Preoperative Risk Stratification of Right Ventricular Function Utilizing Cardiac Magnetic Resonance Imaging Compared With Echocardiographic and Hemodynamic Parameters

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Accurate right ventricle functional analysis prior to mechanical circulatory support continues to be valuable for preoperative stratification of patients at risk for developing right ventricular (RV) failure. While cardiac magnetic resonance imaging (CMR) remains the gold standard, CMR is limited by availability and patient-specific contraindications. Further investigation of other imaging modalities would be beneficial as it may serve as a surrogate to identifying RV systolic dysfunction. A single-center, retrospective study including 29 patients with advanced heart failure was performed. All patients underwent ventricular functional analysis with both CMR and echocardiography, and 19 patients underwent right heart catheterization. Predictability with multimodal assessment of RV function was determined using logistic regression methods. Of the 29 participants, 10 had severe RV dysfunction. Tricuspid annular plane of systolic excursion was a modest predictor of RV dysfunction with odd ratio (OR) of 0.07 (0.01–0.72) and c-statistic of 0.79. Invasive hemodynamic measurement of cardiac index by thermodilution method was also predictive of RV dysfunction but failed to reach statistical significance (OR of 0.03, <0.001–1.28) with c-statistic of 0.83. The role of invasive hemodynamic data in predicting RV function compared with CMR should be further explored among patients with advanced heart failure. *ASAIO Journal* 2020; 66:547–552.

Key Words: right ventricular failure, cardiac magnetic resonance, echocardiography, right heart catheterization

The burden of heart failure is increasing with a projected estimate of 8 million individuals by 2030.[1,2] The shortage in supply of donor hearts for definitive treatment of advanced heart failure necessitates bridging therapies such as total artificial heart and ventricular assist device (VAD). Despite significant advances in mechanical circulatory support devices, a high mortality risk has been persistently associated with 10–40% of patients developing right ventricular failure (RVF) after LVAD implantation. The cause of RVF can be multifactorial due to volume overloading in the setting of mechanical support, septal shift into the left ventricle, and worsening tricuspid regurgitation after device implantation.[3–8]

The Interagency Registry for Mechanically Assisted Circulatory Support defines RVF according to documented elevation in central venous pressure and clinical manifestations, such as peripheral edema, ascites, and worsening hepatic or renal dysfunction.[5] Current risk prediction models for RVF reflect demographic, clinical, hemodynamic, and end-organ function data, but very few studies have incorporated imaging data.[9] Adding imaging factors to RVF predictors in perioperative VAD patients can improve LVAD candidate selection and patient management.

The ideal imaging modality for accurate estimation of right ventricular (RV) function remains elusive given the unique advantages and disadvantages of each exam.[8,10,11] Echocardiography, while widely available, provides an accurate estimate of left ventricular function, but the accuracy for RV functional analysis have been inconsistent across studies.[5,15] Cardiac magnetic resonance imaging (CMR) is considered the reference standard for assessment of both biventricular volume and function; however, it is relatively expensive compared with echocardiography and not widely available.[12,13] Performance of CMR is further hindered by contraindications including implanted cardiac devices or uncontrolled arrhythmias that may lead to MRI image degradation and therefore less accurate estimates of ventricular size and function.[14]

Conversely, invasive RV functional assessment with right heart catheterization (RHC) and hemodynamic monitoring can be used alone or in conjunction with imaging. While RHC is a suitable alternative to imaging for right heart assessment, it is associated with the risks of invasive catheterization. Also, hemodynamic parameters of RV function can by affected by multiple factors during the procedure including individual technique, loading conditions, and hypoxia.

The purpose of this study was to identify the most accurate parameters for predicting RV systolic dysfunction comparable to CMR using more widely available modalities.

Methods

Patient Study Group

We performed an Institutional Review Board approved, single-center, retrospective analysis from April 2013 to July 2015 in 29 patients who underwent evaluation for advanced heart failure to determine the necessity of definitive heart therapy. All patients underwent both a 2-dimensional (2D) echocardiogram

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Table 1. Demographics of Patients Undergoing CMR Analysis for LV Heart Failure Left Ventricle (CMR Analysis)

	Nonsevere LVF	Severe LVF	*p* Value
No. patients	4	25	–
Males	3 (75%)	22 (88%)	0.47
White	3 (75%)	14 (56%)	0.62
Diabetes	2 (50%)	7 (28%)	0.57
Hypertension	4 (100%)	13 (52%)	0.12
Dyslipidemia	1 (25%)	10 (40%)	1.00
Smoker	1 (25%)	5 (20%)	1.00
Atrial fibrillation	1 (25%)	3 (12%)	0.47
GFR >60	2 (50%)	16 (64%)	0.62
Cardiomyopathy	1 (25%)	9 (36%)	1.00
Age (years)	49.50 ± 18.59	58.60 ± 12.98	0.47
BMI (kg/m^2)	28.60 ± 8.87	26.04 ± 4.97	0.68
Creatinine (mg/dl)	2.50 ± 2.64	1.15 ± 0.44	0.42

BMI, body mass index; CMR, cardiac magnetic resonance imaging; GFR, glomerular filtration rate.

and CMR as part of their routine care during the same inpatient admission or within 1 week after hospital discharge. Nineteen of the patients also obtained RHC for hemodynamic assessment of RV function during the same inpatient admission.

Patients were categorized into severe or nonsevere left ventricular failure (LVF) (**Table 1**) and RVF (**Table 2**). Severe LVF was defined as less than 30% left ventricular ejection function (LVEF) using quantitative CMR as the reference standard and qualitative 2D echocardiogram. Severe RVF was classified with the threshold of less than 25% right ventricular ejection fraction (RVEF) detected by quantitative assessment with CMR.

Patient demographics including age, sex, body mass index, race, and comorbidities and hemodynamic data from RHC were obtained from Electronic Medical Records (EMR). Picture archiving and communications system (PACS) and EMR were reviewed for data regarding ventricular size and function provided by echocardiographic and CMR parameters.

Echocardiographic Measurements

Comprehensive 2D echocardiogram examinations were performed on each subject during resting conditions in both the supine and left lateral position. The images were stored digitally and analyzed on a dedicated imaging platform (Xcelera Cardiology Imaging Management, Philips Healthcare, Foster City, CA) by an independent observer who was blinded to the CMR measurements. The reviewer provided qualitative assessments of LVEF using visual estimation.

Table 2. Demographics of Patients Undergoing CMR Analysis for RV Heart Failure Right Ventricle (CMR Analysis)

	Nonsevere RVF	Severe RVF	*p* Value
No. Patients	19	10	–
Males	16 (84.21%)	9 (90%)	1.00
White	9 (47.37%)	8 (80%)	0.13
Diabetes	7 (36.84%)	2 (20%)	0.43
Hypertension	12 (63.16%)	5 (50%)	0.69
Dyslipidemia	7 (36.84%)	4 (40%)	1.00
Smoker	3 (15.79%)	3 (30%)	0.63
Atrial fibrillation	4 (21.05%)	0 (0%)	0.27
GFR >60	14 (73.68%)	4 (40%)	0.11
Cardiomyopathy	6 (31.58%)	4 (40%)	0.70
Age (years)	57.79 ± 14.21	56.50 ± 13.81	0.87
BMI (kg/m^2)	25.18 ± 5.93	28.69 ± 3.89	0.03
Creatinine (mg/dl)	1.35 ± 1.29	1.31 ± 0.47	0.16

BMI, body mass index; CMR, cardiac magnetic resonance imaging; GFR, glomerular filtration rate; RV, right ventricular; RVF, right ventricular failure.

Right ventricular function was qualitatively estimated as normal, mild, moderate, or severe dysfunction. Echocardiographic assessment of RV function was evaluated using the conventional parameters of tricuspid annular plane systolic excursion (TAPSE) and the fractional area of change (FAC). All TAPSE measurements were obtained by echocardiographic M-mode by placing the M-mode cursor at the junction of the tricuspid valve (TV) annulus and the base of the RV free wall. To obtain FAC, the endocardium of the RV was traced from the annulus along the free wall to the apex and back to the annulus along the interventricular septum both in systole and diastole to obtain the end-systolic area and end-diastolic area, respectively. The FAC was calculated as $\left[\frac{\text{EDA}-\text{ESA}}{\text{EDA}}\right]\times 100$.

Multiple diastology based parameters of RV function were evaluated including right atrial pressure (RAP), peak TV regurgitation velocities, and time-velocity integral (TVI). Right atrial pressure estimation was performed using inferior vena cava dimension and collapsibility which was measured at end-expiration from the subcostal view proximal to the junction of the hepatic vein. The continuous-wave Doppler signal of the tricuspid regurgitant (TR) jet was used to estimate the peak TR velocity (TR V_{max}). TVI, which indicates stroke-work distance, was traced from the pulse-Doppler signal in the RV outflow tract.

Invasive Hemodynamic Measurements

Ventricular functional analysis using dynamic hemodynamic assessment was performed using RHC in 19 patients. RHC was performed utilizing a pulmonary artery catheter placed either via right internal jugular or femoral arterial approach during resting conditions in the supine position. Direct measurements of RAP, pulmonary artery systolic pressure, PA diastolic pressure, mean PA pressure (mPAP), cardiac output, and cardiac index were obtained using thermodilution methods. Pulmonary artery wedge pressure was also obtained, and real-time tracings were obtained by a monitor display during performance of the catheterization. Pulmonary vascular resistance was calculated as $\left[\frac{\text{mPAP}-\text{PAWP}}{\text{CO}}\right]$, and cardiac index was calculated as $\left[\frac{\text{CO}}{\text{Body Surface Area (BSA)}}\right]$. Right ventricular stroke-work index (RVSWI) was calculated as $\left[\text{Stroke volume index (SVI)}\right]\left[\text{mPAP}-\text{RAP}\right]\left[0.0136\right]$.

Cardiac Magnetic Resonance Imaging Measurements

Cardiac magnetic resonance imaging was performed on resting participants in the supine position using a 1.5T MRI (Siemens Aera, Siemens Healthcare Solutions, Erlangen, GE) scanner with electrocardiographic gating that included multiplanar long-axis cinematic views of heart throughout the cardiac cycle. Complete coverage of the ventricular short-axis

was obtained from base to apex using 0.8 mm thick images with an 8 mm gap between images.

All images were stored digitally on PACS and were analyzed offline using both PACS and a commercial post-processing cardiac functional analysis software (Syngo.*via*, Siemens Health Solutions, Erlangen, GE). Image analysis was performed by an independent reviewer, a fellowship-trained radiologist with seven years of experience.

Estimates of both LV and RV size and function were performed using semi-automated contouring of the endocardial borders of the both ventricles in both systole and diastole using either manual or edited contours. The ventricular end-diastolic volume (EDV) and end-systolic volume (ESV) were derived by summing the areas of the ventricular cavities on each separate slice and multiplying by the sum of slice thickness and image gap in both diastole and systole, respectively. The stroke volume for each ventricle was automatically derived by post-processing software by subtracting the ESV from the EDV of each ventricle, and these values were utilized to calculate the ejection fraction for both ventricles.

Statistical Analysis

The left and right ventriular functional and size parameters generated by CMR were utilized for sorting severity of biventricular dysfunction. Analysis of the cohorts having either severe versus nonsevere dysfunction of either ventricle was presented as a mean while χ^2 were presented for categorical variables. Statistical comparison of the severe and nonsevere ventricular dysfunction cohorts was performed using either t-test for continous variables or χ^2 for categorical variables. The predictive ability of individual echocardiographic and hemodynamic parameters for assessing RV function was performed by calculating the c-statistic using logistic regression methods. Two-sided p values <0.05 were considered statistically significant, and a kappa statistic was used to measure the agreement between echocardigraphy and CMR for grading the severity of dysfunction of both ventricles.

Results

A total of 29 patients with suspected heart failure related to ischemic cardiomyopathy in 15 patients and nonischemic cardiomyopathy in the remaining 14 patients underwent evaluation with both CMR and echocardiogram to determine biventricular size and function. Ten patients were classified as having severe RV dysfunction, defined as less than 25% RVEF when calculated with CMR, with 4 of patients having severe RV dysfunction related to ischemic cardiomyopathy and 6 patients with nonischemic cardiomyopathy. The mean ages for patients with and without severe RV dysfunction were 57.8 and 56.5 years, respectively. Analysis for clinical determinants associated with severe RV dysfunction did not demonstrate any significant correlation with severe RV dysfunction (**Table 3**).

Among the echocardiographic variables available for analysis, TAPSE modestly predicted RV dysfunction with odd ratio (OR) of 0.07 (0.01–0.72) and c-statistic of 0.79 (**Table 4**). When analyzing the hemodynamic parameters for the 19 subjects who underwent RHC, thermodilution-derived CI also appeared to be predictive of severe RV dysfunction, but this association failed to reach statistical significance with an OR of 0.03 (<0.001–1.28) and c-statistic of 0.83 (**Table 5**).

Table 3. Identification of Demographic Factors Predictive of RVF Severity

	Unadjusted		
Demographics	OR (95% CI)	C-Statistic	*p* Value
Age	0.99 (0.94, 1.05)	0.52	0.81
BMI	1.14 (0.97, 1.35)	0.77	0.12
White	4.44 (0.74, 26.68)	0.66	0.10
Diabetes	0.43 (0.07, 2.61)	0.58	0.36
Dyslipidemia	1.14 (0.24, 5.50)	0.52	0.87
Smoker	2.29 (0.37, 14.25)	0.57	0.38
Creatinine	0.96 (0.45, 2.04)	0.33	0.92
GFR >60	0.24 (0.05, 1.21)	0.67	0.08
Cardiomyopathy	1.44 (0.29, 7.10)	0.54	0.65

BMI, body mass index; OR, odds ratio; GFR, glomerular filtration rate; RVF, right ventricular failure.

When evaluating for LV dysfunction, a total of 25 patients were found to have severe LV systolic dysfunction as determined by having an LVEF of less than 30% when analyzed with CMR. Of these 25 patients, a total of 13 had severe LV failure determined to be related to ischemic cardiomyopathy and 12 had a clinical history of nonischemic cardiomyopathy. Of the aforementioned patients with severe RV systolic dysfunction, all 10 patients with severe RV systolic dysfunction also were determined to have severe RV failure when both were calculated by CMR. No clinical demographics were found to meet statistical significance when correlating for severe LV dysfunction (**Table 6**). The kappa statistic determining agreement for

Table 4. Identification of Echocardiographic Parameters Predictive of RVF Severity

Echocardiogram Parameters	OR (95% CI)	C-Statistic	*p* Value
RV EF (Severe)	2.12 (0.25, 17.93)	0.55	0.49
TAPSE	0.07 (0.01, 0.72)	0.79	0.03
RV EDA	1.14 (0.98, 1.33)	0.73	0.09
RV ESA	1.08 (0.94, 1.23)	0.62	0.27
RV FAC	1.02 (0.96, 1.08)	0.60	0.56
TR max V	1.26 (0.33, 4.89)	0.52	0.74
PASP	1.00 (0.95, 1.06)	0.54	0.92
TV E	16.61 (NA)	0.70	0.21
TV A	0.14 (NA)	0.55	0.82
TV Dec time	12.02 (NA)	0.55	0.68
RV S'	0.25 (0.03, 1.92)	0.94	0.18
PAeDV	3.94 (0.39, 40.05)	0.74	0.25
PAeDP	1.06 (0.92, 1.23)	0.75	0.43
PA VTI	0.80 (0.63, 1.03)	0.73	0.08
RA area	1.08 (0.95, 1.22)	0.63	0.27
IVC size	2.99 (0.41, 22.08)	0.64	0.28
IVC sniff size	2.15 (0.32, 14.34)	0.65	0.43
RAP	1.06 (0.82, 1.36)	0.59	0.67
RV ET	<0.001 (<0.001, 0.40)	0.73	0.04
PVR	2.62 (0.95, 7.19)	0.72	0.06

EDA, end-diastolic area; ESA, end-systolic area; FAC, fractional area of change; IVC, inferior vena cava; OR, odd ratio; PAeDP, pulmonary artery end-diastolic pressure; PAeDV, pulmonary artery end-diastolic velocity; PASP, pulmonary artery systolic pressure; PVR, Pulmonary vascular resistance; RAP, right atrial pressure; RVF, right ventricular failure; TAPSE, Tricuspid annular plane of systolic excursion; TR, tricuspid regurgitant; TV, tricuspid valve.

Table 5. Identification of Hemodynamic Parameters Predictive of RVF Severity

RHC Parameters	OR (95% CI)	C-Statistic	*p* Value
HR	1.05 (0.98, 1.13)	0.70	0.14
RAP	1.04 (0.91, 1.19)	0.57	0.61
PASP	1.00 (0.93, 1.08)	0.48	0.99
PADP	1.02 (0.90, 1.15)	0.59	0.77
mPAP	1.02 (0.97, 1.07)	0.59	0.44
CO (Fick)	0.66 (0.25, 1.77)	0.73	0.41
CO (Thermodilution)	0.57 (0.24, 1.36)	0.69	0.21
Cardiac index (Fick)	0.25 (0.01, 4.32)	0.73	0.34
Cardiac index (Thermodilution)	0.03 (<0.001, 1.28)	0.83	0.07
PAW	1.08 (0.94, 1.23)	0.68	0.27
PVR	0.62 (0.28, 1.40)	0.67	0.25
RVSVI (Fick)	0.79 (0.56, 1.12)	0.77	0.19
RVSVI (Thermodilution)	1.00 (0.99, 1.01)	0.61	0.47

CO, cardiac output; mPAP, mean PA pressure; OR, odd ratio; PADP, PA diastolic pressure; PASP, pulmonary artery systolic pressure; PVR, Pulmonary vascular resistance; RHC, right heart catheterization; RVF, right ventricular failure.

RV dysfunction between CMR and 2D echocardiogram revealed little to no agreement with a kappa statistic of 0.11 (–0.22 to 0.44) (**Table 7**) while a significantly higher agreement was found for determination of severe LV dysfunction with a kappa of 0.39 (0.01–0.76) when comparing the two imaging modalities (**Table 8**).

Discussion

A single-center, retrospective analysis was conducted to evaluate preoperative risk stratification of RV function using CMR, 2D echocardiogram, and RHC in patients being evaluated for heart transplantation or mechanical circulatory support. Echocardiogram with 2D measurements of LV function are more frequently used in clinical practice and are well-established indicators of prognosis in congestive heart failure (CHF).[15] However, after the onset of CHF, the relationship between LVEF and mortality is less clear, and other markers such as indicators of RV function are needed to identify high risk patients.[16] Furthermore, accurate assessment of the function of both ventricles has become increasingly important given the high mortality risk associated with development of RVF after LVAD placement.

Table 6. Factors Predictive of CMR LVF Severity

	OR (95% CI)	C-statistic	*p* Value
Age	0.99 (0.93, 1.05)	0.54	0.68
BMI	1.13 (0.96, 1.33)	0.74	0.15
White	3.50 (0.58, 21.16)	0.64	0.17
Diabetes	0.53 (0.09, 3.28)	0.56	0.5
Hypertension	0.43 (0.09, 2.14)	0.6	0.3
Dyslipidemia	0.75 (0.14, 3.90)	0.53	0.73
Smoker	2.83 (0.45, 18.04)	0.59	0.27
Creatinine	0.42 (0.12, 1,42)	0.64	0.16
GFR >60	1.78 (0.21, 14.86)	0.57	0.6
Cardiomyopathy	1.69 (0.15, 18.71)	0.56	0.67
LV EF (Severe)	12.00 (1.02, 141.34)	0.78	<0.05

BMI, body mass index; CMR, cardiac magnetic resonance imaging; GFR, glomerular filtration rate; OR, odd ratio.

Table 7. Agreement Between Echo and CMR RVF Severity

	CMR Analysis	
Echocardiogram-Analysis	Nonsevere RVF	Severe RVF
Nonsevere RVF	17	8
Severe RVF	2	2
Kappa statistic: 0.11 (95% CI: –0.22, 0.44)		

CMR, cardiac magnetic resonance imaging; RVF, right ventricular failure.

While 2D echocardiography is the most commonly used imaging modality for initial evaluation of cardiac function in CHF patients, accurate estimation of RV function by echocardiography is difficult because of both its anterior intrathoracic position and complex geometry and mechanics.[13,17] Previous studies comparing 2D echocardiogram estimates of RV function with CMR have produced inconclusive results regarding general practice changes.[18]

Our study supports previous research demonstrating that TAPSE is associated with RV dysfunction measurements obtained from CMR.[15,16] Although there was only a modest correlation with RV dysfunction on CMR, TAPSE is probably the best widely available echocardiographic predictor of RV function and can serve as a useful biomarker of RV function in patients presenting with clinically advanced heart failure.

2D echocardiogram with TAPSE as a prognostic factor is easily available, offers reproducibility, and is less dependent on image quality than other RV function echocardiographic parameters, such as FAC and diastolgy measurements. Tricuspid annular plane of systolic excursion has also demonstrated to be an independent predictive biomarker of increased mortality in advanced heart failure patients with a TAPSE of ≤14 mm, irrespective of the etiology or underlying heart rhythm.[14,16] Based on our results, we suggest that definitive echocardiographic assessment using a dedicated RV protocol with TAPSE can provide an acceptable substitute to CMR that is superior to radionuclide angiography and may alleviate the need for additional examinations that may expose the patient to ionizing radiation.[19]

However, we do acknowledge TAPSE provides an indirect and incomplete measurement of RV systolic function because its measurement is dependent on echocardiogram transducer angle and only provides a representation of longitudinal RV function.[17] Additionally, TAPSE exclusively assesses the RV free wall that consists predominantly of longitudinal and oblique myocardial fibers that produce base-to-apex shortening and have a greater role in emptying of RV chamber.[16,20] This retrospective study was unable to evaluate more advanced

Table 8. Agreement Between Echo and CMR LVF Severity

	CMR Analysis	
Echocardiogram-Analysis	Nonsevere LVF	Severe LVF
Nonsevere LVF	3	5
Severe LVF	1	20
Kappa statistic: 0.39 (95% CI: 0.01, 0.76)		

CMR, cardiac magnetic resonance imaging.

estimates of ventricular function using 3-Dimensional ventricular analysis with echocardiography. With the increasing availability of echocardiograms providing advanced analysis, these techniques may provide in the near future more accurate estimates of ventricular size and function utilizing applications of Simpson's rule that could be performed both before and after VAD placement.

Right heart catheterization, on the other hand, despite its risks, continues to provide useful direct assessment of RV filling pressures and function. Right heart catheterization is often performed in advanced CHF patients during periods of decompensation to assess volume status and guide therapies such as mechanical circulatory support or cardiac transplantation.[3,21] Recent studies have shown low RVSWI, elevated RAP, and low mPAP to be markers of RV dysfunction.[3,22] Compared with these previous studies, our findings were unable to replicate these hemodynamic parameter associations with severe RV dysfunction, and only thermodilution-derived CI was predictive of RV dysfunction. However, these results must be interpreted with caution because only 19 participants had hemodynamic parameters available, and we had inadequate power to make definitive conclusions regarding this subgroup. Multi-variate analysis with echocardiographic and RHC parameters demonstrates a higher correlation of RVF severity compared to CMR, the gold standard.

Our study is not without limitations. As previously stated, the small cohort has limited power to detect significant associations, particularly in the subgroup analyses that involved 19 participants with hemodynamic data. Second, our patients had reduced LVEF, and our findings may not be generalizable to those with CHF with preserved LVEF. We also had single measurements of RHC thus limiting us from assessing both intra-observer and intra-procedural variability. While acknowledging the small patient cohort, we find the lack of previous studies correlating the parameters of 2D echocardiographic and CMR in patients with advanced CHF suggests that these results could be beneficial for further prospective studies in this critical area.

Although TAPSE was obtained in all patients, other measurements of RV function such as TVs, FAC, and quantitative RVEF by 2D echocardiogram were not routinely obtained due to lack of a standardized right heart failure echocardiogram protocol for all advanced heart failure patients. Furthermore, our institutional 2D echocardiogram protocol did not routinely include more advanced estimates of left ventricular functional analysis, such as Simpson's rule, fractional shortening, and strain analysis; therefore, these techniques were unable to be routinely assessed in this patient cohort. While these advanced echocardiographic techniques may provide more accurate estimates of LV functional analysis and could possibly provide additional parameters to investigate the relationship between LVEF and mortality, for this investigation the strong correlation between CMR estimates of left ventricular systolic function and qualitative 2D echocardiogram estimates provides continued support that qualitative echocardiographic estimates of LV systolic function using 2D echocardiogram serve as an acceptable surrogate to the reference standards provided by CMR. We expect that with the continuing increase in availability of echocardiogram scanners that provide these techniques on a routine basis, that these parameters can be further investigated.

This study demonstrated that TAPSE is a reproducible measurement of RV function that can be used for risk stratification and evaluation of heart failure patients. Refinements in a time-efficient and cost-effective echocardiographic protocol, including comprehensive multi-parametric RV functional assessment and improvements in technologist skills, may improve evaluation of the anatomic variabilities that limit RV echocardiographic visualization. While these results support current practices, future studies evaluating the multiple echocardiographic and hemodynamic parameters of ventricular function should be applied prospectively to evaluate outcomes and potential of these parameters for the support of management decisions.

A final consideration is that while CMR provides the most accurate estimate of ventricular function, this exam is absolutely contraindicated after placement of a VAD due to the strong magnetic field. Further prospective studies could evaluate the change in echocardiographic and hemodynamic parameters after assist device placement, including TAPSE. Additional evaluation of the size and function of the RV could be performed after ventricular assist placement, which may serve to correlate with clinical outcomes and symptomatology.

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