Reviews

Multimodality Evaluation of the Right Ventricle: An Updated Review

Marijana Tadic, MD, PhD
Department of Cardiology, University Clinical Hospital Centre "Dr. Dragisa Misovic–Dedinje" and Faculty of Medicine, Doktora Subotica 6, Belgrade, Serbia

Address for correspondence:
Marijana Tadic, MD
University Clinical Hospital Centre
"Dr. Dragisa Misovic–Dedinje"
Heroja Milana Tepica 1
11000 Belgrade,
Serbia
marijana_tadic@hotmail.com

ABSTRACT

The assessment of the volumes, function, and mechanics of the right ventricle (RV) is very challenging because of the anatomical complexity of the RV. Because RV structure, function, and deformation are very important predictors of cardiovascular morbidity and mortality in patients with heart failure, pulmonary hypertension, congenital heart disease, or arrhythmogenic RV cardiomyopathy, it is of great importance to use an appropriate imaging modality that will provide all necessary information. In everyday clinical practice, 2-dimensional echocardiography (2DE) represents a method of first choice in RV evaluation. However, cardiac magnetic resonance (CMR) remained the gold standard for RV assessment. The development of new imaging tools, such as 3-dimensional echocardiography (3DE), provided reliable data, comparable with CMR, and opened a completely new era in RV imaging. So far, 3DE has shown good results in determination of RV volumes and systolic function, and there are indications that it will also provide valuable data about 3-dimensional RV mechanics, similar to CMR. Two-dimensional echocardiography–derived strain is currently widely used for the assessment of RV deformation, which has been proven to be a more significant predictor of functional capacity and survival than CMR-derived RV ejection fraction. The purpose of this review is to summarize currently available data about RV structure, function, and mechanics obtained by different imaging modalities, primarily 2DE and 3DE, and their comparison with CMR and cardiac computed tomography.

Introduction

The right ventricle (RV) has long been considered a dispensable cardiac chamber that does not contribute significantly to overall cardiac function. Yet studies published in the last several decades have revealed that RV function has been an important independent predictor of morbidity and mortality in patients with congenital heart disease, heart failure (HF), pulmonary hypertension, and coronary artery disease,[1] and the most recent investigations showed an undoubted correlation between RV hypertrophy and the risk of HF or death in a multiethnic population free of cardiovascular disease.[2]

In clinical settings, 2-dimensional echocardiography (2DE) has been used for RV evaluation; however, cardiac magnetic resonance (CMR) has still been considered the gold standard for RV imaging. The introduction of new imaging techniques, especially echocardiographic tools such as tissue Doppler–derived strain, speckle tracking, and 3-dimensional echocardiography (3DE), could provide an accurate assessment of RV function, mechanics, and structure, comparable with CMR results.[3–5] Cardiac computed tomography (CT) provides precise and reproducible RV volume parameters compared with CMR,[6] as well as comparing with 3DE,[7] and can be considered a reliable alternative in the situation where 3DE is unavailable or the patient is not a suitable candidate for CMR.

The purpose of this review article is to provide a current overview of multimodality imaging of the evaluation of RV size, function, mechanics, and structure, emphasizing the benefits of new imaging techniques in clinical settings and making the comparison, highlighting strengths and limitations of each technique.

Right-Ventricular Structure

Anatomically, the RV is separated into the inflow tract, the outflow tract, and the trabeculated muscular apex. The RV has a triangular shape in the coronal plane and a crescent shape in the transversal plane.[8] Because of its complex shape, geometry, and position in the chest, it is very difficult to obtain adequate 2DE images.

Right ventricular wall thickness, a very useful parameter in the conditions of RV pressure overload, is generally determined by 2DE. The recommendations suggest the usage of the subcostal 4-chamber view for measurements of RV free wall thickness, because of its higher reproducibility and good correlation with RV systolic pressure.[9] However, CMR is still considered the gold standard, whereas 3DE is currently not used for this purpose. According to the current guidelines, abnormal RV wall thickness should be reported in patients with suspected RV and/or left ventricular (LV) dysfunction, using the normal cutoff of 5 mm.

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The first step in calculating RV size is 2DE, which enables determination of many various diameters in different echocardiographic views. Interestingly, some studies have shown that a larger RV diameter in patients with idiopathic pulmonary arterial hypertension represents a marker of a poor prognosis, whereas a greater RV wall thickness reduces the risk of death associated with a dilated RV.[10] Right ventricle size has been shown to be an important predictor of survival in patients with acute pulmonary embolism[11] and chronic pulmonary disease.[12] Comparisons between 2DE and CMR for linear and cross-sectional area measurements of the RV have already been performed in normal subjects,[13] congenital heart disease and RV volume overload,[14] and in patients with end-stage lung disease[15]; the results showed that the correlation between these techniques is moderate. The recommendation proposed that patients with echocardiographic evidence of right-sided heart disease or pulmonary hypertension should ideally have measurements of RV basal, mid-cavity, and longitudinal dimensions on a 4-chamber view.[16] Right ventricle relative size should be compared with the LV diameter to help in determination of RV dilatation.

Transesophageal echocardiography with the mid-esophageal 4-chamber view could also be used for the evaluation of RV size; however, lack of the fixed orientation point for the RV might cause variation in quantitative estimation, with consequent underestimation or overestimation of RV size.[9,16]

Three-dimensional echocardiographic assessment of the RV allows direct en face planimetry of the diameters and the areas, in addition to estimation of RV structural and physiological abnormalities, comparable with CMR and CT imaging that were used as the gold standard techniques.[17]

Evaluation of the RV shape, area, and volume also comprises the visualization of the RV outflow tract (RVOT).[7,16] The RVOT could be visualized by transthoracic or transesophageal 2DE; however, morphologically accurate assessment of the RVOT was obtained only by CT and CMR imaging until recently.[18] New investigations revealed that detailed anatomical information of the RVOT could also be acquired by 3DE.[19]

The technical characteristics of each imaging tool, as well as their strengths and limitations in evaluating RV structure, function, and mechanics, are presented in Table 1.

Right-Ventricular Size

Right ventricular myocardium is a complex 3D network of myocytes in a matrix of fibrous tissue.[18] The subepicardial myocytes are circumferentially organized and surround the subpulmonary infundibulum. At the RV apex, these myofibers turn obliquely and form the subendocardial RV, layer which is aligned longitudinally toward the RV base.[20] The RV contracts through 3 different mechanisms: inward movement of the RV free wall, contraction of the longitudinal myocytes, and traction of the RV free wall.[20] Normally, RV shortening is more longitudinal than radial; however, oblique orientation of septal myofibers is crucial for RV twisting, the essential mechanism for RV contraction. Namely, besides shortening along its longitudinal axis, the septum thickens and contributes >60% of the RV systolic contractile energy.[21]

Considering the fact that RV volumes and ejection fraction are the independent predictors of cardiovascular morbidity and mortality,[22] the accurate estimation of these parameters is crucial for clinical practice. Rudski et al in the current guidelines emphasized that indexed RV end-diastolic diameter (RVEDD) was a predictor of survival in patients with chronic pulmonary disease, and the RVEDD/LVEDD ratio was a predictor of adverse clinical events and/or hospital survival in patients with acute pulmonary embolism.[16] For a long time, CMR and CT had been used as the first choice for the assessment of RV volumes.

The development of 3DE and new software enabled an accurate RV assessment that is comparable with CMR.[23,24] Sugeng et al performed an elegant study about the volumetric quantification of RV volume using CMR, CT, and 3DE imaging and concluded that the elimination of analysis-related intermodality differences enabled good comparisons among these techniques.[7] Interestingly, the accuracy of transthoracic 3DE is similar to transesophageal 3DE.[25] Normal values are provided in Table 2.

The important limitation to 3DE-derived assessment is the lack of recommendation for normal RV volumes. This problem has been recently overcome by the studies published by Tamborini and our group, which investigated 3DE RV volumes in a large number of healthy volunteers and defined age-, body size-, and sex-specific reference values.[26,27] Normal CMR-derived RV reference values have been reported previously.[28]

The large meta-analysis that included 807 subjects revealed underestimation of RV volumes obtained by 3DE comparing with CMR.[29] The authors found that larger RV volumes were related with underestimation, whereas older patient age was associated with overestimation of RV volumes.[29]

There are several potential reasons for this disagreement. First, although 3DE evaluation of RV volumes is free of geometrical assumptions, it is affected by gain settings as well as the thickness and orientation of disks during disk summation.[24] Cardiac MR could also use disk summation as a method of RV volumes determination to a lesser extent. Second, the precise RVOT identification is limited by the same factors as the multiplane 2DE method of disks. Third, complex RV shape might disable the accurate identification of the RV margins close to the RVOT. Fourth, 3DE measurement is relying on the visualization of the endocardial border and the ability to differentiate trabeculae from the myocardium. Interestingly, among these 3 imaging tools, only CMR, which is still considered the gold standard in RV imaging, does not provide a real-time 3D imaging, and the demarcation of the RVOT for this modality depends only on a single coronal view.

Right-Ventricular Function

A gold standard technique for the accurate assessment of RVEF is CMR. However, 3DE provides values that are comparable with CMR.[20,21] The large meta-analysis detected underestimation of 3DE RVEF only in older patients.[29] The problem with reference values of 3DE RVEF has recently been dealt with by the studies published by Tamborini and

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Table 1. Strengths and Limitations of RV Imaging Modalities

	2DE	3DE	CMR	CT
Technical aspects				
Availability	High	Moderate	Moderate	Low
Cost	Low	Low	High	Moderate
Typical scan duration, min	25–30	30–35	40–60	10–15
Safety	High	High	Contraindicated in patients with metallic implants, claustrophobia; potentially nephrotoxic contrast, allergic reaction to contrast; restricted only to hemodynamically stable patients	Ionizing radiation; potentially nephrotoxic contrast, allergic reaction to contrast
Imaging window dependence	Present	Present	Absent	Absent
Temporal resolution	+++	++	++	+
Spatial resolution	+++	++	+++	++++
3D acquisition	No	Yes	Only in selected sequences	Yes
Real-time 3D imaging	No	Yes	Yes, but with limitations	No
Assessment of RV geometry, size, and function				
Evaluation of RV wall thickness	Yes	Yes	Yes	Yes
Determination of RV diameters	++	+++	++++	++++
Accuracy of RV volume	–	+++	++++	++++
Accuracy of RVEF	–	+++	++++	++++
Parameters of RV systolic function	FAC, TAPSE, s	RVEF	RVEF	RVEF
Estimation of RV diastolic function	Only used in clinical practice	Not used	Not used	Not used
Evaluation of RV mechanics	+++	+	++++	+++
Major limitations	Inability to acquire the whole RV in 1 view; geometric assumptions; poor visualization of RV endocardial border; lack of spatial orientation	Stable cardiac rhythm; visualization of RV endocardial border; no data about RV mass	Cost; low availability	Ionizing radiation; potentially nephrotoxic contrast; stable cardiac rhythm with a low heart rate for image acquisition

Abbreviations: 2DE, 2-dimensional echocardiography; 3DE, 3-dimensional echocardiography; CMR, cardiac magnetic resonance; CT, computed tomography; FAC, fractional area change; RV, right ventricle/ventricular; RVEF, right ventricular ejection fraction; s, systolic velocity across lateral segment of tricuspid annulus; TAPSE, tricuspid annular plane systolic excursion.
+ = low, ++ = moderate, +++ = high, ++++ = very high, and – signifies a major limitation of the modality.

our study group.[26,27] Normal CMR-derived RVEF values for adults were reported previously.[28]

Two-dimensional echocardiography is no longer used to assess RVEF. However, 2DE-derived RVEF calculated by the Simpson rule and the area-length method moderately correlated with radionuclide- or CMR-derived RVEF (correlations ranging from 0.65 to 0.80).[20,23] According to the guidelines, 3DE RVEF obtained by the disk-summation method may be used for the report of RV systolic function, with a lower reference limit of 44%.[16] Normal values are shown in Table 2.

Among 2DE parameters of RV systolic function, RV fractional area change (FAC) is an important measure that correlates well with CMR-derived RVEF and is superior to other 2DE methods of estimating RV systolic function.[30] The current guidelines regarding RV assessment claimed that RV FAC was an independent predictor of HF, sudden death, stroke, and/or mortality in studies of patients after pulmonary embolism and myocardial infarction.[16] Two-dimensional echocardiographic FAC is one of the recommended methods of quantitatively estimating RV systolic function, with a

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Table 2. Normal Values of RV Parameters

Parameter	Mean Values (min–max)	Reference
RV basal diameter, mm	33 (24–42)	Current guidelines[16]
RV midcavity diameter, mm	28 (20–35)	Current guidelines[16]
RV longitudinal diameter, mm	71 (56–86)	Current guidelines[16]
RV subcostal wall thickness, mm	5 (4–5)	Current guidelines[16]
RVEDA, cm^2	18 (10–25)	Current guidelines[16]
RVESA, cm^2	9 (4–14)	Current guidelines[16]
3DE RVEDV indexed, mL/m^2	65 (40–89)	Current guidelines[16]
3DE RVESV indexed, mL/m^2	28 (12–45)	Current guidelines[16]
TAPSE, mm	23 (16–30)	Current guidelines[16]
FAC, %	49 (35–63)	Current guidelines[16]
3DE RVEF, %	57 (44–69)	Current guidelines[16]
RV strain, %		
Mean RV strain	−26 (from −21 to −32)	Fine et al[53]
RV free wall strain	−27 (from −24 to −29)	

Abbreviations: 3DE, 3-dimensional echocardiography; FAC, fractional area change; max, maximum; min, minimum; RV, right ventricle; RVEDA, right ventricular end-diastolic area; RVEDV, right ventricular end-diastolic volume; RVEF, right ventricular ejection fraction; RVESA, right ventricular end-systolic area; RVESV, right ventricular end-systolic volume; TAPSE, tricuspid annular plane systolic excursion.

lower reference value for normal RV systolic function of 35%.[16]

Tricuspid annular plane systolic excursion (TAPSE) is another easily obtained 2DE parameter that correlated well with 3DE-derived RVEF.[30] It should be used routinely as a simple method of estimating RV systolic function, with a lower reference value for reduced RV systolic function of 16 mm. However, TAPSE is angle dependent, which is of great importance, because a slight misalignment could result in significantly distorted results regarding RV function assessment.

Doppler-derived nongeometric index of RV global ventricular function—the Tei index—represents an additional useful parameter in assessment of RV global function because of its independence from heart rate or severity of tricuspid regurgitation.[31] However, loading dependence of the Tei index is still unclear, which is why its usage is not widely accepted.

The peak tissue Doppler systolic velocity (s′) in the tricuspid annulus is a measurement of RV longitudinal function. This technique is easy and reproducible but angle dependent, load dependent, and influenced by tricuspid regurgitation.[32] It is recommended to use this parameter as a simple and reproducible measure to assess basal RV free wall function. S′ <10 cm/s is suspected of abnormal RV function, particularly in a younger adult.

The evaluation of RV diastolic function in clinical settings usually implies assessment of the RV inflow by pulsed wave Doppler and evaluation of inferior vena cava and hepatic veins.[16] Rudski et al, in the current guidelines, emphasized that the presence of RV diastolic dysfunction was associated with worse functional class and was an independent predictor of mortality in patients with chronic HF and pulmonary hypertension.[16]

During acute RV pressure overload, RV diastolic function is not affected, whereas chronic RV pressure overload impacts RV diastolic dysfunction, resulting in prolonged diastolic relaxation time and increased RV diastolic stiffness.[33] However, the latest study showed that during acute pressure overload, restoring forces initially decreased, but recovered at advanced stages.[34] This biphasic response is associated with alterations of septal curvature provoked by variations in the diastolic LV-RV pressure balance.

Tissue Doppler echocardiography has been widely used in the evaluation of RV diastolic function.[9,16] The tricuspid E/e′ ratio was proven to be an indicator of RV filling pressure, as well as a marker of RV diastolic dysfunction in pulmonary hypertension.[9,16] However, this parameter is also preload dependent, which represents its limitation.[16]

The data about the impact of RV diastolic dysfunction on the outcome are scarce. Yu et al showed that patients with left-sided HF and RV diastolic dysfunction defined by abnormal filling profiles have an increased risk of unstable angina and hospital readmissions due to HF deterioration.[35]

Right-Ventricular Mechanics

Myocardial deformation imaging is a novel echocardiographic tool for evaluation of global and regional myocardial function. The LV myocardium simultaneously shortens in the longitudinal and circumferential directions and thickens in the radial direction during systole, with opposite changes in diastole. However, there are some very important differences between the LV and RV: the RV is exposed to

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lower afterload compared with the LV; and the anatomical structure of the RV is different, with a thinner wall, the complex crescent-shaped geometry, and the predominance of longitudinal and oblique myofibers in the RV free wall.[36] This is why RV strain and strain rates are more inhomogeneously distributed compared with the LV and demonstrates a reverse baso-apical gradient.[37]

Myocardial deformation measured with 2DE might be obtained with the usage of tissue Doppler–derived or 2DE speckle tracking–derived techniques that highly correlate with CMR-derived strain. Research showed that an acute increase in RV afterload consequently caused an increase in RV myocardial strain rate, a parameter of contractile function; and reduction of peak systolic strain, demonstrating a decrease in RV stroke volume.[38]

Although Doppler-derived strain does not rely on geometrical assumptions, it has several technical issues concerning the angle dependence, high frame rate, drifting of the strain curve, image quality dependence, and influence of age and heart rate that significantly interfere with the accuracy and reproducibility of strain and strain rate. Additionally, RV free wall is considerably thin, thus Doppler-derived RV strain sometimes could not be reliably obtained. The usage of Doppler-derived strain in the assessment of RV function has been currently limited to the apical 4-chamber view and consequently evaluates only RV longitudinal strain. The determination of circumferential shortening and radial thickening requires a short-axis or transverse section, which still cannot be obtained by 2DE.

In comparison with Doppler-derived strain, 2DE strain is angle independent and provides the information about global strain, not only the regional. However, both techniques provide only RV longitudinal strain, and only from the 4-chamber view, because other planes could not yet be provided by 2DE. The major limitation of 2DE strain of the RV is loss of speckles due to motion outside the imaging plane, especially due to excessive motion of the RV lateral wall.[39]

Studies showed that RV longitudinal shortening is a more important contributor to RV systolic function than circumferential shortening.[37] Investigations revealed a great correlation between Doppler-derived and 2DE-derived RV strain.[40] Tee et al claim that 2DE- and CMR-derived strain show “reasonable” agreement; however, the main problems lie in the different techniques that are used in various modalities, great intervendor variability, and lack of reference values for each of these techniques.[41]

Previous research has revealed a strong correlation between 2DE-derived RV strain and CMR-derived RV volumes and RVEF in patients with operated tetralogy of Fallot.[42] It is claimed that 2DE strain of free RV wall is a good predictor of life quality in these patients.[43] Khalaf et al revealed that RV circumferential strain obtained by CMR significantly correlated with LVEF and segmental deformation in repaired pediatric tetralogy of Fallot.[44]

The importance of RV strain was also confirmed among patients with pulmonary hypertension. Namely, Shehata et al, using CMR-derived strain, revealed that RV longitudinal contractility was reduced at the basal, mid, and apical level, and tangential contractility was reduced at the midventricular level in patients with pulmonary hypertension.[45] Global RV strain strongly correlated with the mean pulmonary artery pressure and pulmonary vascular resistance index.[45] Interestingly, 2DE-derived RV longitudinal strain has been shown to be a better predictor of functional capacity than CMR-derived RVEF in patients with tetralogy of Fallot.[46] Henein et al showed RV global longitudinal strain was one of the most accurate predictors that carried the highest risk of mortality in patients with pulmonary hypertension.[47] Vizzardi et al revealed an association between 2DE RV longitudinal strain and mortality in patients with moderate HF.[48] Our study group demonstrated that both 2DE-derived RV strain and 3DE-derived RVEDV and RVEF correlated with functional capacity in patients with systemic hypertension; but only 2DE-derived RV strain was independently associated with peak oxygen uptake.[49] Similar results were obtained by Leong et al in the group of patients with HF.[50]

From the latest studies it could be concluded that 2DE RV longitudinal strain could be used as a good predictor of outcome in patients with pulmonary hypertension, HF, or tetralogy of Fallot, or in patients with a left ventricular assist device.

Cardiac MR was the first method that provided multidirectional strain assessment, including area strain.[44,49] The development of 3DE enabled echocardiographic assessment of RV mechanics in different directions, similar to CMR. There is only 1 study that has investigated 3DE RV mechanics.[51] Atsumi et al included 35 normal subjects, 8 patients with arrhythmogenic RV cardiomyopathy, and 8 patients with pulmonary arterial hypertension, and determined RV longitudinal and circumferential strain as well as area change ratio.[51] The comprehensive analysis of 3DE RV deformation included separate evaluation of all these parameters for inflow tract, apical region, outflow tract, and septum.[51] The authors described good interobserver and intraobserver variability for all measurements of 3D RV mechanics assessed by correlation coefficients (between 0.7 and 0.9); however absolute percentage error largely varied depending on RV wall (12%–44.2%).[51] This shows that reproducibility of this new technique is still relatively low in comparison with 2DE or CMR studies. Additionally, this study revealed that each segment of the RV has a different direction of contraction, which could be the reason why area fractional change, an integrated parameter of longitudinal and circumferential strain, might represent the most reliable indicator of RV deformation.

According to the contraction timing results of this study, the apical anterior wall and septum wall contracted first, and then other regions followed, as has been previously described.[52] Atsumi et al showed that the RV anterior wall contracted more than other regions; additionally, the results of longitudinal and circumferential strain revealed that contractile direction changed significantly in each segment, unlike the LV wall, which showed almost identical difference between longitudinal and circumferential strain in all segments.[51]

These findings confirm the complexity of RV geometry and structure and suggest that a reduction in longitudinal

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strain might indicate RV endocardial damage, whereas a reduction in circumferential strain could imply epicardial damage.

The benefit of 3DE-derived RV strain is an accurate angle-independent identification of RV motion with concurrent estimation of longitudinal and circumferential strain and RV area change ratio. However, the main limitation to the study by Atsumi and coworkers was the lack of validation of 3DE RV strain with generally accepted methods such as 2DE- or CMR-derived strain.[51]

The current guidelines do not provide normal range of 2DE RV strain and strain rates because there were not enough data regarding 2DE RV mechanics and the cutoff values at the time when recommendations were published. However, nowadays many studies are available on this topic, thus it could be proposed to determine RV mechanics in all patients with suspected right-sided heart disease. Normal values are provided in Table 2.

Conclusion

Right ventricular function and mechanics has been proven to be an important indicator of overall cardiac function and an important predictor of cardiovascular morbidity and mortality. In the current guidelines regarding RV assessment, the authors emphasized the importance of RV function evaluation, which represents one of the most powerful independent predictors of outcome following myocardial infarction, even in the absence of overt RV infarction. Right ventricular function is also an independent predictor of outcome in patients with HF, pulmonary disease, pulmonary embolism, and congenital heart disease, before and after heart transplantation.

Because of their high availability, 2DE and 3DE represent the first choice among imaging techniques for the assessment of the RV; 3DE is particularly important due to its similarity with CMR and CT measurements. After initial echocardiographic assessment, CMR should be performed as the second-line imaging technique, in cases when surgical intervention is planned due to congenital heart disease or when the differentiation of diagnosis is needed, such as in patients with possible arrhythmogenic RV dysplasia, metabolic storage diseases, or cardiac tumors. Cardiac MR allows visualization of anatomy, tissue characterization, quantifying function, and calculating flows. However, suspicion of each of these aforementioned diseases needs further investigation, primarily cardiac biopsy. Computed tomography should be considered in patients with particular contraindications for CMR (eg, those with metallic implants). Computed tomography usually represents the first-line diagnostic technique in patients with suspected pulmonary embolism. Compared with CMR, CT tends to overestimate RV volumes.

The multimodality in the assessment of RV function and deformation allows us the comparison of the same parameters between different techniques. This is particularly significant for the patients who are undergoing cardiac surgery and need an accurate evaluation of RV function. In these patients, using ≥2 imaging modalities is recommended, and one of them should be CMR.

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