruction (MPR).

Results A total of 53 patients were studied. Thirty-six (69.7%) of the patients were female. The mean age of patients was 66.21 ± 11.91 years. 3DVCA using DP was significantly correlated with the 2D method in terms of MR severity ($p = 0.006$). There was a significant correlation between the results of 3DE DP and 2DE magnetic resonance voiding cystography (MRVC) diameter ($r = 0.503$ and $p = 0.0001$). A significant correlation was also found between the result of DP and MPR-derived VCA using 3D ($r = 0.97$ and $p = 0.0001$).

Conclusion TEE is an invaluable method to decide the severity and mechanism of patients with MR, especially if TTE does not give adequate information. The method proposed in this study for evaluation of MR severity and mechanism using 3D TEE could be a helpful option, especially in the above-mentioned conditions. In this study, 3D direct planimetry had an acceptable correlation with 2DE MRVC and also with 3D MPR-derived VCA.

Keywords Mitral regurgitation, Three-dimensional echocardiography, Vena contracta area

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Introduction

Mitral regurgitation (MR) is the most common valvular heart disease. The estimated prevalence of significant MR is about 2 to 3% in the general population [1]. Echocardiography is the standard method for the evaluation of MR mechanism and severity. The recommended parameters for assessment of MR severity are vena contracta (VC) width, effective regurgitant orifice area, and estimation using the proximal iso-velocity surface area method ($EROA_{PISA}$). Due to known pitfalls of various echocardiographic parameters for defining MR severity, a multiparametric approach is recommended according to guidelines statements [2]. Unreliable results of two-dimensional echocardiography (2DE) in the evaluation of a significant proportion of patients with MR, especially in cases with functional MR due to the non-circular shape of the cross-sectional area, conveyed the focus of interest to 3-dimensional echocardiography (3DE) [3]. 3DE has modified the functional and morphological evaluation of VHDs, leading to a better understanding of the valvular dysfunction mechanism and, finally, surgical planning. Direct assessment of valvular stenosis by 3D planimetry reduces measurement errors and is closer to real dimensions. Direct measurement of the vena contracta area using 3D color Doppler has more accuracy than standard 2D evaluation [4]. However, due to some technical matters, the 3DE method is still not routinely used in many centers. These issues include more time expenditure and being dependent on the experience of operators. On the other hand, in circumstances when performing transthoracic echocardiography (TTE) is impossible and there is an urgent need for understanding the mitral valve (MV) pathologies, Trans-esophageal Echocardiography (TEE) is almost the only option, and 3D-TEE could be more helpful due to providing an en-face view. This study evaluates a simple method for determining Vena Contracta Area (VCA) using 3DE.

Materials and methods

Patients

To our knowledge, no similar study has been published assessing these factors. Therefore, this study was designed as a pilot study to assess a total of 53 patients diagnosed with MR who were referred to the Echocardiography Department of Madani Heart Center for evaluation of MR from October 2016 to March 2018 were entered in this prospective study. Patients with prior mitral surgery, poor echocardiographic image quality, and patients without self-consent for participation were excluded from this study.

2D-(TTE) and TEE measurements

2D-TTE was performed on all 53 patients in the left lateral decubitus position using the digital ultrasound machine Philips EPIQ 7(Philips Healthcare). 2D grayscale, color Doppler, and Doppler imaging were acquired. Three consecutive loops were obtained and saved in a cine loop format. After local anesthesia and mild conscious sedation using Propofol, TEE was performed in fasting conditions. Accordingly, the severity of MR was calculated via Vena Contracta Width (VCW) and color flow Doppler according to the American Society of Echocardiography guidelines. The narrowest part of the MR jet in color Doppler in zoomed enhanced parasternal or apical long axis views of TTE and 75°/120°/0° of TEE were considered as VCW.

3D-TEE measurements

3D-TEE was conducted on the same patients. The MR severity was calculated using Multiplanar Reconstruction (MPR) and DP. We started with a 3D data set from 3D zoom mode over 4beats. Then, we worked on both 3D blocks alone with superimposed colors to measure direct 3D color planimetry and 3D blocks with a series of perpendicular 2D planes (MPR). In 3D superimposed color, we scrolled to see the widest MR jet and then cropped directly to reach the VCA. After that, we did a measurement of VCA directly from the en-face view. In the MPR method, we scrolled the systolic frame and found the widest MR jet using multiple orientations of planes. Then, when we realized all cut planes were at the optimized position, we selected a short axis plane to measure the CSA of the MR jet as VCA on enface optimized plane. Accordingly, the largest systolic VCA frame was measured by direct planimetry of the signal of color flow Doppler (Fig. 1). For visualization of the VCA in a 3D en-face view, the image plane was manually adjusted in a way to make it perpendicular to the jet direction, and then the image plane was cropped. Afterward, the cropped plane was repositioned along the direction of the jet until the narrowest jet cross-sectional area had been visualized at the VC level. Then, VCA was calculated using manual planimetry of the signal of the color Doppler flow.

Analysis of echocardiographic images

All echocardiographic images were analyzed using QLAB (Phillips Healthcare) by two experienced echocardiologists.

Ethical considerations

The echocardiographic protocol and data of the study were approved by the ethics committee of Tabriz University of Medical Sciences, Tabriz, Iran. Informed written self-consent was obtained from all of the patients, and patients' data remained confidential.

Statistical analyses

For all statistical analyses, the SPSS™ software was used. In this study, a comprehensive statistical approach was employed to evaluate the diagnostic performance of the diagnostic method. The specificity and sensitivity were calculated using standard methods based on the

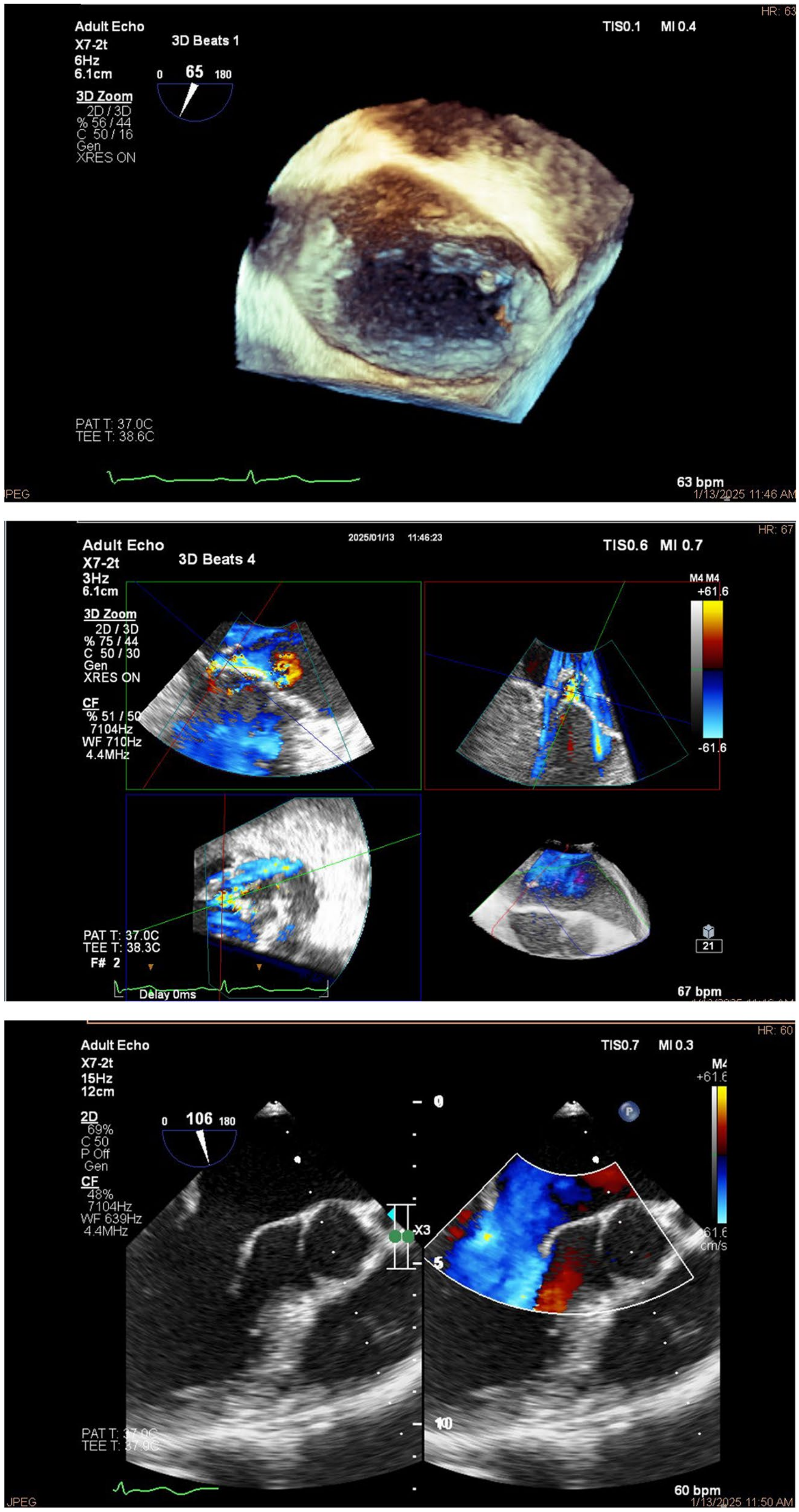


Fig. 1 Showing measuring the largest systolic VCA frame by direct planimetry of the signal of color flow Doppler

two-by-two probability table derived from the results of the diagnostic method compared to the reference standard. The normal distribution of data was assessed via the Kolmogorov–Smirnov test. The chi-square test was used to compare the qualitative variables. Pearson correlation coefficient was used to test the correlation between two quantitative data. Also, the Spearman correlation coefficient was applied for this purpose where needed. Further, Bland-Altman analysis was used to assess the agreement between the findings of MPR and DP. $P \leq 0.05$ was considered statistically significant in all comparisons.

Results

Demographic and echocardiographic findings of the patients are presented in Table 1. Also, as demonstrated in Table 2, there was a significant relationship between MR degree obtained by 2D superimposed color Doppler and 3D-derived VCA (DP). There was also a significant relationship between Color 3D direct planimetry (DP) and MPR-derived VCA ($P < 0.001$). 3D VCA (DP) was correlated with the 2D method (MR VC diameter) in evaluating MR severity ($P < 0.001$). Moderate MR was found in 14 patients using 2D-TEE based on the criteria that were defined in the methods section. Assessment of these patients with 3D-TEE proved the findings of the 2D method in all of the cases. In addition, 2D echocardiography revealed severe MR in 39 patients, and the 3D method confirmed the results of 2D-TEE in 35 cases ($P <$ 0.001). There was a significant relationship between the results of 3DE DP and 2DE MRVC diameter (r = 0.503 and $P < 0.001$). Also, a significant correlation was found between the findings of 3D DP and MPR-derived VCA (r = 0.97 and $P < 0.001$). Furthermore, the specificity and sensitivity of DP in the diagnosis of moderate to severe MR were calculated to be 94% and 97%, respectively. Finally, Bland–Altman analysis showed an agreement between the findings of DP and MPR-derived VCA (Figs. 2 and 3).

Discussion

The findings of this study showed that the results of 3DE DP using the zoom method correlated well with the findings of 2D MRVC diameter (VCW) in the diagnosis of significant MR, with higher specificity and sensitivity. Also, a good or even excellent agreement was found between the results of DP and MPR-derived VCA methods, besides less time required than MPR-derived VC or other methods like the full volume method.

The advantages of the DP method that were evident in our study were that the en-face view offered by 3D echocardiography precisely determines the regurgitant jet shape and the location of the orifice between scallops and shows jet irregularities away from geometric assumption.

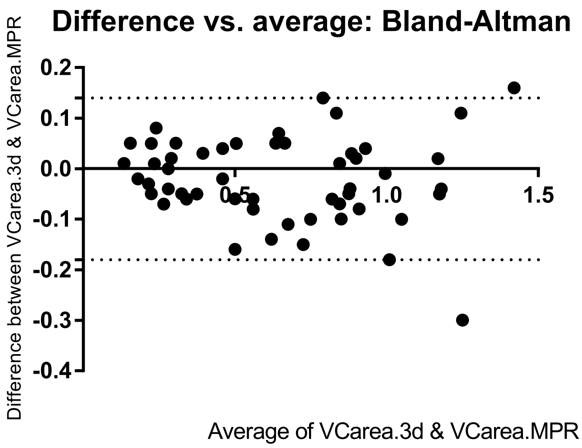
Table 1 Demographic and echocardiographic characteristics of patients

Variables		n/Mean	%/SD
Age (years)		66.21	11.91
Sex	**Male**	17	32.1
	Female	36	67.9
MR severity	**Moderate**	14	26.4
	Severe	39	73.6
TR severity	**No TR**	2	3.8
	Mild	16	30.2
	Mild to moderate	10	18.9
	Moderate	13	24.5
	Moderate to severe	3	5.7
	Severe	9	17
AR severity	**No TR**	10	18.9
	Mild	23	43.4
	Mild to moderate	5	9.4
	Moderate	5	9.4
	Moderate to severe	1	1.9
	Severe	2	3.8
MR pathology	**Primary**	26	49.1
	Functional	19	35.8
	Combined	8	15.1
LVEF (%)		41.67	13.0
LVEDD (mm)		50.9	7.6
LVESD (mm)		36.2	8.3
LAV (ml/m^2)		71.21	32.70
MRVC (mm)		6.27	2.17
VC area using MPR (cm^2)		0.65	0.33
RAA (cm^2)		19.28	7.05
RVDD (mm)		36.54	5.74
RVSP (mmHg)		49.73	17.23
TAPSE (mm)		18.55	3.34
VC area using 3D echo (cm^2)		0.63	0.32

LVEF Left ventricular ejection fraction, *LVEDD* Left ventricular end diastolic diameter, *LVESD* Left ventricular end systolic diameter, *LAV* Left atrial volume, *MRVC* Mitral regurgitation vena contracta, *RAA* Right aortic arch, *RVDD* Right ventricular diastolic dimension, *RVSP* Right ventricular systolic pressure, *TAPSE* Tricuspid annular plane systolic excursion

Table 2 Correlation of mitral regurgitation assessment techniques

Variables	MR 2D	3D DP	MPR-derived VCA
MR 2D	1	0.461	0.425
P-value	-	< 0.001	< 0.001
3D DP	0.461	1	0.970
P-value	< 0.001	-	< 0.001
MPR-derived VCA	0.425	0.970	1
P-value	< 0.001	< 0.001	-



Mean difference: -0.3
Upper limit of agreement [-0.3+(1.96×0.1667)]
Lower limit of agreement [-0.3-(1.96×0.1667)]

Fig. 2 Bland–Altman plot for evaluation of agreement between the findings of VCA direct planimetry (DP) and MPR-derived VCA in the diagnosis of MR severity. VCA: vena contracta area; MPR: multiplanar reconstruction; MR: mitral regurgitation. Mean difference: −0.3. Upper limit of agreement [−0.3 + (1.96 × 0.1667)]. Lower limit of agreement [−0.3-(1.96 × 0.1667)]

Also, the exact position of the orifice can be defined using this method. Besides, in certain circumstances when the 3D TEE is the only alternative, like in the operating room, post cardiac surgery status, in critically ill patients without acceptable transthoracic view, or in a catheterization room, this method could be the unique tool for mitral valve evaluation as an accurate and quick method.

According to ASE guidelines, vena contracta width is a simple semi-quantitative marker of MR severity. However, this parameter has several limitations including, overestimation of MR severity secondary to flow dependency and flow entertainment which occurs in central jets, variable size of dynamic regurgitant orifice, narrow range of different MR grades leading to misclassification of MR secondary to minor errors in diameter assumption, technical errors in instrument setting, suboptimal inter-observer agreement and unreliability in cases with multiple jets [5].

Factors that have an impact on VCA are the anatomic orifice geometry and the fluid viscosity. The VCA has a high dependency on the mitral valve orifice geometry. When the regurgitation orifice is asymmetric, like in functional MR, the 2D VCA could be less accurate [6].

Although VC width is a somewhat load-independent parameter, due to the circular assumption of orifice area in this method, underestimation occurs in secondary or non-circular orifice areas [7].

After introducing 3DE as a tool for determining MR severity, Validation of 3D VC area and regurgitant volume based on 3D VC area was confirmed in comparison with 2D methods [8], LV ventriculography [9], cardiac MR [10] and integrated approach based on ASE guidelines recommendations with promising results in favor of 3DE. Later, it was shown that 3DE could overcome the limitations of 2DE in the assessment of the shape and size of the VCA. Subsequently, several studies demonstrated the superiority of 3DE to 2DE in the assessment of VCA, especially in asymmetric VCA cases. The superiority of 3DE was confirmed in several studies, including the cases with central, eccentric, and even multiple jets [11–17].

Due to the promising results of 3DE in the evaluation of valvular heart disease, several studies were performed in this regard. Although in a systematic review, the results for valvular heart disease were controversial

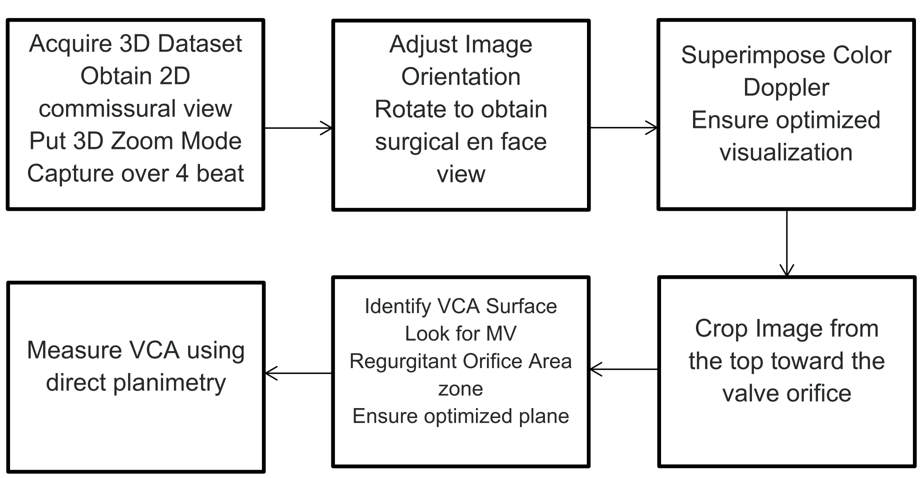


Fig. 3 Demonstration of the 3D-DP operation to enhance the reproducibility of the method

regarding the comparison between 2 and 3DE, the findings were in favor of 3DE superiority [18].

According to the findings of a recent study, VCA measurement using 3DE is a reliable method for MR quantification and is superior to EROA using the PISA method [19].

The advantage of 3DE for assessing VCA is the fact that this measure is independent of geometric and flow assumptions. Another advantage is the higher potency of this method for the differentiation of moderate from severe MR in various etiologies of MR [20].

The pivotal role of 3DE in determining MR severity is selecting the appropriate management strategy for the patient. In this regard, estimation of MR severity using 3DE could alter the surgical management of patients due to a better understanding of MV regurgitant pathology [21].

Despite the previously proposed limitations of 3DE including difficulty in finding the highest velocity across the VCA, limited spatial and temporal resolution, dynamic changes of VCA shape and size, translation artifacts, lower frame rate and image resolution, and time-consuming, 3D VCA has been found a useful method for assessment of valve regurgitation accurately and quickly [22–24]. 3D echocardiography was also introduced as a more comprehensive assessment of the MV apparatus compared to 2D echocardiography, which can delineate the spatial relationship between MV and LV and bimodal/saddle shape of the mitral annulus [25].

Advantages of 3DE over other modalities are the absence of ionizing radiation, compatibility with implanted cardiac devices, and portability, which is more important, especially in critically ill patients [24]. Recent studies also emphasize the usefulness of 3D echocardiography in the assessment of the morpho-anatomic characteristics as well as its ability to provide insight into the underlying mechanism(s) of MR [26].

The posterior position of the mitral valve, coupled with its proximity to the esophagus, makes the TEE an ideal method for evaluating this structure. A narrow imaging sector and a single-beat acquisition are usually sufficient for MV evaluation. Echocardiographers could have the same view as surgeons' in-face view, making a common language between them for more close cooperation during the surgery [27].

Comprehensive visualization of MV apparatus components makes the 3D TEE an optimal modality in the operating room. Optimal MV repair needs a delicate understanding of MV anatomy and pathology. Careful determination of rheumatic MR commissural fusion extent, the involved leaflets and scallops in the degenerative myxomatous valve, and differentiation between indentation and cleft are more applicable via 3DTEE. Guiding complex interventional procedures is the other prominent role of 3D TEE. Foreshortened or off-axis views are not the limitations of 3DE as opposed to 2DE. Lower temporal resolution as a result of higher spatial resolution could be modified by multi-beat acquisition with stitching volumes together, although this requires a motionless position [28, 29]. This study's proposed zoom method eliminates this limitation.

TEE has a pivotal role in the perioperative period of patients undergoing cardiac surgery from preoperative evaluation until the post-surgery period [30]. In critically ill patients, echocardiography is an important diagnostic, imaging, and monitoring tool, and TEE is the only alternative modality in patients with poor acoustic windows. [31], post thoracic surgery, while the thorax is not intact, or the position of the patient did not permit the operator to complete evaluation via TTE.

The full volume method was the predominant method for the evaluation of MR severity in previous studies, however, this method has some limitations, including stitching artifacts due to the acquisition of multiple frames, and it is also time time-consuming method.

In our study, Zoom mode was used for image acquisition. In this method, besides our results being comparable with 2DE and MPR-derived data, it was also a quick method for data acquisition. This method is applicable in the aforementioned status, while the TEE is the only option for valvular heart disease evaluation, like in the operating room, in critically ill patients, in post-surgery conditions, and the catheterization room when there is an urgent need for quick and accurate assessment. In compound mitral valve pathologies, like a combination of functional MR and the existence of a cleft, 3DE might be more accurate than 2DE.

This method has been applied in a few recent studies [32]. In limited conditions, confirmation of the validity of this method seems to be imperative in different conditions.

Although in our study, the results of DP of MV using the zoom method were comparable with the results of the MPR method, it might be better if other sensitive modalities like cardiac MR could validate the accuracy of this method. This study had several limitations. First, it was a single-centre study that had a small sample size. Also, the patient's heart rhythm was not specified. Finally, the perfect plane of 3D VCA could be difficult to determine in patients with eccentric MR. This inappropriate cropping could lead to an overestimation of VCA. Therefore, subsequent multi-center, large-sample studies are suggested to be conducted to support the findings.

Conclusion

This study concluded that 3D direct planimetry had a significant correlation with 2DE MRVC and also with 3D MPR-derived VCA, which suggests that assessment of MR severity using 3D TEE could be a helpful option, especially in conditions in which a fast assessment is necessity.

Abbreviations

MR	Mitral Regurgitation
VC	Vena contracta
3DE	Three-dimensional echocardiography
3DP	3D planimetry
2DE	Two-Dimensional Echo-cardiography
TEE	Trans-esophageal Echocardiography
MV	Mitral Valve
VCW	Vena Contracta Width
VCA	Vena Contracta Area
MPR	Multiplanar Reconstruction
DP	Direct Planimetry
CSA	Cross-sectional area
LVEF	Left ventricular ejection fraction
LVEDD	Left ventricular end diastolic diameter
LVESD	Left ventricular end-systolic diameter
LAV	Left atrial volume,
MRVC	Mitral regurgitation vena contracta,
RAA	Right aortic arch
RVDD	Right ventricular diastolic dimension
RVSP	Right ventricular systolic pressure
TAPSE	Tricuspid annular plane systolic excursion

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Clinical trial number

Not applicable.

Authors' contributions

M.T., D.A., and M.C. contributed to writing the text. S.H. contributed to modifying text mistakes. M.T. and M.C. contributed to the design of the work M.C., D.A., and M.T. contributed to preparing tables and figures. S.H. and M.T. contributed to analyzing data. M.T., D.A., and M.C. contributed to collecting data. S.H. contributed to submitting the manuscript and will coordinate between authors. B.A. contributed to revising the manuscript and sub-analyzing data as requested in the revision. All authors reviewed the manuscript.

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Data availability

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

The study process was reviewed and approved by the ethics committee of Tabriz University of Medical Sciences, according to the Declaration of Helsinki. Before collecting data, informed consent was obtained from all patients. All methods were carried out according to relevant guidelines and regulations.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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