3D echocardiography: evaluation of the right ventricle

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Purpose of review

Evaluation of right ventricular (RV) volume, function and mass has been challenging because of its unique cavity geometry. However, it is indispensable, especially in patients with signs of right-sided heart failure and those with congenital heart diseases. Thus, many investigations on the RV have been published to this end. Although clinical investigations of the RV have been focused on the use of 2-dimenisonal (2D) echocardiography, progressive development of three-dimensional (3D) echocardiography has made it possible to evaluate the RV in clinical settings lately.

Recent findings

Accuracy of newly developed real-time 3D echocardiography for determining RV volume and function has been reported with the use of magnetic resonance imaging (MRI). A slight but significant underestimation of MRI derived RV volumes by 3D echocardiographic methods have been found in multiple recent human studies. One of the in-vitro studies rightly reported the importance of technical factors, causing the inaccuracy of 3D echocardiography.

Summary

Despite the development of new real-time 3D echocardiographic systems, there still exist limitations in clinical settings due to technical factors. Thus, the combination of conventional 2D and Doppler methods and 3D echocardiography is recommended in the evaluation of the RV at the present time.

Keywords

3D, animal, echocardiography, in vitro, right ventricle

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Introduction

Evaluation of right ventricular (RV) volume, function and mass is challenging because of its unique cavity geometry. However, it is indispensable, especially in patients with signs of right-sided heart failure and those with congenital heart diseases. Many investigations on the RV have been published for this end. Although clinical investigations on the RV have been focused on the use of 2-dimenisonal (2D) echocardiography, progressive development of three dimensional (3D) echocardiography has made it possible to evaluate the RV in clinical settings. In this manuscript, I will focus on the review of publications within the last 3 years on the use of 3D echocardiography to evaluate RV volume; function and other RV related abnormalities. Older publications of 3D echocardiography on RV were well reviewed by Sheehan [1] and Shiota [2]. I will organize recent publications based on the nature of the study, that is, nonhuman (*in vitro* and *in vivo*) validation of 3D echocardiographic RV volume determination, validation of RV volume determinations in humans using magnetic resonance imaging (MRI) or other nonechocardiographic references, and finally clinical applications of 3D echocardiography on RV related abnormal cardiac conditions.

In-vitro and in-vivo validation of 3D echocardiography for determining right ventricular volume, function and mass

In 2006, Chen *et al.* [3] published an interesting in-vitro validation study of RV volume and mass. In this study, 10 excised porcine hearts were employed and values of RV silicone latex cast and free wall mass measured by water displacement served as reference values. Measurements of RV volume and free wall mass were determined by several 3D echocardiography methods (2-plane methods, 4-plane methods, 8-plane methods and 16-plane methods) and 2D length biplane Simpson methods. There was no significant difference between measurements of RV volume with 3D echocardiography with 16-plane method (mean 64 ml), 8-plane (62 ml) and the reference values of RV silicone latex casts (63 ml). No significant difference was found between measurements of RV free wall mass with 16-plane (73 g), 8-plane (71 g) and the reference values of RV free wall masses (76 g) [3].

In 2007, Hoch *et al.* [4] used displacements of water from latex RV models derived from excised lamb hearts for investigating the accuracy of real-time 3D echocardiography for determining RV volumes. 3D derived RV volumes were calculated off-line using summation of disks method. There was excellent agreement between real-time 3D echocardiography and displacement of water using 5-mm cut planes with optimal gain settings, and short-axis tracings. However, different gain settings, a slice thickness of 13 mm or greater and long-axis tracings significantly affected RV volume determination. Thus, the investigators concluded that specific variables such as gain settings will alter volume measurements and must be considered in clinical studies.

In 2008, Liu *et al.* [5] used 16-excised formalin fixed porcine hearts for evaluating a newly developed real-time 3-D tri-plane echocardiography, which acquires three apical rotational cross-sectional images simultaneously. Actual RV volume was obtained by spilling water in the RV cavity into a graduated cylinder for measurement, which served as a reference standard for comparison. Excellent correlation and agreement between 3D tri-plane imaging derived RV volume and the actual one for excised porcine hearts were observed ($r = 0.979$, $P < 0.001$, mean difference = 2.2 ml). The authors concluded that this type of real-time 3D tri-plane echocardiography provided us with a new method for rapid and accurate quantification of RV volume.

As seen earlier, these in-vitro and non human studies have demonstrated excellent agreement between RV volume values derived from 3D echocardiography and those by reference standards.

Clinical validation of 3D echocardiography for determining right ventricular volume and function

As for clinical validation studies, in 2006, Prakasa *et al.* [6] evaluated whether transthoracic real-time 3D echocardiography could adequately assess RV morphology, volume and function in patients with arrhythmogenic right ventricular dysplasia. The authors used MRI as a reference standard for determining absolute RV volumes as often used for the validation of older types of 3D echocardiography. Transthoracic real-time 3D echocardiography was prospectively performed in 58 patients. All patients, except 15 patients with arrhythmogenic right ventricular dysplasia with implanted defibrillators, underwent MRI. There was a good correlation between 3D echocardiography and MRI for RV end-systolic volume ($r = 0.72$, $P = 0.0001$), RV end-diastolic volume ($r = 0.50$, $P = 0.0001$), and the RV ejection fraction ($r = 0.88$, $P = 0.001$). The authors concluded that 3D echocardiographic measurements of RV volumes and ejection fractions closely correlate with MRI values and may be useful in the follow-up of patients with arrhythmogenic right ventricular dysplasia. However, in this clinical study, real-time 3D echocardiography underestimated MRI derived RV volumes, especially end-systolic volumes, significantly.

In 2007, Niemann *et al.* [7] employed MRI to validate the accuracy of real-time full matrix-array transthoracic 3D echocardiography for determining RV size and function in 30 patients (14 with grossly normal cardiac anatomy and 16 with major congenital heart disease). The RV ejection fraction measured by 3D echocardiography had a correlation coefficient of 0.91 with MRI derived RV ejection fraction. The RV end-diastolic volume was measured at 71 ± 15 ml with 3D echocardiography and at 70 ± 15 ml with MRI ($r = 0.99$), end-systolic volume measured 40 ± 10 ml with 3D echocardiography and 39 ± 10 ml with MRI ($r = 0.98$) [7].

Gopal *et al.* [8] investigated the accuracy of 2D echocardiography and real-time 3D echocardiography with both disk summation and apical rotation methods for the assessment of RV volume and function. MRI was again used as a reference standard in this study. Real-time 3D echocardiography with the disk summation technique showed the least underestimation of and thus the best agreement with MRI derived RV volumes. Also, in this study, normal reference ranges of indexed volumes for RV end-diastolic volume, end-systolic volume, stroke volume, and ejection fraction were reported as follows: 38.6–92.2 ml/m^2, 7.8–50.6 ml/m^2, 22.5–42.9 ml/m^2, and 38.0–65.3%, respectively, for women and 47.0–100 ml/m^2 23.0–52.6 ml/m^2, 14.2–48.4 ml/m^2 and 29.9–58.4%, respectively, for men.

Grison *et al.* [9] validated the accuracy of reconstruction 3D transesophageal echocardiography (TEE) to measure RV volumes in 25 pediatric patients (age of 1 to 14 years, mean 4 years and weight of 8.5–57.4 kg, mean 18.6 kg) with secundum atrial septal defects, compared with direct RV volume measurements performed during the intervention. In the last five patients a newer 3D TEE machine was used that was equipped with a 3600-crystal real-time 3D probe. To validate the 3D TEE measurements, these were compared with the volume of the RV directly measured in the operating room at the end of the surgical procedure, injecting physiologic saline solution through the tricuspid valve using a graduate syringe. A close comparison was found between RV volumes measured by 3DE and direct volume measurements ($P < 0.00001$) although 3D TEE measures overestimated the surgically determined values. This overestimation had a mean of 9% with values comprised between 3 and 19%.

Jenkins *et al.* [10] investigated in 50 patients (43 men, age 62 ± 11 years) with left ventricular wall motion abnormalities whether real-time 3D echocardiography was superior to 2D echocardiography for the follow-up of RV function. In this study, RV volumes and ejection fraction were studied with 2D echocardiography with three different methods (area-length, the modified two-dimensional subtraction method, and the Simpson method of discs). MRI was again used as a reference standard. MRI derived RV end-diastolic volume (87 ± 22 ml) was slightly underestimated by real-time 3D echocardiography (mean difference, -3 ± 10 ml; $P < 0.05$), with a greater mean difference for 2D echocardiography with the area length method (-29 ± 10 ml; $P < 0.05$), and the Simpson method of discs (-29 ± 23 ml; $P < 0.05$), and was greatly overestimated by the 2D subtraction method (mean difference, 26 ± 23 ml; $P < 0.05$). Similarly, the mean MRI end-systolic volume (46 ± 17 ml) was slightly underestimated by real-time 3D echocardiography (-4 ± 7 ml; $P < 0.05$), compared with 2D area–length method (-16 ± 8 ml; $P < 0.05$) and the Simpson method of discs (-16 ± 8 ml; $P < 0.05$), and was overestimated by the 2D subtraction method (14 ± 13 ml; $P < 0.05$).

In 2008, Lu *et al.* [11•] tried to validate transthoracic real-time 3D echocardiography with full-volume acquisition mode for assessment of RV volumes and RV ejection fraction in 17 children (mean age 10.6 ± 2.8 years) by employing MRI as a reference standard. RV end-systolic volume and end-diastolic volume were measured using a disk summation method by manually tracing the endocardial borders. Good correlations between RT3DE and MRI were found (RV end-diastolic volume, $r = 0.98$, $P < 0.001$; RV end-systolic volume, $r = 0.96$, $P < 0.001$; RV ejection fraction, $r = 0.89$, $P < 0.001$). However, there was a small underestimation of RV end-diastolic volume by real-time 3D echocardiography, mean difference = -7.0 ± 9.0 ml, $P < 0.01$.

As seen earlier, in contrast to non-human validation studies, in clinical studies, there have been consistent underestimation of MRI derived RV volumes by 3D echocardiography. This trend has been known for many years [1].

Clinical evaluation of right ventricular volume and function by 3D echocardiography

In 2006, Kjaergaard *et al.* [12] reported RV volumes and function in 54 healthy individuals (26 men and 28 women, age range: 21–86, mean 59 years) using transthoracic real-time 3D echocardiography with the full volume mode. There were significant differences in RV end-diastolic volume between men and women (129 ± 25 vs. 102 ± 33 ml, $P < 0.01$). However, adjusting to lean body mass (but not the body surface area or height) eliminated this difference (2.1 ± 0.5 vs. 2.2 ± 0.4 ml/kg, P = not significant).

Endo *et al.* [13] examined the accuracy of 3D long-axis analysis in multiple planes (longitudinal axial plane method) for assessment of RV volumes and RV ejection fraction. 3D echocardiographic images were analyzed in 40 individuals with a broad range of RV function. RV end-diastolic and end-systolic volumes were calculated by both short-axis disc summation method and longitudinal axial plane method. Excellent correlation was obtained between the two methods for RV end-diastolic volume, RV end-systolic volume, and RV ejection fraction ($r = 0.99$, 0.99, 0.94, respectively; $P < 0.0001$ for all comparisons). The authors concluded that 3D longitudinal-axis analysis is a promising technique for the evaluation of RV function, and may provide an alternative method of assessment in patients with suboptimal short-axis images.

In 2007, Kjaergaard *et al.* [14] employed transthoracic real-time 3D echocardiography to evaluate RV ejection fraction in 20 patients with arrhythmogenic RV cardiomyopathy and 32 age-matched and sex-matched control individuals. Patients with arrhythmogenic RV cardiomyopathy had a decreased RV ejection fraction (0.47 ± 0.08 vs. 0.53 ± 0.05, $P < 0.01$) as compared with controls.

In 2008, Tamborini *et al.* [15••] investigated the feasibility of transthoracic 3D RV analysis in 200 subjects (48 normals, 104 patients with valvular heart disease, 20 patients with idiopathic dilated cardiomyopathy and 28 patients with pulmonary hypertension). This study compared and correlated 3D RV data with classic 2D and Doppler parameters, including tricuspid annular plane systolic excursion and peak systolic velocity on Doppler tissue imaging, RV fractional shortening area, RV stroke volume by the Doppler method, and pulmonary arterial systolic pressure. 3D derived RV diastolic and systolic volumes were 103 ± 38 and 46 ± 28 ml, respectively. RV ejection fraction was correlated negatively with pulmonary arterial systolic pressure and positively with tricuspid annular plane systolic excursion, peak systolic velocity, and fractional shortening area. 3D echocardiography showed that patients with pulmonary hypertension had the largest RV volumes and the lowest RV ejection fraction and those with idiopathic dilated cardiomyopathy were characterized by lower RV ejection fraction than those of patients with valvular disease. At least one good 3D acquisition of the RV was achieved in all individuals in a mean time of 3 ± 1 min and the RV image quality was good in most individuals (85%). Thus, the investigators concluded that the new quantitative 3D method to assess RV volumes and function was feasible, relatively simple, and not time consuming.

Liang *et al.* [16] used transthoracic real-time 3D echocardiography in 60 patients with tetralogy repair at 14.3 ± 7.2 years after surgery and in 29 healthy controls. The left ventricular systolic dyssynchrony index was also derived from the dispersion of time to minimum regional volume using a 16-segment 2D model. The prevalence of left ventricular mechanical dyssynchrony in patients was very high (93%). The time to minimum regional volume was significantly longer in all of the six basal segments and the midposterior segment in patients than controls. Multivariate analysis identified 3D echo derived RV end-diastolic volume as a significant correlate of the left ventricular systolic dyssynchrony index.

Ostenfeld *et al.* [17] compared the feasibility of 3D echocardiographic volumetric measurements of the four heart chambers in three different views in 40 patients planned for a routine transthoracic 2D echocardiography. Parasternal, apical and subcostal views were used for 3D echocardiography. In this study, RV was adequately visualized in only 12 (30%) patients by 3D echocardiography.

In 2009, Tamborini *et al.* [18] evaluated RV function in 40 patients with mitral valve prolapse undergoing surgical valvular repair and to compare and correlate 3D RV ejection fraction with 2D derived tricuspid annular plane systolic excursion and peak systolic velocity of tricuspid annulus before and after surgery. Transthoracic 2D and 3D echocardiography were performed presurgery and 3, 6, and 12 months postsurgery. Tricuspid annular plane systolic excursion (15.5 ± 3, 16.5 ± 3, and 18.5 ± 4 mm at 3, 6, and 12 months, respectively) and peak systolic velocity of the tricuspid annulus (11.9 ± 2, 12 ± 2, and 12.8 ± 3 cm/s at 3, 6, and 12 months, respectively) were significantly ($P < 0.001$) lower after surgery in comparison with presurgical values. On the contrary, preoperative RV ejection fraction (58.4 ± 4%) did not change after surgery (56.9 ± 5, 59.5 ± 5, and 58.5 ± 5% at each step).

Without the validation of 3D echo derived RV volume determination, comparisons between 2D and 3D echocardiographic parameters require careful interpretations.

Other clinical application of 3D echocardiography related to right ventricle

In 2006, Anwar *et al.* [19] reported assessment of pulmonary valve and right ventricular outflow tract using real-time 3D echocardiography in 50 patients with congenital heart disease (mean age 32 ± 9.5 years, 60% female). By real-time 3D echocardiography, the pulmonary valve was visualized sufficiently in 68% and the RV outflow tract excellently in 40%.

Scheurer *et al.* [20] reported the feasibility and utility of real-time transthoracic 3D echocardiography to guide RV endomyocardial biopsies in 28 consecutive cardiac catheterizations in children aged 18 months to 16 years who were undergoing endomyocardial biopsy. There were no complications, including no new tricuspid valve leaflet flail or pericardial effusion. 3D echocardiography reportedly proved to be a reliable noninvasive modality to properly direct the bioptome to the desired site of biopsy within the right ventricle.

In 2006 and 2007, Acar *et al.* [21] and Vettukattil *et al.* [22] respectively, applied real-time 3D echocardiography to patients with Ebstein's anomaly. In these studies, real-time 3D echocardiography was thought to be a promising tool to offer insights into the morphology and to evaluate the efficacy of surgical valve repair in patient with Ebstein's malformation.

In 2007, Medina *et al.* [23] reported the use of transthoracic 3D echocardiography in a 30-year-old man presenting with fevers and fatigue. 3D echo revealed an anterior coronary sinus of Valsalva aneurysm with fistula formation into the RV with vegetation on the fistulous tract, and a bicuspid aortic valve without vegetation.

In 2008, Byrne *et al.* [24] reported the use of 3D echocardiography to demonstrate migration of a systemic venous stent into the RV in a 65-year-old man who underwent palliative intervention for inferior vena cava compression secondary to malignant mesothelioma. 3D echocardiographic images revealed evidence of a free-stent trapped in the tricuspid valvular apparatus causing severe tricuspid regurgitation.

Wertman *et al.* [25] reported an 83-year-old man with mobile spheric masses. Transthoracic real-time 3D echocardiography was useful to characterize the morphology and extent of the masses in the right atrium and RV. The lesions resolved with prolonged anticoagulation, suggesting thrombi as the origin.

Betrian Blasco *et al.* [26] reported an asymptomatic 1-month-old girl who had a very redundant, thin, freely mobile structure in the right atrium, moving rapidly in the RV during systole and out during diastole through the tricuspid orifice. Transthoracic real-time 3D echocardiography allowed definition of the structure in all the planes and dimensions, and the relationship of the structure with the right atrium and ventricle.

These clinical studies are quite interesting and demonstrate unique images of the RV and RV related cardiac abnormalities only possible with 3D echocardiography.

Conclusion

Despite the development of new real-rime 3D echocardiographic systems, there still exist limitations for evaluating RV volume and function mostly due to technical factors in clinical settings. Thus, the combination of conventional 2D and Doppler methods and 3D echocardiography is recommended in the evaluation of RV at the present time.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:
- • of special interest
- •• of outstanding interest

Additional references related to this topic can also be found in the Current World Literature section in this issue (pp. 000–000).

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