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Multimodality Imaging of the Right Ventricle

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Opinion Statement

Right ventricular (RV) structure and function is clinically important in a wide range of conditions. While conventional echocardiography (echo) methods are widely used, its limitations in RV assessment due its complex geometry are well recognized. New applications of traditional echo methods as well as emerging echo techniques including 3-dimensional (3D) echo and speckle tracking strain have the potential to overcome limitations of conventional echo though widespread clinical use remains to be seen. Volumetric methods using cardiac magnetic resonance (CMR) and computed tomography (CT) provide accurate assessment of RV function without geometric assumptions. In addition, tissue characterization imaging for myocardial scar and fat using CMR and CT provides important information regarding the RV beyond structure and function alone and has clinical applications for diagnosis and prognosis in a broad range of pathologies. Limitations also exist for these two advanced modalities including availability and patient suitability for CMR and need for contrast and radiation exposure for CT. The complementary role of each modality for the RV as well as emerging evidence for the use of each imaging method in diagnosis and management of RV pathologies are outlined in this study.

Introduction

Right ventricular (RV) assessment using complementary multi-modality imaging methods has drastically improved understanding of right ventricular anatomy and function. Echocardiography (echo) represents the most widely available tool to assess RV function, though its limitations in evaluation of the RV are well described. The emergence of advanced echo methods including 3D echo and strain imaging has the potential to overcome known limitations of traditional echo techniques. CMR and CT offer volumetric assessment of the right ventricle with high spatial resolution.

Right Ventricle Background

Anatomy and Function

The RV wraps around the left ventricle (LV) and is pyramidal in shape. Three distinct anatomic regions give rise to functionally distinct segments: the inflow tract, the body and

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the outflow tract. The RV is distinct from the LV in that it has a more apically displaced tricuspid valve (TV) septal leaflet relative to the mitral valve, a moderator band, three or more papillary muscles, a trileaflet tricuspid valve, and coarse trabeculations. In addition, the RV has a thinner wall and a mass one fifth of that of the LV.

The RV myocardium is made up of two layers. The first is a deep, subendocardial layer of longitudinal fibers that result in systolic contraction of the base toward the apex. The second is a superficial circumferential layer of fibers responsible for inward contraction. RV systolic function is characterized by RV free wall motion, the contraction of spiral muscles that enable basal-apical shortening characteristic of systole and interventricular septal motion, which allows for biventricular interdependence.

The RV's predominant motion involves longitudinal shortening. This includes systolic descent of the basal portion of the free wall toward the apex and peristaltic contraction from the inflow to the outflow portions of the RV. Unlike in the LV, twisting and rotational movements do not contribute significantly to RV contraction.

Cardiovascular Outcomes Are Predicted by RV Function

Increasing data support the importance of RV function with respect to clinical outcomes in a broad range of conditions. RV function quantified on echo and SPECT has been shown to be linked to increased morbidity and mortality, including prolonged hospital stays in a broad cohort of patients with ischemic and non-ischemic cardiomyopathy.^{1,2,3,4} RV function has also been shown to be linked to adverse cardiac outcomes and impaired functional status among patients with coronary artery disease^{5,6}. Lastly prior studies have demonstrated RV size and function to be a critical prognostic indicator in pulmonary arterial hypertension (PAH) and congenital heart disease.^{7,8,9,10} Despite the role of the RV in stratification of prognosis, non-invasive evaluation of the RV remains challenging due to several key anatomic factors.

Challenges

The RV is crescentic in shape and, unlike the LV, cannot be characterized using simple geometric assumptions. The RV has three distinct anatomical components: the inlet, body and outlet – these three components of the RV cannot be simultaneously imaged in a single 2D plane. Furthermore, extensive trabeculations of the RV result in difficulties with image analysis leading to variability in reproducibility and accuracy. Marked load dependence can also lead to variation in shape and size, which can lead to day-to-day variation in volumes and ejection fraction. From a technical standpoint, the RV's retrosternal position results in difficulties with ultrasound wave transmission¹¹ and linear dimensions and area can differ markedly with minor rotations in the transducer¹² during echo acquisition.

Multi-Modality Imaging

Using multiple imaging modalities to assess the RV enables evaluation of several key characteristics including volume, shape, mass, and tissue properties.¹³ The emergence of additional techniques, including strain using speckle tracking, and three-dimensional echo,

as well as CMR and CT, allow for even better characterization of the RV. Strength and limitations of each modality are outlined in Table 1.

While CMR is currently considered the reference standard for evaluation of the RV, due to wider availability, two-dimensional (2D) echo is most frequently used in clinical practice. While 2D echo allows for calculation of RV wall thickness and size, three-dimensional (3D) echo provides en face planimetry of volumes and also provides full 3D dataset to assess for RV structural and regional abnormalities. Both 3D echo and CMR allow for absolute, accurate calculation of RV volume and RVEF. However, additional 2D echo methods, including fractional area shorting, TAPSE, the Tei index, Doppler tissue imaging and speckle tracing of the RV free wall, provides accurate assessment of the RV when used together thereby supporting 2D echo use as a screening tool. When echo assessment is inadequate and CMR is unavailable or unsuitable, CT is also used for quantitative RV assessment.¹⁴

Echocardiography

RV Linear Dimensions

Complex RV geometry and the lack of specific anatomic reference points make quantification of 2D linear measurements a challenge. Rather than using the conventional apical four-chamber view to calculate RV linear dimensions and areas, the RV-focused apical four-chamber view, accessible with a lateral or medial transducer orientation, allows for better estimation of dimensions.¹⁵ Guideline-driven recommendations emphasize that RV size should be measured from a four-chamber view, and that it be evaluated in the context of the left ventricle. A qualitative assessment of the RV using the LV as a reference in a standard apical four-chamber view provides a frame of reference. Without fixed reference points that ensure optimal RV linear measurements, the current recommendation is to make basal and mid cavity measurements followed by a longitudinal measurement.¹⁶

Further studies have validated the use of several linear measurements with 2D echo to improve accuracy. A study of 272 patients with CAD who underwent echocardiography and CMR within a narrow interval found that it was feasible to obtain a complete set of linear dimensions for all patients, and measurements made in parasternal long axis right ventricular outflow tract (RVOT) and four-chamber RV basal diameter were well-correlated with CMR volumes.¹⁷ In another study, linear fractional shortening on echo was used as a measure of RV dysfunction in a population of 168 patients with HFrEF who underwent echocardiography and CMR within a narrow interval. All fractional shortening indices were lower among patients with RV dysfunction, and acquisition of these indices was feasible in 93% of the patients within the population. When compared to CMR-quantified RVEF, fractional shortening measurements were independently associated with EF.¹⁸

RV Systolic Function: TAPSE, S', FAC and RIMP

Several methods are used to calculate RV systolic function, including tricuspid annular plane systolic excursion (TAPSE), tissue Doppler-derived tricuspid lateral annular systolic velocity (S'), 2D fractional area change (FAC), and RV index of myocardial performance (RIMP).

TAPSE is obtained from a standard apical four-chamber view and measures systolic excursion of the RV annular segment along its longitudinal plane. The assumption is that the greater the RV systolic excursion measurement, the greater the function of the RV. Measurement of RV systolic function by way of TAPSE is simple, less dependent on optimal image quality, and fairly reproducible. However, the measurement is made in a single RV segment to represent a complex 3D structure. Therefore, it is both angle and load dependent.¹⁶ RV dysfunction as calculated by TAPSE has been more associated with the development of new onset heart failure in non-obese patients versus obese patients following acute myocardial infarction (MI).¹⁹

Systolic excursion velocity, known as RV S' , represents the longitudinal velocity of excursion of the tricuspid annulus and basal free wall segment of the RV by way of pulsed tissue Doppler and color-coded tissue Doppler.¹⁶ These are valuable regions for measurement within the RV given that they are among the most reliably and reproducibly imaged areas. An apical four-chamber view is used with tissue Doppler mode region of interest to highlight the RV free wall. S' is read as the highest systolic velocity. Pulsed tissue Doppler derived S' is considered a reproducible measure to assess basal RV function. Color-coded tissue Doppler has less evidence and a wider confidence interval, so it is currently used primarily for research. Limitations include angle dependence, technical issues such as alignment difficulties, and a lack of validation in non-sinus rhythm.

FAC is a percentage derived from the difference between end-diastolic area and end-systolic area of the RV, divided by end-diastolic area and multiplied by 100.¹⁶ RV FAC correlates well with RVEF determined by CMR.²⁰ RV dysfunction, defined by percent of FAC decrease, was identified as an independent predictor of death and the development of HFrEF following MI.²¹ The VALIANT ECHO study then demonstrated that decreases in FAC after MI were associated with an increased risk of non-fatal and fatal cardiovascular outcomes, including heart failure and stroke.²² Limitations to widespread use of FAC center on poor reproducibility, challenges in image quality and discernment of endocardial trabeculations from the free wall borders, and RV apical foreshortening. Furthermore, the RV outflow tract is not part of the calculation, so its contribution is left out.

RIMP allows for an estimate of RV systolic and diastolic function. It is defined as the ratio of isovolumic time to ejection time and is obtained by way of pulsed Doppler and tissue Doppler methods.¹⁶ It depends on a constant R-R interval in order to minimize error. Furthermore, it is less reliable with elevated right atrial (RA) pressures. RIMP continues to have utility in the determination of RV function across a range of presentations. It is highly reproducible and enables calculation of RV function. In a recent study of 268 patients post-TAVR, measurements of RV dysfunction by way of RIMP were associated with worse survival following the procedure.²³ However, it is important to avoid RIMP if patients have varying R-R intervals and elevated RA pressures.

3D Echocardiography

There are numerous advantages to 3D echocardiography. First, it allows visualization of inflow, outflow and apical regions of the RV without geometric assumptions. In addition, the technique is well validated against CMR derived volume (though typically underestimated in

CMR).²⁴ The validation of 3D echo against CMR has also been demonstrated in a population of patients with LV dysfunction.²⁵ 3D echo measurements also correlate well with data obtained by 2D and Doppler methods.²⁶ Calculation of RV volumes by way of 3D imaging requires specific equipment and training and depends heavily on adequate 2D image quality, a regular rhythm, and patient cooperation. In addition to RV and stroke volumes, ejection fraction can also be calculated.¹⁵ The absence of sufficient established reference values was cited as a limitation in the past; however, reference values are now available (Table 2).¹⁵

Recent analyses demonstrate the prognostic value of RVEF calculated by 3D echo with a significant association between 3D RVEF and future cardiac death and major adverse cardiac events.²⁴ 3D echo will also play a key role prior to and following percutaneous valve replacement.^{27, 28} In a study that compared 2D versus 3D echo methods in a population of patients with congenital heart disease, it was found that 3D echo improved RV size and function assessment.²⁹

Strain

Automated functional imaging allows for the assessment of global and regional RV function. Myocardial strain can be evaluated by tracking frame-to-frame movement of the speckles, or natural acoustic markers, within the myocardium on two-dimensional gray scale images. This method does not rely on geometric assumptions. It provides a sensitive and rapid measure of segmental, mechanical changes within the RV as well as global longitudinal RV function.³⁰ Evaluation of the RV is performed in a two-chamber view. Speckle tracking is an angle-independent method, which is based upon routine 2D images.

In a study of 125 patients, global longitudinal RV strain measurements were obtained with manual tracing. These strain measurements were found to correlate well with standard measures of RV chamber and RVOT performance. TAPSE and RVOT systolic excursion were noted to correlate most closely with strain measures.³¹ Global longitudinal strain measures were also found to be predictive of outcomes in a population of 98 patients with HFrEF, and in another study of 60 patients with HFrEF, global longitudinal strain was noted to be the only variable associated with cardiac death or heart failure hospitalization.^{32, 33} Strain in this population of 60 patients was a stronger predictor of outcome than TAPSE, RV fractional area change, RV myocardial performance index and tissue Doppler peak myocardial velocity

Cardiac MRI

CMR represents the reference standard to accurately assess the dimensions, mass, and function of the RV. CMR provides high-resolution 3D images of the RV, which enable accurate assessments of RV systolic and diastolic volumes, which can then be used to calculate ejection fraction. Steady-state free precession (SSFP) is the pulse sequence typically used for cine-CMR for volumetric quantification and provides outstanding endocardial definition. CMR phase velocity encoded imaging can also be used to calculate flow through semilunar and AV valves, allowing for quantification of regurgitant fractions, cardiac output and shunt fraction.¹² CMR methods correlate closely with in vivo pathology;

it is accurate and highly reproducible leading to minimal operator variation. Fully automated segmentation framework now exists for the RV³⁴ and further work is needed to validate these methods to increase efficiency. Limitations of CMR includes breath hold requirement for image acquisition, patient contraindication including pacemaker/defibrillator as well as cost and availability issues. Methods including parallel imaging and navigator based techniques can be used to truncate or eliminate breath hold times.

CMR is known to provide valuable prognostic information for the RV. In addition to accurate quantification of RV size and function, CMR provides information regarding RV tissue properties, which cannot be done with existing echo techniques. For example, in pulmonary hypertension (PH), late gadolinium enhancement (LGE) at the RV insertion point (RVIP) has been shown to provide risk stratification for morbidity and mortality incremental to traditional CMR indices including EF. LGE at RVIP has been associated with more advanced disease and poor prognosis PH.³⁵ Non-ischemic fibrosis identified on CMR has also been linked to greater degree of RV dilation and afterload and is independently associated with increased mortality in patients with cardiomyopathy.^{36, 37} In patients with arrhythmogenic RV Cardiomyopathy (ARVC), CMR indices are critical components of the diagnostic criteria, which includes CMR derived RVEF and end diastolic volume.³⁸ RV volumetric and functional assessment is important in a wide range of congenital heart disease conditions. For example, RV functional indices are used as for assessment of pulmonary valve replacement in patients with repaired tetralogy of Fallot.

CT

CT functional assessment of the RV is performed using retrospective ECG gating. While this method requires increased radiation exposure, it provides dynamic images throughout the cardiac cycle allowing for precise and reproducible quantification of RV volume and function.³⁹ While CMR is traditionally used more frequently for quantification of volumes and ejection fraction, CT can be used as an alternative modality when CMR is contraindicated or unavailable.¹⁴ CT like CMR provides multiplanar imaging of the RV with excellent endocardial definition and high spatial resolution.³⁸ CT can also provide assessment of tissue properties including identification of myocardial replacement with fat as seen in ARVC.

Setting CT apart from echo and CMR is its ability to comprehensively assess the pulmonary arterial vasculature as well as lung parenchyma and thereby provide information regarding pathophysiology of RV dysfunction and its sequelae. Concurrent chest CT and cardiac CT can be employed as a single exam in select cohorts for this purpose. Limitations to widespread use of CT are due to use of nephrotoxic contrast and ionizing radiation, and limited accessibility as compared to echo. It is also important to note that unlike echo and CMR, CT is unable to assess right-sided valvular and hemodynamic parameters. Lastly, non-gated CT has also been shown to be useful in the evaluation of the RV. For example, in acute pulmonary embolism, ventricular diameter ratio has been noted as an independent predictor of 30-day mortality.⁴⁰ Septal displacement and contrast reflux within the inferior vena cava are also implicated in RV failure and worse outcomes.⁴¹

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Figure.

M-mode derived TAPSE and tissue Doppler measured S' obtained in apical four-chamber view (normal >1.6 cm and >10 cm/s, respectively) [top left]. Speckle tracking echo for RV global longitudinal strain assessment (normal $>20\%$) [bottom left]. 3D full volume acquisition in RV focused view for RV volumes and ejection fraction (normal $>44\%$) [right].

Table 1

Complementary Role of CMR, CT and Echo

	CMR	CT	2D Echo	3D Echo
Imaging Variables				
RV Systolic Function				
Global Assessment	✓	✓✓	✓✓	✓✓
Regional Assessment	✓✓	✓✓	✓	✓✓
RV Volumes	✓✓	✓✓	-	✓✓
Tissue Characterization (e.g. fat)	✓✓	✓	-	-
RV Hemodynamics (e.g. PA pressure)	-	-	✓✓	-
Accessibility				
Availability/portability	-	-	✓✓	✓✓
Speed of Exam	-	✓✓	✓✓	✓
Contrast/Radiation Exposure	-	✓✓	-	-

Table 2

Right Ventricular Normative Values

	Cardiac Magnetic Resonance ¹		3D Echocardiography ²		Computed Tomography ³	
	Men	Women	Men	Women	Both genders	
	Mean ± SD (95% CI)	Mean ± SD (95% CI)	Mean ± SD (95% CI)	Mean ± SD (95% CI)	Mean ± SD (95% CI)	Mean ± SD (95% CI)
RV end-diastolic volume						
mL	142 ± 31 (96–201)	110 ± 24 (77–155)	-	-	175 ± 48 (81–269)	
mL/m ²	82 ± 16 (57–101)	69 ± 14 (49–95)	61 ± 13 (35–87)	53 ± 11 (32–74)	93 ± 20 (54–133)	
RV end-systolic volume						
mL	54 ± 17 (28–85)	35 ± 13 (18–57)	-	-	82 ± 29 (25–139)	
mL/m ²	31 ± 9 (17–48)	22 ± 8 (10–34)	27 ± 9 (10–44)	22 ± 7 (8–36)	-	
RVEF (%)	62 ± 1 (50–75)	69 ± 1 (58–81)	-	-	58 ± 8 (42–74)	