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Echocardiographic Linear Fractional Shortening for Quantification of Right Ventricular Systolic Function - a Cardiac Magnetic Resonance Validation Study

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Abstract

Background—Echocardiography (Echo)-based linear fractional shortening (FS) is widely used to assess left ventricular dysfunction (LV_{dys}), but has not been systematically tested for right ventricular dysfunction (RV_{dys}).

Methods—The population comprised LV_{dys} patients with and without RV_{dys} (EF<50%) on cardiac MRI (CMR): Echo included standard RV indices (fractional area change [FAC], TAPSE, S' and FS in parasternal long axis (RV outflow tract [RV_{OT}]) and apical 4-chamber views (width [RV_{WD}], length [RV_{LG}])).

Results—168 patients underwent echo and CMR (3±3 days); FAC (46±9 vs. 28±11), TAPSE (1.9±0.4 vs. 1.5±0.3) and S' (11.4±2.3 vs. 10.0±2.6, all p < 0.001) were lower among RV_{dys} patients, as were FS indices (RV_{OT} 32±8 vs 17±10 | RV_{WD} 40±11 vs 22±12 | RV_{LG} 16±5 vs 9±4%; all p<0.001). FS indices yielded similar magnitude of correlation with CMR RVEF (r=0.73–0.56) as did FAC (r=0.70), which was slightly higher than TAPSE (r=0.47) and S' (r=0.31; all p<0.001). FS indices decreased stepwise vs. CMR RVEF tertiles, as did FAC (all p<0.001). In multivariate analysis, FS in RV_{OT} (regression coefficient 0.51 [CI 0.37–0.65]), RV_{WD} (0.30 [0.19–0.41]), and RV_{LG} (0.45 [0.20–0.71]; all p < 0.001) were independently associated with CMR RVEF. FS indices yielded good overall diagnostic performance (AUC: RV_{OT} 0.89 [CI 0.82–0.97] | RV_{WD} 0.87 [0.78–0.96] | RV_{LG} 0.80 [0.70–0.90]; all p<0.001) for CMR-defined RV_{dy} (RVEF<50%).

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Conclusions—RV linear FS provides RV functional indices that parallel CMR RVEF. Parasternal long-axis RV_{OT} width, 4-chamber RV width and length are independently associated with RVEF, supporting use of multiple FS indices for RV functional assessment.

Keywords

right ventricle; echocardiography; cardiovascular magnetic resonance

Introduction

Right ventricular (RV) systolic dysfunction impacts prognosis and therapeutic decision-making for heart failure patients, [1–3] among whom differentiation between isolated left ventricular (LV) and bi-ventricular (BiV) systolic dysfunction is of substantial importance. Echocardiography (echo) derived linear fractional shortening (FS) is widely used to assess LV function, and has been shown to correlate with volumetric quantification and clinical outcomes. [4–7] However, RV linear fractional shortening has yet to be validated, with geometric complexity of the RV raising concern as to the use of a single linear parameter for assessment of global RV function. Consistent with this, American Society of Echocardiography (ASE) guidelines include discussion of linear RV dimensions as indices of RV size, without insight as to the utility of fractional shortening for assessment of RV function.[8]

Recent work by our group has shown RV linear dimensions – as measured on routine echo without tailored imaging – to correlate with RV chamber size as quantified by the reference standard of cardiac magnetic resonance imaging (CMR).[9] Importantly, our data demonstrated linear dimensions obtained in different orientations to be independently associated with CMR-derived end-diastolic and end-systolic volume, supporting use of multiple linear indices when assessing RV size on echo. However, assessment of fractional shortening as an index of systolic function was limited by low prevalence of RV dysfunction, prohibiting systematic evaluation of this approach. Given the fact that linear fractional shortening can be measured in multiple orientations (a key advantage over established 2D echo indices such as Tricuspid annular plane systolic excursion [TAPSE] or peak tricuspid annular systolic velocity [S']) and retrospectively obtained in pre-existing datasets (potentially enabling stratification of RV function in large scale population-cohorts), lack of data concerning utility of this approach is a key gap in knowledge.

This study tested linear fractional shortening on echo as an index of RV dysfunction among a broad cohort of heart failure patients undergoing echo and CMR within a narrow interval. In all patients, a uniform echo protocol was performed – analysis was limited to conventional orientations (parasternal long axis, apical 4-chamber) acquired in nearly all echo exams, rather than tailored RV-focused imaging. Study aims were three-fold: (1) determine correlation of echo-quantified RV fractional shortening in different orientations with volumetric right ventricular ejection fraction (RVEF) as quantified by CMR, (2) compare linear fractional shortening to conventional echo indices of RV function (e.g. fractional area change [FAC], TAPSE, S'), (3) derive and validate linear fractional shortening cutoffs for diagnosis of CMR-evidenced RV dysfunction.

Methods

Population

The study comprised a cohort of patients with isolated LV and BiV systolic dysfunction ($EF < 50\%$), in whom CMR and echo were performed within a 2 week interval: patients were identified from a pre-existing clinical CMR registry of patients undergoing clinical imaging at Weill Cornell Medical College (New York, NY). LV and BiV dysfunction patients were matched (2:1) for gender and body size (BSA). CMR was used as the reference standard for cardiac function; patients with conditions known to compromise CMR quantification (i.e. atrial fibrillation) or with indeterminate landmarks with which to standardize RV linear dimensions (i.e. complex congenital heart disease) were excluded. No patients were otherwise excluded based on image quality or clinical characteristics.

Demographic data were collected with respect to heart failure related indices, including atherosclerosis risk factors, coronary artery disease history, and medication regimen. This study was conducted with approval of the Weill Cornell Institutional Review Board.

Imaging Protocol

Echo and CMR were each performed using standardized protocols.

Echocardiography—Echocardiograms were performed by experienced sonographers using commercially available equipment. Images were acquired in parasternal, as well as apical 2-, 3-, and 4- chamber orientations as detailed in ASE guidelines.[7, 8, 10] Ancillary imaging was performed to assess RV function, including M-mode for TAPSE, as well as tissue Doppler for S' and RV index of myocardial performance (RIMP), each of which was assessed in apical 4-chamber orientation.[8]

CMR—CMR was performed using 1.5 Tesla scanners. Cardiac structure and function were assessed via cine-CMR, for which data was acquired using a steady-state free precession pulse sequence: images were acquired in standard LV short- and long-axis planes. Short axis images were acquired throughout the RV such that images extended from the pulmonic valve through the RV apex.

RV Chamber Quantification

CMR and echo were quantified independently, blinded to clinical history and results of other modalities. Analyses were performed by dedicated readers with experience in each respective modality (echo - AS [CMR - JWW), for whom high reproducibility has been previously been reported. [10]

Echocardiography—To directly assess utility of routine echo as applied in routine clinical practice, RV linear dimensions (at end-systole and end-diastole) were acquired only in standard orientations – parasternal long axis and apical 4-chamber – which were not tailored for RV-directed imaging. In each orientation, analysis was performed using optimally on-axis imaging frames, for which end-diastole and end-systole were respectively

selected based on the image in which the RV size was maximal or minimal. RV linear dimensions were measured using the following landmarks:

- In the apical 4-chamber view, RV dimensions were measured in three locations (1) basal RV width (maximal transverse diameter in basal third of RV), (2) mid RV width (maximal transverse diameter in mid third of RV, at approximate level of LV papillary muscles), (3) RV length (maximal distance from tricuspid annulus to apex).
- In the parasternal long axis view, proximal RV outflow tract (RVOT) width was measured as the maximal distance (perpendicularly oriented) between the RV free wall and septal-aortic junction.

Figure 1 provides representative examples of linear measurements as acquired in each echo orientation.

Conventional echo indices of RV function (TAPSE, S', RIMP) as well as FAC (planimetered in apical 4-chamber) were quantified in accordance with consensus guidelines and methods applied in our prior research.[7, 10] Pulmonary artery systolic pressure was calculated using the modified Bernoulli equation ($4 [\text{peak tricuspid regurgitant [TR] velocity}]^2 + \text{right atrial [RA] pressure}$), for which TR velocity was measured via Doppler and RA pressure based on inferior vena caval size and collapsibility.[11]

CMR—Cine-CMR was used to quantify cardiac chamber size and function. RV basal and apical image positions were defined in accordance with standard criteria, with the basal RV defined by the image in which the pulmonic valve or valve annulus was visualized, and the apex defined by the distal-most image in which RV myocardium was visualized. End-diastole and end-systole were defined based on the respective frames demonstrating the largest and smallest cavity size. RVEF was calculated based on end-diastolic volume (EDV) and end-systolic volume (ESV). Cine-CMR analysis was performed using a previously validated automated algorithm shown to yield excellent agreement with manual planimetry quantified cardiac chamber size and phantom-verified volumes as well as high reproducibility for both LV and RV quantitative indices.

Statistical Methods

Propensity scoring (derived from gender, BSA) was used to select study patients within respective BiV and LV systolic function groups. Comparisons between groups were made using Student's t-test (expressed as mean $\pm$ standard deviation [SD]) for continuous variables. Categorical variables were compared using Chi-square or, when fewer than 5 expected outcomes per cell, Fisher's exact test. Bivariate correlation coefficients, as well as univariable and multivariable regression analyses were used to evaluate associations between continuous variables: overall diagnostic test performance of echo linear fractional shortening was evaluated in relation to volumetric RVEF on CMR using receiver operator characteristics (ROC) curves, which were first used to establish normative cutoffs in a derivation cohort (50% of population) and then to evaluate test performance in a validation cohort. Statistical calculations were performed using SPSS 22.0 (SPSS Inc. [Chicago, IL]). Two-sided $p < 0.05$ was considered indicative of statistical significance.

Results

Population Characteristics

The population comprised 168 patients with LV systolic heart failure (EF<50%) who underwent echo and CMR within a mean interval of 3.4 ± 3.4 days; 91% of patients underwent imaging via both modalities within 1 week.

Table 1 details clinical and imaging characteristics of the population, as well as comparisons between patients with and without BiV dysfunction. As shown, groups were of similar age, gender, and body size (all $p=NS$). Conversely, CAD was less common among patients with BiV dysfunction ($p<0.001$), consistent with non-ischemic etiology of heart failure.

Regarding imaging, patients with BiV had more advanced adverse cardiac remodeling, with RV dysfunction accompanied by increments in LV and RV chamber size, as well as decrement in LVEF (all $p<0.001$).

RV Linear Dimensions

Complete acquisition of all 4 linear fractional shortening indices (at both end-systole and end-diastole) were obtainable in 93% (156/168) of patients – all patients had at least 1 linear parameter acquirable (mean 3.8 ± 0.6): Among each parameter tested, proximal RVOT width was most commonly acquirable (98%), followed by basal and mid RV width (both 96%), and RV length (95%) – acquisition rates were equivalent to that of conventional RV assessment via FAC (96%), and slightly higher than S' (90%), TAPSE (88%), and RIMP (82%).

Table 2 compares echo end-diastolic and end-systolic dimensions - as well as derived fractional shortening - between patients with or without RV dysfunction on CMR. Results are presented for the overall cohort (left), as well as patient subgroups with non-ischemic (center) and ischemic (right) cardiomyopathy. As shown, all fractional shortening indices were lower among patients with RV dysfunction, paralleling RV conventional indices (all $p<0.001$). Results were generally similar among sub-groups, with lack of significance for RV length, S', and RIMP among CAD patients likely attributable to lower prevalence of RV dysfunction in this group.

RV Volumes

Figure 2 stratifies FAC and linear fractional shortening indices in relation to strata of CMR-quantified RVEF, demonstrating linear and area based echo indices to decrease in parallel with volumetric EF (all $p<0.001$). For example, FAC was 2-fold lower among patients with severely reduced RVEF (<30%) compared to those with preserved RVEF (23.3 ± 7.3 vs. $46.5\pm 9.0\%$), paralleling proximal RVOT width (10.3 ± 6.6 vs. $32.2\pm 8.0\%$), mid width (17.3 ± 9.4 vs. $40.3\pm 10.8\%$), and length (7.4 ± 2.8 vs. 15.9 ± 5.3).

Table 3 reports correlations between CMR-quantified RV chamber volumes and echo-quantified RV linear dimensions. As shown, linear dimensions in all planes correlated significantly with respective end-diastolic and end-systolic RV volumes ($p<0.001$). Regarding fractional shortening, proximal RVOT width (as measured in parasternal long

axis) and mid RV width (as measured in apical 4-chamber orientation) yielded greatest magnitude of correlation with RVEF ($r=0.73$, 0.66 respectively), which were of similar magnitude to that yielded by FAC ($r=0.70$; all $p<0.001$). Bland-Altman plots for echo-derived fractional shortening indices vs. CMR RVEF are illustrated in Figure 3. As shown, all echo fractional shortening indices systematically underestimated RV function in relation to CMR RVEF (i.e. negative mean displayed on y-axes). Limits of agreement with between CMR and echo were similar for all fractional shortening indices (basal RV width -45.9 to -2.1 [range 43.8] | mid RV width -38.5 to -5.8 [range 44.34] | RV length -58.1 to -15.6 [range 42.4] | proximal RVOT width: -41.4 to -5.9 , [range 35.50]), and equivalent to that yielded by FAC (-30.2 to 9.4 [range 39.7]). Of note, magnitude of underestimation yielded by RV length varied in relation to systolic function, and was greatest for patients with preserved RVEF.

Table 4 reports results of multivariate regression modeling, for which impaired RVEF was tested in relation to linear echo dimensions. Results demonstrate fractional shortening measured in each echo orientation to be independently associated with RVEF ($p=0.001$). Of note, the observed regression coefficient for end-diastolic proximal RVOT width (0.51 [CI $0.37-0.65$]; $p<0.001$) would indicate that a 10% decrement in echo-quantified fractional shortening would correspond to a 5 point decrease in volumetric RVEF.

Diagnostic Performance for Impaired RVEF

Echo quantified linear dimensions were tested with regard to diagnostic test performance for impaired RVEF ($<50\%$) as defined by CMR: linear fractional shortening cutoffs were first determined in a derivation cohort (50% of population), and then tested in a validation cohort. Table 5A reports diagnostic test performance of individual fractional shortening parameters based on cutoffs established a-priori in the derivation cohort (in which cutoffs selected for optimal test sensitivity and minimum specificity $\geq 80\%$): Validation cohort results demonstrate moderate sensitivity and specificity for RV width as measured in apical 4-chamber and parasternal long axis views. Table 5B reports corresponding diagnostic test performance of conventional RV indices, using cutoffs encompassed in consensus ASE guidelines. As shown, linear fractional shortening performed similarly to conventional echo indices of RV function. For example, proximal RVOT and mid RV width each yielded similar sensitivity (82%, 75%) to that of FAC (79%), albeit slightly lower specificity (74%, 76%, 87% respectively). Overall test performance of linear fractional shortening indices in the validation cohort is illustrated in Figure 4.

Discussion

This study – conducted among LV systolic heart failure patients with and without RV dysfunction – provides new insights regarding quantitative echo indices for RV contractile performance. There are several key findings: (1) RV linear fractional shortening indices were readily obtainable on routine echo – at least one parameter was obtained in all exams; 93% yielded complete acquisition of 4 multi-dimensional linear fractional shortening indices: all indices stratified between patients with and without RV dysfunction (RVEF $<50\%$) as quantified by the reference of CMR. (2) All RV linear dimensions correlated with

volumetric indices of both RV size and systolic function on CMR (all $p < 0.001$). Echo-orientation specific correlations were moderate for mid RV width (4-chamber) and proximal RVOT width (parasternal long axis) as analyzed at RV end-diastole (0.54–0.57) and end-systole (0.72–0.76), corresponding to near equivalent correlations for RVEF (0.66–0.73 respectively; all $p < 0.001$). (3) Multi-dimensional assessment of fractional shortening yielded incremental utility for RV dysfunction: in multivariable regression analysis, fractional shortening measured in each echo orientation was independently associated with RVEF ($p < 0.001$) – the regression coefficient was highest for proximal RVOT width (0.51 [CI 0.37–0.65]; $p < 0.001$), corresponding to a 5 point decrease in RVEF for each 10% decrement in fractional shortening. (4) Derived cutoffs for RV linear fractional shortening yielded reasonable diagnostic performance (in a subsequent validation cohort) for CMR-defined RV dysfunction: Accuracy (74–77%) was similar to that of conventional indices (74–77%) and only slightly less than that of FAC (84%). Taken together, these data indicate that linear fractional shortening on routine 2D echo provide physiologic indices of RV performance that parallel volumetric RV dysfunction as measured by less widely available volumetric modalities such as CMR.

It is important to recognize that singular indices of RV fractional shortening provide limited insight into global RV function, paralleling conventional parameters such as TAPSE or S' . Our results demonstrate that apical 4-chamber evidenced RV length and mid width performed similarly to TAPSE and S' (all of which extrapolate global RV function from 2D measurements in the infero-basal RV) – each parameter correlated with volumetric RVEF to a lesser magnitude than did FAC. On the other hand, methods such as TAPSE and S' provide a one dimensional assessment of RV function derived from longitudinal motion, which may be suboptimal due to concomitant translational motion or focal injury in other RV regions. A key advantage of linear fractional shortening concerns the fact that multiple linear parameters (obtained in different RV regions) can be obtained from routine echo, providing a more comprehensive evaluation of global RV function. This concept is consistent with our multivariate analysis, which demonstrated each linear fractional shortening index (obtained in different orientations) to be independently associated with RVEF as well as good overall predictive performance of our model (model $r = 0.81$; $p < 0.001$).

Regarding magnitude of agreement between echo and CMR, it should be noted that whereas fractional shortening indices yielded good discriminatory capacity between aggregate patient groups with and without CMR-evidenced RV dysfunction, magnitude of agreement with precise RVEF varied – as evidenced by data shown in Bland-Altman plots (Figure 3). Regarding reasons for this, we note that linear fractional shortening provides a limited window with respect to global RV performance, in that individual linear parameters may not reflect changes in RV regions external to a given 2D plane. More broadly, echo cutoffs for impaired RV function are generally lower than that of CMR, and thus comparison of the two parameters would be expected to yield substantial mean differences as was observed in our dataset. For example, consensus echo guidelines for FAC uses a cutoff of 35% for impaired RV function,[8] whereas multiple population based CMR studies in have used a cutoff of 50% for impaired RVEF.[12] Consistent with this, our dataset showed that all echo fractional shortening indices systematically underestimated RV performance in relation to CMR (i.e. negative as displayed on y-axes). Taken together, our data shows that FS can be used to

broadly stratify groups and should not be employed as a precise index of RV performance paralleling volumetric RVEF.

Our findings extend upon prior research by our group and others concerning quantitative echo methods for RV function and chamber remodeling. Yamaguchi et al., studying 81 patients with left heart failure, reported that RV fractional shortening (measured in parasternal long axis) correlated with fractional area change ($r=0.37$; $p=0.0008$) as well as BNP-evidenced heart failure severity ($r=-0.38$, $p=0.0005$), and independently predicted event free survival.[13] Similarly, Lindqvist et al. reported that RV fractional shortening (in parasternal short axis) differed between a cohort of 112 patients and controls ($p<0.0001$), and correlated with RV long axis excursion (i.e. TAPSE).[14] Interestingly, Anavekar et al. reported that echo-quantified RV fractional shortening indices did not significantly correlate with CMR-quantified RVEF.[15] While the reason for this discordance with other prior literature and our current results is uncertain, we speculate that this may be attributable to overall sample size ($n=36$) and limited number of patients ($n=10$) with impaired RV function ($RVEF<50\%$), both of which were over 4-fold smaller than our current study.

Regarding conventional RV functional indices included in current ASE guidelines, it is important to recognize that prior studies have shown TAPSE and S' to generally correlate with volumetric indices of RV function, and predict adverse prognosis.[16–18] On the other hand, limitations of TAPSE and S' are acknowledged in consensus ASE guidelines [8], and these indices have been shown to yield limited sensitivity and predictive value in heart failure cohorts receiving ventricular assist devices and undergoing cardiac surgery.[19–22] Our study did not directly test echo indices in relation to outcomes, but instead to a CMR surrogate of RVEF which has itself been validated as a prognostic index.[23] Future research is warranted to test whether RV linear fractional shortening can be used to stratify prognosis, and augment predictive value of echo for patients in whom conventional indices are unavailable or known to be limited.

Several limitations should be noted. First, our protocol tested conventional 2D echo rather than newly available approaches such as real time three-dimensional echo (RT3DE). While RT3DE enables quantification of RV function that has been shown to yield improved accuracy over 2D methods, [24–26] widespread availability and clinical application of this approach remains challenging. 3D echo requires dedicated full volume image acquisition and post processing, both of which require technical expertise for accurate chamber delineation. Second, RV function was evaluated among patients with left heart failure (half of whom had CAD), and thus results may not necessarily be extrapolated to other cohorts – such as patients with congenital heart disease or primary RV dysfunction. On the other hand, it is possible that linear fractional shortening may be particularly valuable in such cohorts, among whom the superior RV free wall can be regionally impaired (e.g. due to surgical repair or volumetric regurgitation) and not well visualized on apical 4-chamber imaging, but potentially assessable via proximal RVOT shortening in parasternal long axis. Ongoing studies are focused on testing these concepts. Third, it should be noted that while our findings provide validation of echo-quantified linear fractional shortening indices as markers of RV dysfunction, clinical outcomes were not evaluated and thus the prognostic utility of these echo variables is not established. In this context, we believe the current study provides

key initial results necessary to inform the design of future large scale-population based research aimed at independently testing diagnostic performance of echo-derived RV fractional shortening as well as discerning utility of this approach for prediction of adverse clinical outcomes.

In conclusion, this study demonstrates that RV linear fractional shortening – as measured on routine clinical echo – provides indices of systolic function that correlates with CMR-quantified volumetric RVEF to a similar magnitude as do conventional parameters such as TAPSE and S'. Parasternal long-axis RVOT width as well as 4-chamber RV mid width and length is each independently associated with CMR RVEF, supporting use of multiple fractional shortening indices for echo-based assessment of RV function.

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Figure 1. RV Linear Fractional Shortening Indices

Graphic illustration of echo-based linear fractional shortening indices as measured with respect to RVOT width (parasternal long axis; top), mid RV width (apical 4-chamber; middle), and RV length (apical 4-chamber; bottom) [green = diastole, yellow = systole]. Panels A and B provide representative examples of patients with preserved (52.5%) and impaired (33.3%) RVEF on CMR, paralleling differences in RVOT width (29.0 vs. 12.1%), mid RV width (54.8 vs. 13.3%), and RV length (14.3 vs. 2.0%) as measured via echo fractional shortening.

Figure 2. Echo Fractional Area Change and Linear Shortening in Relation to CMR RVEF

Echo-quantified RV functional indices (mean $\pm$ standard deviation) in relation to CMR-quantified RVEF strata (<30%|30–50%| 50%) [panel A; black bars = fractional area change, B-D; grey bars = linear fractional shortening]. Note similar stepwise decrements in both FAC and linear fractional shortening in parallel with impaired RVEF (all $p < 0.001$ for trend).

Figure 3. Comparison between Echo RV Performance Indices and CMR RVEF

Bland-Altman plots demonstrating magnitude of agreement between echo-derived fractional shortening indices and CMR RVEF (center fine line = mean, outer bold lines = limits of agreement [$1.96 \times \text{standard deviation}$]). **3A** provides Bland-Altman plots for each linear fractional shortening parameter; **3B** provides plot for FAC.

Figure 4. Diagnostic Performance of Linear Fractional Shortening for Impaired RVEF

Receiver operating characteristics curves for linear fractional shortening indices in relation to RVEF<50% as established by the reference standard of CMR. Note that proximal RVOT width and mid RV width yielded near equivalent overall diagnostic performance (as assessed via area under curve), whereas RV length yielded slightly lesser performance.

Table 1

Clinical and Imaging Characteristics

	Overall (n=168)	Isolated LV Dysfunction (n=112)	Biventricular Dysfunction (n=56)	P
CLINICAL				
Age (year)	57±15	58±15	56±16	0.49
Male gender	70% (117)	70% (78)	70% (39)	1.00
Body Surface Area	1.92±0.24	1.92±0.25	1.93±0.25	0.88
Coronary Artery Disease Risk Factors				
Hypertension	60% (100)	59% (66)	61% (34)	0.82
Hypercholesterolemia	59% (99)	63% (70)	52% (29)	0.18
Diabetes Mellitus	36% (61)	35% (39)	39% (22)	0.57
Tobacco Use	42% (71)	46% (51)	36% (20)	0.22
Family History	40% (67)	38% (43)	43% (24)	0.58
Coronary Artery Disease	48% (81)	62% (69)	21% (12)	<0.001
Prior Myocardial Infarction	38% (64)	50% (56)	14% (8)	<0.001
Percutaneous Intervention	26% (44)	37% (41)	5% (3)	<0.001
Coronary Artery Bypass Grafting	7.7% (13)	8.0% (9)	7.1% (4)	1.00
Cardiovascular Medications				
Beta-blocker	82% (137)	86% (96)	73% (41)	0.049
ACE-Inhibitor/Angiotensin Receptor Blocker	54% (90)	51% (57)	59% (33)	0.33
Loop diuretic	45% (76)	33% (37)	70% (39)	<0.001
HMG CoA-Reductase Inhibitor	65% (110)	75% (84)	46% (26)	<0.001
Aspirin	72% (121)	77% (86)	63% (35)	0.052
Thienopyridine	27% (45)	36% (40)	9% (5)	<0.001
CARDIAC MORPHOLOGY/FUNCTION				
Cardiac Magnetic Resonance				
Left Ventricle				
Ejection fraction (%)	34.3±10.9	37±9	28±12	<0.001
Stroke Volume (ml)	62.4±19.7	65.2±18.4	56.9±21.2	0.01
End Diastolic Diameter	6.0±0.8	5.9±0.6	6.4±0.9	<0.001
End-diastolic volume (ml)	192.4±61.0	178.8±45.7	219.6±77.0	<0.001
End-systolic volume (ml)	130.0±58.1	113.6±40.5	162.7±72.7	<0.001
Myocardial Mass (gm)	176.8±55.2	169.5±52.3	191.4±58.1	0.02
Anteroseptal wall thickness (cm)	1.1±0.3	1.1±0.3	1.0±0.2	0.43
Posterolateral wall thickness (cm)	0.9±0.2	0.9±0.2	0.9±0.2	1.00
Relative wall thickness	0.3±0.1	0.3±0.1	0.3±0.1	0.08
Right Ventricle				
Ejection fraction (%)	50.6±13.0	58.2±6.3	35.5±9.3	<0.001
Stroke Volume (ml)	66.9±18.1	68.8±18.2	63.1±17.4	0.054
End-diastolic volume (ml)	140.2±46.4	119.5±33.3	181.6±41.1	<0.001
End-systolic volume (ml)	73.3±41.1	50.7±17.7	118.5±37.2	<0.001

	Overall (n=168)	Isolated LV Dysfunction (n=112)	Biventricular Dysfunction (n=56)	P
Left Atrial Size				
Area (cm ²)	23.4±6.2	21.8±5.0	26.4±7.2	<0.001
Diameter (cm)	3.9±0.7	3.7±0.6	4.1±0.8	0.001
Right Atrial Size (cm²)	19.1±5.8	17.5±4.3	22.3±7.0	<0.001
Pulmonary Arterial Pressure * (mmHg)	38.4±12.2	34.5±8.4	43.9±14.5	<0.001

Data presented as mean ± standard deviation.

* Data available in 78% of population.

Table 2

Linear Dimensions Stratified by CMR-Evidenced RV Dilation or Dysfunction

	Overall Population				Non-ischemic Cardiomyopathy				Ischemic Cardiomyopathy			
	Isolated LV Dysfunction (n=112)	Biventricular Dysfunction (n=56)	P		Isolated LV Dysfunction (n=43)	Biventricular Dysfunction (n=44)	P		Isolated LV Dysfunction (n=69)	Biventricular Dysfunction (n=12)	P	
Linear Indices												
End Diastolic Dimensions												
Basal RV width (mm)	36.7±5.9	45.2±7.3	<0.001		36.7±6.0	45.4±7.6	<0.001		36.6±5.9	44.3±6.3	<0.001	
Mid RV width (mm)	25.7±6.0	32.3±7.9	<0.001		26.0±6.4	32.3±8.5	<0.001		25.5±5.7	32.2±5.2	<0.001	
RV length (mm)	87.3±9.5	93.1±8.8	<0.001		87.3±8.1	93.3±9.4	<0.001		87.3±10.3	92.2±6.5	0.12	
Proximal RVOT width (mm)	32.4±4.9	38.1±7.1	<0.001		32.4±5.0	37.7±7.6	<0.001		32.5±4.8	39.9±4.4	<0.001	
End Systolic Dimensions												
Basal RV width (mm)	25.7±5.5	36.6±7.2	<0.001		25.7±5.9	37.0±7.4	<0.001		25.7±5.3	35.4±6.7	<0.001	
Mid RV width (mm)	15.5±5.2	25.4±8.1	<0.001		15.5±5.7	25.8±8.7	<0.001		15.5±4.9	23.7±5.9	<0.001	
RV length (mm)	73.5±10.1	85.0±9.0	<0.001		73.5±9.2	85.3±9.5	<0.001		73.5±10.6	83.9±7.0	0.002	
Proximal RVOT width (mm)	22.0±4.5	32.0±7.9	<0.001		22.2±4.3	32.0±8.4	<0.001		21.9±4.7	31.9±5.2	<0.001	
Fractional Shortening												
Basal RV (%)	30.0±9.0	19.1±7.2	<0.001		30.0±10.5	18.7±7.3	<0.001		30.0±7.9	20.5±6.9	<0.001	
Mid RV (%)	40.1±10.9	22.2±11.9	<0.001		41.2±10.7	21.0±11.9	<0.001		39.4±11.0	27.0±10.9	0.001	
RV length (%)	15.9±5.3	8.7±3.7	<0.001		15.9±5.2	8.6±3.8	<0.001		16.0±5.4	9.0±3.8	<0.001	
Proximal RVOT (%)	32.1±8.0	16.8±10.1	<0.001		31.3±7.7	15.9±10.6	<0.001		32.7±8.3	20.3±7.5	<0.001	
Conventional Indices												
End Diastolic Area (cm ²)	19.0±4.5	26.0±5.8	<0.001		18.9±4.6	26.1±6.2	<0.001		19.1±4.5	25.4±3.7	<0.001	
End Systolic Area (cm ²)	10.3±3.4	18.9±5.5	<0.001		10.3±3.4	19.1±5.7	<0.001		10.3±3.4	18.1±4.8	<0.001	
Fractional Area Change (%)	46.4±9.1	27.6±10.7	<0.001		46.2±9.6	27.1±10.6	<0.001		46.5±8.9	29.7±11.5	<0.001	
TAPSE	1.9±0.4	1.5±0.3	<0.001		1.9±0.4	1.5±0.4	<0.001		1.8±0.4	1.6±0.3	0.05	
RVS'	11.4±2.3	10.0±2.6	0.001		11.5±2.4	9.9±2.6	0.004		11.3±2.3	10.4±3.0	0.29	
RIMP	0.47±0.17	0.60±0.23	<0.001		0.45±0.18	0.58±0.20	0.004		0.48±0.16	0.68±0.37	0.16	

Table 3

Echo-Quantified RV Parameters in Relation to CMR Quantified RV Volumes and Function

	Correlation Coefficient (r)	P	Regression Equation
Diastolic Chamber Size			
Linear parameters			
Basal RV width	0.67	<0.001	$y = 4.13x - 22.8$
Mid RV width	0.57	<0.001	$y = 3.64x + 38.9$
RV length	0.45	<0.001	$y = 2.19x - 55.2$
Proximal RVOT width	0.54	<0.001	$y = 3.96x + 4.23$
Area (4-chamber)	0.72	<0.001	$y = 5.61x + 20.5$
Systolic Chamber Size			
Linear parameters			
Basal RV width	0.75	<0.001	$y = 3.91x - 41.0$
Mid RV width	0.72	<0.001	$y = 3.80x + 2.22$
RV length	0.52	<0.001	$y = 1.94x - 76.4$
Proximal RVOT width	0.76	<0.001	$y = 4.19x - 33.0$
Area (4-chamber)	0.81	<0.001	$y = 5.76x - 2.22$
Contractile Function			
Fractional Shortening			
Basal RV width	0.56	<0.001	$y = 0.75x + 30.7$
Mid RV width	0.66	<0.001	$y = 0.61x + 29.5$
RV length	0.59	<0.001	$y = 1.30x + 32.9$
Proximal RVOT width	0.73	<0.001	$y = 0.84x + 28.1$
Fractional area change	0.70	<0.001	$y = 0.70x + 22.3$
RVS'	0.31	<0.001	$y = 1.60x + 33.0$
TAPSE	0.47	<0.001	$y = 15.7x + 23.0$

Table 4

Multivariable Regression for Right Ventricular Ejection Fraction

<i>Correlation Coefficient =0.81; p<0.001</i>			
Variable	Regression Coefficient (95% Confidence Interval)	P	Partial Correlation
Fractional Shortening Mid RV width (%)	0.30 (0.19 – 0.41)	<0.001	0.40
Fractional Shortening RV length (%)	0.45 (0.20 – 0.71)	0.001	0.27
Fractional Shortening Proximal RVOT width (%)	0.51 (0.37 – 0.65)	<0.001	0.50

Diagnostic Performance of Fractional Shortening and Derived Echo Indices for CMR RV Dysfunction

Table 5

A. Cohort-derived Linear Fractional Shortening Cutoffs*						
Fractional Shortening	Cutoff (%)	Sensitivity (%)	Specificity (%)	Accuracy (%)	PPV (%)	NPV (%)
Proximal RVOT width	27	82	74	77	62	89
Mid RV width	32	75	76	76	62	85
RV length	10	54	85	74	65	78

B. Conventional Parameters of RV Function					
	Cutoff *	Sensitivity	Specificity	Accuracy	NPV
FAC (%)	35	79%	87%	84%	76%
TAPSE (cm)	1.6	60%	79%	74%	63%
RVS' (cm/s)	10	69%	81%	77%	67%

* optimized for sensitivity using a minimum specificity cutoff of 80%

* Cutoffs based on ASE guidelines