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Assessment of right ventricular function by real-time three-dimensional echocardiography improves accuracy and decreases interobserver variability compared with conventional two-dimensional views

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Aims Two-dimensional echocardiographic (2DE) assessment of right ventricular (RV) function is difficult, often resulting in inconsistent RV evaluation. Real-time three-dimensional echocardiography (RT3DE) allows the RV to be viewed in multiple planes, which can potentially improve RV assessment and limit interobserver variability when compared with 2DE.
Methods and results Twenty-five patients underwent 2DE and RT3DE. Views of 2DE (RV inflow, RV short axis, and apical four-chamber) were compared with RT3DE views by four readers. RT3DE data sets were sliced from anterior–posterior (apical view) and from base to apex (short axis) to obtain six standardized planes. Readers recorded the RV ejection fraction (RVEF) from 2DE and RT3DE images. RVEF recorded by RT3DE ($RVEF_{3D}$) and 2D ($RVEF_{2D}$) were compared with RVEF by disc summation ($RVEF_{DS}$), which was used as a reference. Interobserver variability among readers of $RVEF_{3D}$ and $RVEF_{2D}$ was then compared. Overall, mean $RVEF_{DS}$, $RVEF_{3D}$, and $RVEF_{2D}$ were $37 \pm 11\%$, $38 \pm 10\%$, $41 \pm 10\%$, respectively. The mean difference of $RVEF_{3D} - RVEF_{DS}$ was significantly less than $RVEF_{2D}$–$RVEF_{DS}$ ($3.7 \pm 4\%$ vs. $7.1 \pm 5\%$, $P = 0.0066$, *F*-test). $RVEF_{3D}$ correlated better with $RVEF_{DS}$ ($r = 0.875$ vs. $r = 0.69$, $P = 0.028$, *t*-test). $RVEF_{3D}$ was associated with a 39% decrease in interobserver variability when compared with $RVEF_{2D}$ [standard deviation of mean difference: 3.7 vs. 5.1, (RT3DE vs. 2DE), $P = 0.018$, *t*-test].
Conclusions RT3DE provides improved accuracy of RV function assessment and decreases interobserver variability when compared with 2D views.

Introduction

Accurate assessment of right ventricular (RV) function has important clinical utility including prognostic information in patients with LV cardiomyopathy, mitral valve disease, pulmonary embolism, pulmonary hypertension, congenital heart disease,[1–4] and chronic obstructive lung disease.[5,6] Assessment of RV function by two-dimensional echocardiogram (2DE) has been limited because of the asymmetric, pyramidal shape of the RV, which does not lend itself to geometric assumptions, and can vary greatly depending on the particular imaging plane (*Figure 1*). This results in considerable variability and inaccuracy of RV function assessment.

The three-dimensional (3D) echocardiographic assessment of RV function has permitted an increase in assessment accuracy.[7–13] Prior 3D techniques required extensive reconstruction from 2D images, which limits its widespread clinical application. Recent development of real-time 3D echocardiography (RT3DE) can provide an RV image that encompasses all portions of its asymmetric shape,[14–16] allowing 3D assessment of the RV in a rapid and reproducible manner. In our study, we hypothesized that RT3DE could improve the accuracy and limit variability of RV function assessment in comparison with conventional 2D methods.

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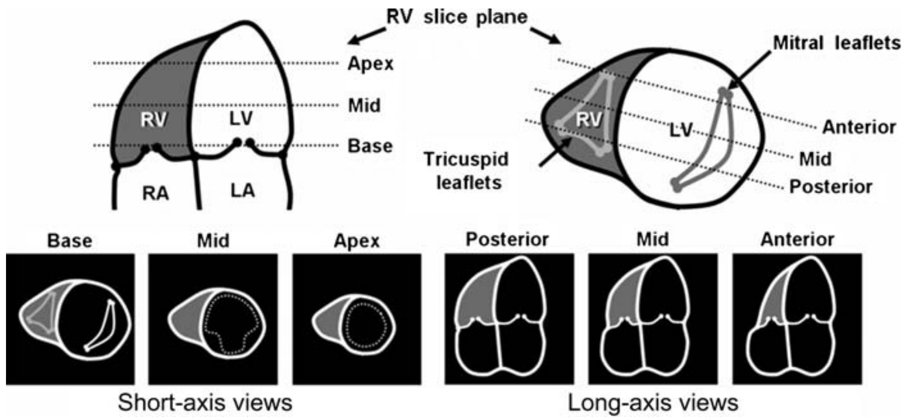

Figure 1 Assessment of RV function by two-dimensional echocardiogram varies greatly depending on the particular imaging plane. RV, right ventricle; LV, left ventricle; RA, right atrium; LA, left atrium.

Methods

This prospective study was approved by our Institutional Review Board.

Patient population

We prospectively studied consecutive adult patients referred by physicians for echocardiography with a diagnosis of clinical right heart failure, inclusive of RV infarction (three), biventricular heart failure (three), chronic obstructive lung disease (two), pulmonary hypertension from concomitant mitral valve disease (four), atrial septal defect left with right shunt (two), and presence of moderate or greater tricuspid regurgitation (three). Of 17 patients, 12 had dilated RV chamber. From this prospective group, patients with technical adequate acquisition of the RV (inflow tract and main body with apical trabecular component) echocardiographic images and no major arrhythmia (including atrial fibrillation that might restrict accurate 3D reconstruction) were selected for inclusion in our study. Ultimately, approximately 20% of the RV RT3DE acquisitions from these patients were excluded for reason of inapplicable quantitative analysis.

Echocardiography two-dimensional and real-time three-dimensional echocardiographic images

The 2D images of the RV were acquired using a Sonos 7500 (Philips Medical Systems, Bothek, WA, USA) with a S3 transducer for standard views (RV inflow, short axis of RV at base to midventricular levels, and apical four-chamber views).

RT3D data sets of the RV were obtained using Sonos 7500 (Philips Medical systems) with an X4 matrix transducer. Full volume data sets were obtained in the parasternal short axis and apical four-chamber windows with respiration suspended for the seven heart beats acquisition.

Both 2D and 3D RV data sets were transferred to a magnetic optical disk and analysed offline with Echoview 5.2 software (Tom Tec imaging Systems, Munich, Germany). Four observers of varying experience (senior echocardiographer, senior fellow, and two attending cardiologists) viewed both 2D and RT3DE data sets on all patients in a blinded fashion.

Analysis of right ventricular function

Two-dimensional assessment of right ventricle by observers

The 2D views of the RV were displayed on a computer monitor and observers were asked to record a visually estimated RV ejection fraction (RVEF). To standardize RV function estimation, RVEF was considered to be abnormal if RVEF $< 45\%$.

Six real-time three-dimensional echocardiography-derived views

RT3DE data sets of the RV were analysed off-line using Echoview 5.2 from Tom Tec Imaging Systems. A full volume parasternal short axis RT3DE data set of the RV was sliced from base to apex to obtain views of the RV at three levels: base, midpapillary, and apex. Similarly, a full volume apical RT3D data set of the RV was sliced in an anterior to posterior direction at three levels: five-chamber view, four-chamber view, and a posterior-oriented four-chamber view with coronary sinus in view. The observers were asked to record a visually estimated RVEF in a manner similar to their 2D estimation of RVEF. The RV slicing planes of the RT3DE data sets are demonstrated in *Figure 2*.

Real-time three-dimensional disc summation method

A quantitative measure of RV ejection was performed as a standard reference. RVEF was calculated using disc summation method.[9,10,14] Global RVEF was computed for all patients. The software provided evenly spaced, parallel, horizontal slices of RV, wherein manual tracing of RV endocardial boundaries was done at end-systolic and end-diastolic frames.[14,17] The horizontal slice tracings were reflected as rectangular boxes in the longitudinal apical four-chamber as well as the orthogonal RV inflow two-chamber view. A reference RV anterior wall lateral line starting from RV apex propagating along the endocardial border towards the basal horizontal plane was drawn (Figure *3*). This reference line was used for consistency when tracing the RV endocardial boundary at short-axis plane. The slices were summed to include the most apical slice up through the basal slice that contained the RV inflow tract and main body with apical trabecular component (but excluding RV outflow tract and right atrium). The software provided the end-diastolic and end-systolic volume, which were determined through multislice with summation of lumen areas. RVEF calculation method by disc summation has been validated against magnetic resonance imaging (MRI) by several clinical studies.[14,17]

Observer variability

To assess interobserver variability, the mean standard deviation (SD) of the difference of each observer's recorded RVEF from that of the average of all observers' RVEF was compared for 2D and RT3DE. To assess agreement of RVEF by 2D and RT3DE methods with that of RVEF by disc summation, a Bland–Altman plot was performed.[18]

To gauge $RVEF_{DS}$ intraobserver variability, RVEF assessment was repeated for RT3DE data sets by one observer after 7 days. To gauge $RVEF_{DS}$ interobserver variability, RVEF assessment was performed by two independent observers (C.S. and Y.C.).

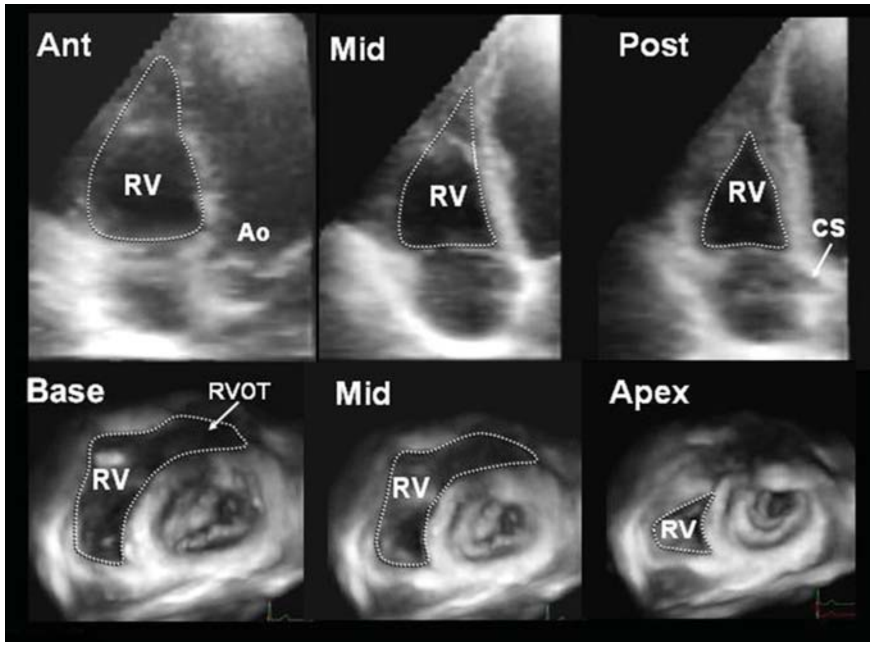

Figure 2 Display of the RV slicing planes of the real-time three-dimensional echocardiography data sets is demonstrated. RV, right ventricle; LV, left ventricle; RA, right atrium; LA, left atrium; Ao, aorta; CS, coronary sinus.

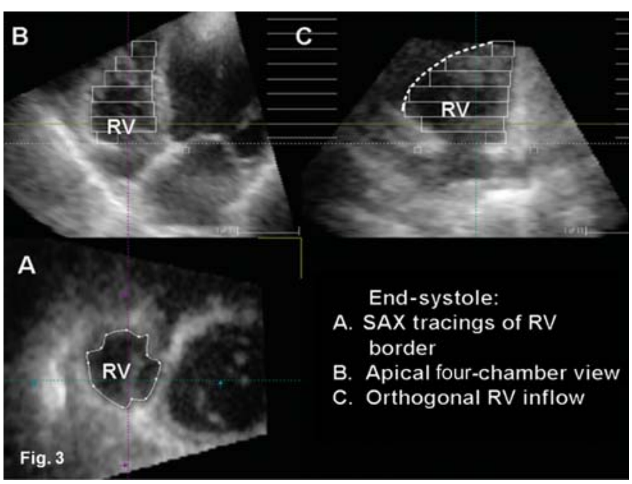

Figure 3 Manual tracing of short-axis slices (*A*) of right ventricular (RV) endocardial boundaries translated as evenly parallel horizontal rectangular boxes as displayed on apical four-chamber (*B*) and orthogonal RV inflow view (*C*). Because of thin RV anterior wall, a reference line was drawn for consistency in RV inflow view (C). SAX, short axis.

Statistical analysis

Data are expressed as mean $\pm$ SD. To compare the accuracy of RT3DE vs. 2DE, RVEF assessment relative to $RVEF_{DS}$ (used as a standard reference) was compared, i.e. the mean difference of $RVEF_{3D} - RVEF_{DS}$ was compared with the mean difference of $RVEF_{2D} - RVEF_{DS}$ by *F*-test.

Linear regression was used to compare correlation coefficients of $RVEF_{2D}$ and $RVEF_{3D}$ to $RVEF_{DS}$. *Z*-transformation of correlation coefficients was performed to determine significant differences between correlation coefficients. Significant differences in interobserver variability were assessed by *F*-test.

Intraclass correlation coefficients, kappa-statistics, and contigency table were calculated to determine interobserver agreement. Statistical analysis was performed with SPSS software for Windows (SPSS Inc, Chicago, IL, USA). A probability value <0.05 was considered significant.

Results

Patients

There were 25 patients (eight with normal RVs and 17 with abnormal RVs; mean age of 55 ± 30 years). The patients were divided into Groups A and B with cut-off value (based on disc summation method) of RVEF $\geq 45\%$ (normal) and $<45\%$ (abnormal), respectively.

Accuracy of $RVEF_{3D}$ and $RVEF_{2D}$ compared with $RVEF_{DS}$

The mean and SD of $RVEF_{DS}$, $RVEF_{3D}$, and $RVEF_{2D}$ for the entire group ($n = 100$; i.e. 25 patients $\times$ assessments by four observers) as well as for patients divided in Group A (RVEF $\geq 45\%$) and Group B ($<45\%$) are shown in *Table 1*. Overall, the mean of the $RVEF_{3D}$ was not significantly different from the mean of the $RVEF_{DS}$ (37 ± 11 vs. $38 \pm 10\%$, $P = 0.717$ by *t*-test), whereas $RVEF_{2D}$ was significantly different from $RVEF_{DS}$ (37 ± 11 vs. $41 \pm 10\%$, $P = 0.028$ by *t*-test). As seen in *Table 2*, the mean difference of $RVEF_{3D}$ minus $RVEF_{DS}$ was significantly less than the mean difference of $RVEF_{2D}$ minus $RVEF_{DS}$ ($3.7 \pm 4\%$ vs. $7.1 \pm 5\%$, $P = 0.0066$ by *F*-test). This was consistent with better accuracy of $RVEF_{3D}$ compared with $RVEF_{2D}$, relative to the standard reference ($RVEF_{DS}$). Overall, as shown in *Figure 4A*, $RVEF_{3D}$ also had a higher correlation with $RVEF_{DS}$ than did $RVEF_{2D}$ ($r = 0.875$ vs. $r = 0.69$, $P = 0.028$ by *t*-test), particularly in patients with abnormal RV function (Group B, $r = 0.69$ vs. $r = 0.50$, $P = 0.00\,001$ by *t*-test), as shown in *Figure 4B*.

Interobserver variability and agreement

Table 3 shows that $RVEF_{3D}$ decreased interobserver variability by 39% when compared with $RVEF_{2D}$ (3.69% vs. 5.13%

Table 1 Right ventricular ejection fraction (RVEF) by disc summation, real-time three-dimensional echocardiography (RT3DE), and two-dimensional (2D) echocardiography

	$RVEF_{DS}$ (%)	$RVEF_{3D}$ (%)	$RVEF_{2D}$ (%)	*P*-value
Normal	52 ± 4	50 ± 6*	49 ± 7**	NS
Abnormal	32 ± 5	33 ± 7*	$37 \pm 8^{\dagger}$	0.00001
Total	37 ± 11	$38 \pm 10^{\S}$	$41 \pm 10^{\S\S}$	0.028

Patients were divided into Group A (RVEF $\geq$ 45%) and Group B (RVEF $<$ 45%). Mean and standard deviation of $RVEF_{DS}$, $RVEF_{3D}$, and $RVEF_{2D}$ for both the Groups A and B ($n = 25$).
t-Test, *P = NS for $RVEF_{3D}$ vs. $RVEF_{DS}$.
**P = NS for $RVEF_{2D}$ vs. $RVEF_{DS}$.
$^{\dagger}P = 0.00001$ for $RVEF_{2D}$ vs. $RVEF_{DS}$.
$^{\S}P = 0.718$ for $RVEF_{3D}$ vs. $RVEF_{DS}$.
$^{\S\S}P = 0.028$ for $RVEF_{2D}$ vs. $RVEF_{DS}$.

Table 2 Improved accuracy of $RVEF_{3D}$ vs. $RVEF_{2D}$

RV function	Mean difference $RVEF_{DS} - RVEF_{3D}$ (%)	Mean difference $RVEF_{DS} - RVEF_{2D}$ (%)	*P*-value
Total	3.7 ± 4	7.1 ± 5*	0.0066

**F*-test, $P = 0.0066$ for $RVEF_{2D}$ vs. $RVEF_{DS}$.

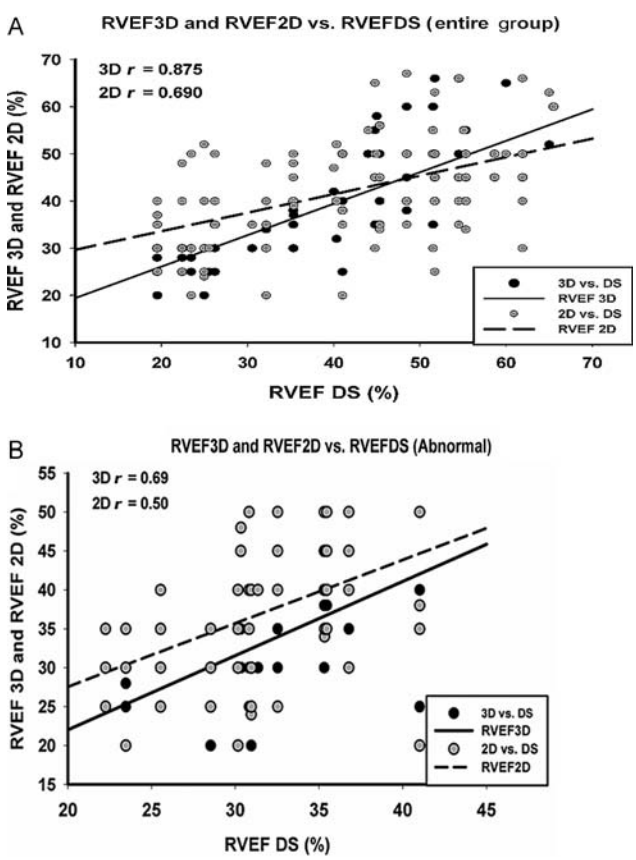

Figure 4 Linear regression comparison of $RVEF_{3D}$ and $RVEF_{2D}$ with $RVEF_{DS}$ showing a stronger correlation of $RVEF_{3D}$ (continuous line) than $RVEF_{2D}$ (interrupted line) to $RVEF_{DS}$ in the entire group (*A*) and in the abnormal RVEF group (*B*).

Table 3 Comparing with $RVEF_{2D}$, $RVEF_{3D}$ decreases the interobserver variability

Difference of RVEF − average of all readers	$RVEF_{3D}$	$RVEF_{2D}$	Decrease of
Total	3.69%	5.13%	39%*

Comparing with $RVEF_{2D}$, $RVEF_{3D}$ decreases the interobserver variability. RVEF, right ventricular ejection fraction; 2D, two-dimensional echocardiography; 3D, three-dimensional echocardiography.
**t*-Test; $P = 0.018$.

(SD), by *t*-test, $P = 0.018$). The Bland–Altman plot indicated better agreement between $RVEF_{3D}$ and $RVEF_{DS}$ than between $RVEF_{2D}$ and $RVEF_{DS}$, with a mean difference between the two methods of $-0.5 \pm 10.2\%$ and $-3.2 \pm 15.6\%$, respectively (*Figure 5*). $RVEF_{2D}$ had a greater overestimation of RVEF when compared with $RVEF_{3D}$.

The interobserver intraclass correlation coefficients as single measures were higher than 0.795 for $RVEF_{3D}$ compared with 0.497 for $RVEF_{2D}$, both having $P < 0.05$. Intraclass correlation values are consistently higher in $RVEF_{3D}$ compared with $RVEF_{2D}$ suggesting better interobserver agreement. Table *4* shows that kappa-statistic and contigency table, both are consistently higher in $RVEF_{3D}$ compared with $RVEF_{2D}$.

Interobserver and intraobserver variability for quantitative measurement of RVEF by disc summation ($RVEF_{DS}$) were 2.5% and 2.1%, respectively (C.S, and Y.C.).

Discussion

Our study demonstrates that evaluation of RV function by RT3DE results in greater accuracy and decreased variability in assessment when compared with standard 2D methods. Because the ventricle has dense trabeculations, complex geometric structure, and physiology, reliable assessment of RV function is difficult. Most methods require the measurement of RV dimensions, but conventional imaging methods such as angiography[19,20] and radionuclide methods[21] are of limited use because of the RV's position in the thorax. Recently, magnetic resonance imaging (MRI) has been validated as an accurate technique for determining RV volumes *in vivo*.[22–24] However, the high cost, long examination time, and non-portability of MRI limits the extensive use of this technique in clinical practice, especially for serial follow-up studies of RV function. Thus echocardiography remains indispensable in the clinical setting.

The complex structural geometry of the RV hinders accurate assessment of RV volume and function on conventional 2DE. Volumetry by 2D, either by single-plane or biplane Simpson's rule, depends on geometric assumptions and is subject to image plane-positioning errors.[25,26] Because of difficulties in obtaining standard and consistent imaging planes of the RV by 2DE, assessment of RV function using this method has been discrepant. This can also limit its clinical applications, especially in serial assessment of RV function for prognostic information in disease states such as cardiomyopathy, chronic lung disease, pulmonary embolism, and post-operative congenital heart disease.

This present study demonstrates that RT3DE data set offers the advantage of examining the RV in a standardized

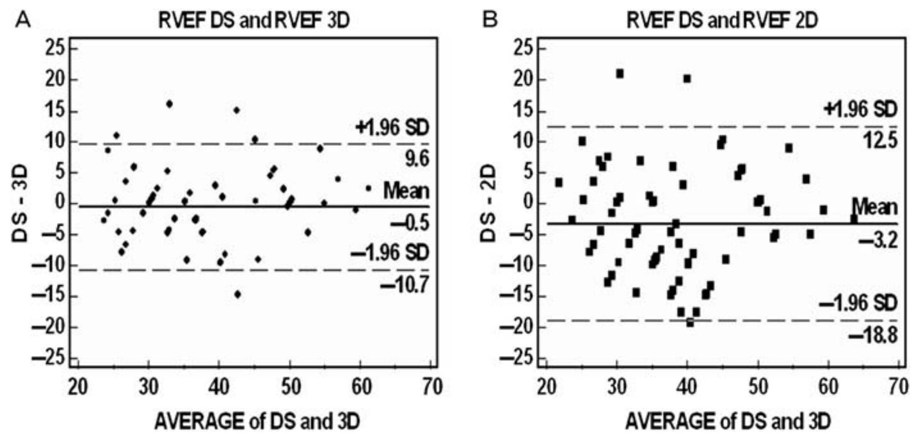

Figure 5 Bland–Altman plot showing better agreement between $RVEF_{3D}$ compared with $RVEF_{DS}$ (left panel) than $RVEF_{2D}$ with $RVEF_{DS}$ (right panel) method. RVEF, right ventricular ejection fraction; RT3DE, real-time three-dimensional echocardiography; 2DE, two-dimensional echocardiography; DS, disc summation method.

Table 4 Kappa and contingency coefficient of $RVEF_{2D}$, $RVEF_{3D}$ compared with $RVEF_{DS}$

	Coefficient	2D	*P*-value	3D	*P*-value
Reader 1	Kappa	0.277	0.020	0.452	<0.001
	Contingency	0.778	0.035	0.799	0.010
Reader 2	Kappa	*		0.576	<0.001
	Contingency	0.681	0.214	0.827	0.001
Reader 3	Kappa	0.268	0.022	0.502	<0.001
	Contingency	0.726	0.219	0.819	0.002
Reader 4	Kappa	0.220	0.053	0.773	<0.001
	Contingency	0.768	0.056	0.878	<0.001

Based on kappa-statistic and contigency table, comparing with $RVEF_{2D}$, $RVEF_{3D}$ increases the interobserver agreement. RVEF, right ventricular ejection fraction; 2DE, two-dimensional echocardiography; 3DE, three-dimensional echocardiography.

*Kappa statistics cannot be computed. It requires a symmetric two-way table in which the values of the first variable match the values of the second variable.

fashion, which allows for more accurate function assessment and decreased observer variability. In addition, RT3DE provides a data set that encompasses the entire RV and accounts for its asymmetric shape. These advantages of RT3DE over 2DE were observed in general and especially, among abnormal RV function group.

Importantly, our study showed $RVEF_{3D}$ comparing with $RVEF_{2D}$ offered lesser interobserver variability with a decrease of 39% (3.69% vs. 5.13%, $P = 0.018$, *t*-test, respectively).

Limitations

Comparison of RV assessment by RT3DE and 2DE was evaluated visually by observers and was thus qualitative in nature. However, the qualitative assessment was compared with a reference standard of RVEF measured quantitatively using a well-validated disc summation method.[14,17] Nevertheless, subjective visual assessment of RV function is the most commonly employed method in present clinical practice.[27] Another limitation was the number of patients investigated in this study was small, and it is therefore difficult to make generalizations based on our sample size.

Limitations to real-time three-dimensional echocardiography

The process of obtaining an RT3DE data set requires versatile acquisition from multiple acoustic windows that ideally, after post-processing, would yield a complete dynamic 3D data set of good quality. However, in our experience such a multi-window acquisition of good quality is not possible if the windows are too far apart (e.g. parasternal and apical). Electrocardiogram triggering is a limitation to all real- and non-real-time methods, since in the presence of irregular rhythms or atrial fibrillation, image quality will deteriorate. Higher heart rates will lead to a shortened and incomplete cardiac cycle (with loss of a true end-systolic frame).

Conclusion

The assessment of RV function by RT3DE improves accuracy and decreases interobserver variability compared with conventional 2D views.

Conflict of interest: none declared.

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