

1 **Background:**

2 Dilated cardiomyopathy (DCM) is the second most common aetiology of heart failure
3 in the general population(1). The hallmark of DCM is enlargement of one or both
4 ventricles with systolic dysfunction. This diagnosis contains a spectrum of primary
5 familial or secondary etiologies, such as infection, inflammatory or toxins affecting
6 the heart. In a contemporary cohort of 250 DCM patients using cardiac magnetic
7 resonance (CMR), Gulati et al. (2) showed that right ventricular ejection fraction
8 (RVEF) $\leq 45\%$ was an independent predictor of transplant-free overall survival and
9 major heart failure events.

10

11 Right ventricular contraction is predominantly driven by longitudinal, followed by
12 radial shortening. In contrast to the LV, twisting and rotational movements do not
13 contribute significantly to RV contraction(3). Strain is a measure of tissue
14 deformation and is defined as percentage of relative shortening of myocardial fibres
15 at end-systole compared with end diastole. As the ventricle contracts, muscle
16 shortens in the longitudinal dimensions and therefore longitudinal strain is a negative
17 number. Conversely, myocardial wall thickens in radial dimensions during systole
18 and therefore radial strain is a positive number. Echocardiography speckle tracking
19 (STE) determined RV longitudinal strain provides prognostic information that is
20 incremental to conventional echo parameters such as TAPSE and S', and is an
21 independent predictor of severe adverse events in patients with pulmonary
22 hypertension (4-6). Strain rate is a measure of the change in strain over time. Strain
23 and strain rate can be measured in different directions, which are radial, longitudinal
24 and circumferential. These directions are demonstrated in figure 1.

25

26 The latest 2015 American Society of Echocardiography and the European
27 Association of Cardiovascular Imaging guidelines incorporate RV strain in their
28 recommendations regarding ventricular functional assessment(7). Strain

29 measurement by speckle tracking echocardiography (STE) is based on tracking of
30 characteristic speckle patterns created by interference of ultrasound beams in the
31 myocardium. For CMR, a software called feature/ tissue-tracking (CMR-TT) which is
32 analogous to STE has been developed to determine strain and strain rate
33 measurements derived from steady state free precession cine sequences(8). CMR-
34 TT software works by identifying myocardial features on steady-state free precession
35 cine images and tracking them from frame to frame. Two of its advantages are time-
36 efficiency with no additional sequences being required for analysis. It agrees well
37 with myocardial tagging, which is considered the reference standard for CMR
38 quantitative deformation assessment(8-10).

39

40 Left and right ventricular systolic function as determined by cardiac magnetic
41 resonance imaging (CMR) derived ejection fraction is regarded as the gold standard
42 due to its high accuracy and high inter and intra-observer reproducibility. RV analysis
43 in particular due to its geometric complexity can be time consuming and is not
44 routinely performed. Therefore in the context of DCM, where RV ejection fraction
45 (RVEF) provides prognostic information(2), omitting this information removes
46 prognostic information in the final CMR scan report but including this information
47 results in longer post-processing time. Therefore for CMR assessment of DCM,
48 CMR-TT could help identify cases that require contouring to determine RVEF. Due to
49 its time efficiency relative to RV endocardial contouring, it could help streamline
50 cases, which should or should not be contoured.

51

52 In this study, we have three aims. Firstly, we want to compare CMR-TT with STE and
53 determine how well CMR-TT and STE correlates with RVEF. Secondly compare
54 CMR-TT and STE against other conventional methods for estimating RV systolic
55 function. Thirdly, determine a cut-off value to determine RV ejection fraction <45% for
56 CMR-TT and how this compares to STE.

57

58 **Methods:**

59 Institutional research ethics approval was obtained for this prospective study.

60 Patients were recruited from the cardiology clinics of a single centre in Hong Kong

61 (see figure 2) from August 2015 to February 2016. Inclusion criteria were patients

62 with echocardiography reports indicating an LV ejection fraction (LVEF) $\leq 40\%$ and

63 diagnosis of DCM. Patients with a reported LVEF $\leq 40\%$ were reviewed. Exclusion

64 criteria were age >85 years, atrial fibrillation, device implantation, metallic implants

65 including prosthetic heart valves, poor mobility, long-term oxygen therapy and

66 claustrophobia. Written consent was obtained from all patients. Echocardiography

67 and CMR were performed within 48 hours of each other.

68

69 **Echocardiography:**

70 All echocardiograms were performed in the left lateral decubitus position with a

71 commercially available ultrasound system (Vivid 9, General Electric Healthcare, USA)

72 and a 3.5 MHz transducer. In accordance with recommendations from the American

73 Society of Echocardiography, standard views and parameters of the left and right

74 heart were obtained using 2D echocardiography. Conventional apical three-chamber

75 view, apical two-chamber view, apical four-chamber view and RV-focused apical four

76 chamber view images were obtained for speckle tracking. 3 consecutive cardiac

77 cycles of each view were recorded. In particular, while obtaining images intended for

78 speckle tracking analysis, sector widths were optimized to allow complete myocardial

79 visualization while maximizing frame rate to 50-80 frames per sec. Echocardiograms

80 were performed by the same operator who was blinded to the CMR results. Tricuspid

81 annular plane systolic excursion (TAPSE) was measured by M-mode

82 echocardiography with the cursor optimally aligned along the direction of the tricuspid

83 lateral annulus in the apical four-chamber view. It was determined in the M-mode

84 view as the distance between the basal, end diastolic position of the tricuspid

85 annulus taken at the beginning of the electrocardiogram (ECG) QRS complex and its
86 greatest apical long-axis movement. S' was the peak systolic annular velocities
87 measured by pulsed-tissue wave Doppler imaging (TDI) with the sample volume
88 placed at the level of tricuspid annulus from the apical four chamber view. RV
89 fractional area change (RVFAC) was performed according to American Society of
90 Echocardiography (ASE) guidelines(11).

91

92 **Speckle-Tracking Echocardiography:**

93 For RV STE, RV-focused apical four chamber view images were analysed off-line by
94 means of commercially available semi-automated 2D strain software (EchoPac BT13,
95 GE Healthcare, USA). For RV STE (see figure 3), the automated function imaging
96 (AFI) technique designated for LV strain measurements in the traditional apical long
97 axis view were similarly employed. RV was divided into six segments (basal free wall,
98 mid free wall, apical free wall, basal septum, mid septum and apical septum). RV
99 endocardial borders of the four-chamber views were then detected and tracked
100 automatically throughout the cardiac cycle. Manual adjustments of the endocardial
101 border contouring and the width of the region of interest were made. The software
102 would then identify timing of aortic closure by ECG (i.e. end systole) which marks the
103 start of the measurement perform the strain analysis. The quality of tracking of each
104 segment would be checked by the software and results of those segments with
105 satisfactory quality would be displayed. RV GLS was obtained by averaging
106 measurements of the strain from the total six segments while RV FWS was obtained
107 by averaging the measurements of strain from the three segments of the RV free wall.

108

109 Images were sent to a well experienced echocardiography laboratory(12, 13) in
110 strain analysis for blinded analysis. Inter and intra-observer variability of STE
111 measurements were assessed by using all the cases.

112

113

114 **CMR**

115 CMR examination was performed on a 1.5T GE Signa HD scanner within 48 hours
116 from echocardiography was performed. LV 2-chamber cine, 3-chamber cine, 4-
117 chamber cine, RV 2-chamber cine, axial cine stack and short-axis cine stack images
118 was acquired. The cine sequences used a steady-state free-precession sequence
119 and images were acquired in end-expiration with retrospective ECG gating. Imaging
120 parameters were as follows: Echo time (TE) = 1.5msec, repetition time (TR) =
121 3.4msec, flip angle 45°, temporal resolution was on average 27-30msec, spatial
122 resolution was 1.43mm x 1.43mm, slice thickness was 8mm, and 25 phases were
123 acquired for each cine sequence. Analysis was performed by two readers; a
124 dedicated analyst and a Society of Cardiovascular Magnetic Resonance level 3
125 radiologist who were blinded to the clinical information. A CMR post processing
126 software (CMR42, Circle Cardiovascular Imaging, Calgary, Canada) was used to
127 outline the left and right ventricular endocardial and epicardial contours on the short
128 axis images and the extent of the LV and RV is determined on the short axis images
129 as well as by cross-referencing with the long axis images. Further checks to ensure
130 the accuracy of the RV measurements were performed by acquiring phase contrast
131 images of main pulmonary artery with a velocity encoding of 150cm/sec to ensure
132 the RV stroke volumes matched the contoured RV stroke volumes unless tricuspid
133 regurgitation was demonstrated. The LV was contoured in order to confirm the
134 accuracy of the RV contouring as stroke volumes should be equal. The short axis
135 contours were used to calculate end-diastolic, end-systolic volumes, stroke volumes
136 and ejection fraction. End-diastolic and end-systolic volumes were corrected using
137 body surface area (Mosteller method).

138

139

140 **CMR Tissue Tracking (CMR-TT)**

141 CMR-TT RV strain analysis was performed using CMR42 tissue tracking. Analysis
142 required contouring of the RV endocardial surface as well as the septal wall.
143 Subsequently, the RV epicardial wall was contoured and the tissue tracking tool
144 would track the RV free wall only (see figure 4). This was completed for a single end-
145 diastolic phase image only. The software subsequently identified the myocardial
146 features within the boundaries of the endocardial and epicardial contours and
147 propagated to the other 24 phases. The other phases were quickly assessed to
148 ensure propagation, and assessed to ensure accuracy. This procedure takes less
149 than 1 minute to perform. Inter and intraobserver variability was assessed. All cases
150 were contoured by a first and second observer separately and the cases were re-
151 contoured again by the first observer more than 2 weeks after the initial contouring.
152 CMR TAPSE was performed on 4-chamber cine images by measuring the distance
153 between the RV apex and the lateral aspect of the tricuspid annulus in end-diastole
154 and end-systole. The difference between these two measurements was recorded as
155 the CMR TAPSE. RV corrected TAPSE (Co-TAPSE) is a modified version of TAPSE
156 which involves measuring the distance between the lateral aspect of the tricuspid
157 annulus and the LV apex in end-diastole and end-systole. The difference between
158 these distances is then divided by the length in end-diastole and multiplied by
159 100(14).

160

161 **Statistical Analysis:**

162 All continuous variables were expressed as mean \pm standard deviation. Categorical
163 variables were expressed as a percentage of the total number. For patients with or
164 without decreased RVEF (<45 and >45), continuous variables were compared using
165 2-tailed unpaired Student T test or Mann-Whitney U test depending on whether the
166 variable was normally distributed or not. Categorical variables were compared using
167 Fisher exact test where appropriate. Correlation with strain and RVEF and correlation
168 between STE and CMR-TT were performed using Pearson correlation analysis. Intra

169 and inter-observer variability were compared by intra-class correlation coefficient
170 (ICC) using 2-way mixed model of absolute agreement, bias and level of agreement.
171 Receiver operating characteristic (ROC) curve was used to explore cut-off values of
172 STE and CMR-TT for detecting impaired RVEF. Data were analyzed by STATA 14
173 (StataCorp, Texas, USA). A p-value <0.05 were considered statistically significant.

174

175 **Results:**

176 Table 1 shows characteristics of the patient cohort divided into two groups based on
177 RVEF \leq 45% or RVEF>45%. Statistically significant differences between the two
178 groups were seen in the RV parameters only. Age, gender, heart rate and LV
179 parameters were not significantly different.

180

181 **Correlation of CMR-TT, STE and other RV analysis methods with CMR-derived**

182 **RVEF:**

183 Table 2 demonstrates the different parameters obtained with CMR-TT and STE and
184 how these correlated with RVEF. The best variables for correlation with CMR derived
185 RVEF was CMR-TT RV free wall longitudinal strain (FLS), STE FLS and STE RV
186 global longitudinal strain (GLS) (r=-0.68, r=-0.79, r=-0.82, p value <0.001 respectively)
187 (see figure 5). CMR-TT RV free wall radial strain (FRS) and radial systolic strain rate
188 showed moderate correlation with RVEF (r=0.66, p<0.01 and r=0.56, p<0.001
189 respectively). In terms of correlation between STE FLS and CMR-TT FLS, moderate
190 correlation was demonstrated (r=0.56, p=0.002).

191

192 **Inter-Observer and Intra-Observer Variability:**

193 The inter and intra-observer variability analyses for CMR-TT FRS, CMR-TT FLS,
194 STE FLS and STE GLS are demonstrated in table 3. These parameters show
195 excellent agreement for inter and intra-observer variability. The CMR-TT parameter

196 with the lowest variability and best agreement was the RV FLS while for STE it was
197 RV GLS.

198

199 **Comparison of CMR-TT and STE with Other Methods for Estimating RVEF:**

200 The different RV estimation parameters are listed in table 2. STE GLS had a higher
201 correlation with RVEF than S', TAPSE and FAC. CMR-TT FLS showed better
202 correlation than CMR TAPSE and Co-TAPSE. The ROC curves showed that STE
203 GLS had higher accuracy at identifying RVEF<45% than S', TAPSE and FAC. For
204 CMR-TT, the ROC curves also showed superior accuracy at identifying RVEF<45%
205 than CMR TAPSE and Co-TAPSE.

206

207 **Cut-off value for STE and CMR-TT in detection of RVEF<45%:**

208 For CMR-TT FLS the best cut-off value to provide the highest correctly classified
209 cases with RVEF<45% was $\geq -24.4\%$ (AUC=0.87), with 100% sensitivity and 66.7%
210 specificity (see figure 6).

211

212 For STE, GLS had the highest AUC closely followed by STE FLS. The cut-off values
213 providing the highest correctly classified results were $\geq -20.9\%$ (AUC=0.88), with 100%
214 sensitivity and 60% specificity and $\geq -22.0\%$ (AUC=0.87) with 78.6% sensitivity and
215 80% specificity respectively (see figures 7 & 8).

216

217 If the cut-off for STE was set at -20% as per American and European guideline
218 suggestions, FLS would have 57.1% sensitivity and 80.0% specificity with a correctly
219 classified percentage of 69.0%. For GLS, this would be 85.7% sensitivity and 60.0%
220 specificity, with overall a correctly classified percentage of 72.4% of all cases.

221

222 **Discussion:**

223 Our study aimed to compare the correlation and reproducibility of CMR derived
224 RVEF with CMR-TT and STE as well as explore the cut-off values for determining
225 RVEF \leq 45%. The CMR-TT and STE parameters which showed the best correlations
226 with CMR derived RVEF were CMR-TT FLS, STE FLS and STE GLS. Compared to
227 previous papers(15-17), STE GLS in our study showed the best correlation with CMR
228 derived RVEF followed by STE FLS, which was only slightly lower but still showed
229 excellent correlation with CMR derived RVEF. In addition, the CMR-TT strain rate
230 parameter was shown to correlate less well than CMR-TT strain, which is in keeping
231 with the known literature(8).

232

233 On the ROC curves, CMR-TT FLS, STE FLS and STE GLS (see figures 6-8) showed
234 very good accuracy with AUC of 0.87, 0.87 and 0.88 respectively. These parameters
235 were also highly reproducible with ICC values of >0.9 and in terms of comparison
236 with a previous paper assessing CMR-TT RV global longitudinal strain, that study
237 also obtained an ICC values >0.9 for inter and intra-observer reproducibility(18). The
238 STE FLS and GLS cut-off values of -22.0% and -20.9% were not too different from
239 the recent internationally recommended \geq -20% cut-off(7) in determining RVEF $<$ 45%.
240 However, our STE cut-off values were different to a study by Focardi et al(19) which
241 recommended a cut-off value of -17.0% and demonstrated very high accuracy with a
242 96% sensitivity and 93% specificity (AUC 0.92) to detect an RVEF \leq 45%. In
243 comparison to our study, the differences could be accounted for by the patient
244 cohorts. The patients used in Focardi et al's study had varied pathologies but were
245 predominantly made up of myocarditis, hypertrophic cardiomyopathy and
246 arrhythmogenic right ventricular dysplasia (ARVD) patients. However, our study
247 looked at DCM patients only and on comparison our cohort had larger biventricular
248 volumes and lower LVEF. These differences could account for the different accuracy
249 of the STE FLS and GLS despite the similar echocardiography equipment and STE
250 software, which were used in both studies.

251

252 To the best of our knowledge, setting a cut-off value for CMR-TT FLS to determine
253 RVEF<45% has never been done before and our study has shown that this is
254 feasible with a high degree of accuracy. Further study is warranted to determine if
255 this could be used practically. In situations where the RV is not the chamber of
256 interest, CMR readers typically use several methods including their experience and
257 subjective judgments to determine if RVEF is decreased before committing to formal
258 RVEF quantification. However, there are other semi-quantitative methods, which
259 CMR readers also utilize such as TAPSE(20, 21), RV fractional area change(22) and
260 Co-TAPSE(14), which have been shown to provide faster semi-quantitative
261 assessment to identify RV systolic dysfunction. In our study, we compared the
262 correlation and ability of CMR TAPSE and Co-TAPSE with CMR-TT FLS and
263 showed that CMR-TT FLS had better correlation and was a better tool for identifying
264 RVEF<45%. Interestingly, the paper which studied Co-TAPSE, showed superiority of
265 Co-TAPSE over CMR feature tracking RV GLS as well as CMR TAPSE(14).
266 However this study cannot be directly compared to ours for three reasons. Firstly, our
267 study set out to test whether these different RV parameters could identify an
268 RVEF≤45% whereas the study looking at Co-TAPSE was looking to determine if the
269 different parameters could differentiate normal volunteers from non-ischaemic DCM
270 patients. Secondly, CMR RV global longitudinal strain was used whereas our study
271 used CMR RV free wall strain and did not include the LV septal wall in the analysis
272 so the RV analysed was different between our studies. Lastly, CMR feature tracking
273 was used rather than tissue tracking which are different software tools created by
274 different vendors and have been previously demonstrated to have some differences
275 in strain results(10). We believe that setting the analysis tools to identify an RVEF≤45%
276 would be more clinically useful and as mentioned previously has prognostic
277 implications(2). However, both studies showed that CMR TAPSE was not the most
278 accurate of the various methods tested. This in keeping with another CMR study,

279 which showed weak correlation between traditional TAPSE and RV systolic
280 function(21). Some echocardiography studies have gone further to show that TAPSE
281 is not predictive of mortality(5, 23). CMR TAPSE is likely less accurate in terms of
282 estimating the RVEF as it is load dependent. Larger RV volumes would require larger
283 displacement of the tricuspid annulus to maintain RVEF since RV systolic function is
284 predominantly determined by longitudinal contraction(24). CMR TAPSE does not
285 account for this and in the context of DCM may explain its reduced accuracy.

286

287 In keeping with RV physiology, the CMR-TT free wall radial strain showed lower
288 diagnostic accuracy in identifying RV systolic dysfunction than free wall longitudinal
289 strain but there was still moderate correlation with RVEF. RV radial strain is not a
290 parameter which is commonly assessed with STE(25) but our CMR-TT software
291 including those from different vendors has been able to assess this parameter(26).
292 This allows CMR-TT RV strain to potentially add further information on the RV
293 systolic function and RV longitudinal strain, which is not usually available on
294 echocardiography. However to the best of our knowledge, the evidence for the
295 usefulness of RV radial strain is currently lacking.

296

297 Whether the high diagnostic accuracy of CMR-TT identifying RVEF<45% seen in this
298 study can be recreated with other CMR strain analysis software should be
299 investigated. Currently, CMR feature tracking (CMR-FT) software provided by
300 TomTec Imaging systems (TomTec, Unterschleissheim, Germany)(27) has
301 dominated most of the research literature(28) but with the arrival of other software
302 tools created by different vendors, further studies to check the validity of these newer
303 software tools are needed.

304

305 CMR-TT remains a relatively new method for assessing RV systolic function. Prior to
306 the development of CMR-TT, other CMR methods such as tagging, strain encoding

307 (SENC), and displacement encoding with stimulated echoes (DENSE) have been
308 employed to assess strain. Their various strengths and weaknesses have been
309 detailed previously(29). However, one reason for the lack of uptake in the clinical
310 setting of these various techniques has been due to the additional sequences and
311 post-processing required(28, 30, 31). Another method for assessing myocardial
312 function is tissue phase mapping (TPM). This sequence is based on phase contrast
313 imaging with higher temporal resolution and the measurements are in velocities
314 rather than strain or strain rate(32). Like SENC, DENSE and tagging, TPM requires
315 additional sequence acquisitions. A relatively recent development, which uses a
316 similar principal to CMR-TT of making use of the routine cine images, is deformation
317 tracking. This technique has the added advantage of incorporating data from a larger
318 image domain compared to CMR-TT(33), but it is limited to specialist research
319 groups and not widely available unlike CMR-TT which can be purchased. Until
320 recently, a drawback of CMR-TT was the lack of prognostic data in contrast to the
321 well-established prognostic data in STE. However, a recent study of 210 DCM
322 patients has demonstrated that CMR-TT LV strain analysis is predictive of mortality
323 as well as providing incremental risk stratification beyond ejection fraction,
324 biomarkers and clinical information(34). Nonetheless, CMR-TT still has several
325 disadvantages such as the assumption that in-plane displacements or boundaries
326 represent actual deformation or movement of the myocardium. Another issue with
327 CMR-TT is the limitation of cine sequence temporal resolution, which is lower than
328 echocardiography. Our CMR cine sequences had an average temporal resolution of
329 27-30msec whilst STE typically had temporal resolution of 10-15msec. This could
330 account for the poorer correlation of CMR-TT with RVEF compared to STE but it is
331 probably not the sole issue. While we are not aware of any studies, which correlated
332 RVEF with RV strain, there are several studies comparing LV strain parameters with
333 LVEF. These studies have shown very good or excellent correlation of LV strain
334 parameters and LVEF. In a study by Onishi et al, they demonstrated that LV global

335 circumferential strain and LV GLS had a correlation of $r=0.95$ and $r=0.88$
336 respectively(35). In another study, Maret et al showed good correlation between LV
337 global longitudinal strain and LVEF ($r=0.79$) at time when CMR-TT was a new
338 technology(36). One difference with the scanning parameters in these two studies
339 and ours was their cine sequences produced 30 frames per R-R interval whilst ours
340 produced 25 frames per R-R interval. In one study, the temporal resolution was
341 stated to be 26-41msec which is similar or slightly worse than our study. Our group
342 postulates that part of the reduced correlation may again be due to the lower
343 temporal resolution. Since our study's RV longitudinal strain is 50% more than LV
344 longitudinal strain, missing end diastole and end systole by lower temporal resolution
345 would translate into greater variability. Therefore this results in reduced correlation
346 with RVEF.

347

348 *Study Limitations:*

349 Our study has several limitations. Firstly, the study has a small number of patients
350 despite identifying 299 patients who fitted the inclusion criteria. After consideration of
351 the exclusion criteria, patient consent and removal of suboptimal MR cases, we were
352 left with 29 patients. However despite this, our results have indicated that CMR-TT
353 and STE is a potentially useful and accurate tool in identifying $RVEF < 45\%$ in DCM
354 patients. Thereby identifying patients with a worse prognosis and may help improve
355 workflow. Secondly, the CMR-TT and STE did not analyse other types of strain such
356 as circumferential strain as this was not available with the current software.

357

358 **Conclusion:**

359 Of the available strain parameters, STE GLS and CMR-TT FLS show the best
360 correlation with RVEF as well as excellent reproducibility on inter and intra-observer
361 analysis. STE GLS has a higher correlation with RVEF than other standard
362 echocardiography parameters (ie. S', TAPSE and FAC), while CMR-TT FLS shows

363 better correlation than CMR TAPSE and Co-TAPSE. Cut-off values for STE and
364 CMR-TT were recommended and could be a useful tool for fast and accurate echo
365 and CMR analysis of the RV systolic function.

366

367 **List of Abbreviations:**

368 ASE –American Society of Echocardiography

369 AUC –Area under the curve

370 BSA –Body Surface Area

371 CMR –Cardiac magnetic resonance

372 CMR-TT –Cardiac magnetic resonance tissue tracking

373 CMR-FT –Cardiac magnetic resonance feature tracking

374 Co-TAPSE –Corrected tricuspid annular plane systolic excursion

375 DCM –Dilated cardiomyopathy

376 DENSE – Displacement encoding with stimulated echoes

377 ECG -Electrocardiogram

378 FAC –Fractional area change

379 FLS –Free longitudinal strain

380 FRS –Free radial strain

381 GLS –Global longitudinal strain

382 ICC –Intraclass correlation coefficient

383 LV –Left ventricle

384 LVEDV –Left ventricular end-diastolic volume

385 LVESV –Left ventricular end-systolic volume

386 LVEF –Left ventricular ejection fraction

387 ROC –Receiver operating characteristic

388 RV –Right ventricle

389 RVEDV –Right ventricular end-diastolic volume

390 RVESV –Right ventricular end-systolic volume

391 RVEF –Right ventricular ejection fraction
392 RVFAC –Right ventricular fractional area change
393 SENC – Strain encoding
394 STE –Speckle tracking echocardiography
395 TAPSE –Tricuspid annular plane systolic excursion
396 TDI –Tissue doppler imaging
397 TPM – Tissue phase mapping

398

399

400 **Conflicts of interest:** None

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403

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546 **Figure 1.** Radial (blue arrows), longitudinal (red arrows) and circumferential (orange
547 arrows) directions as demonstrated on a short axis and 4-chamber cine image for the
548 left ventricle and right ventricle.

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550 **Figure 2.** Flow Chart of Patient Recruitment

551

552 **Figure 3.** Echocardiography speckle-tracking of the right ventricle. The Automated
553 Functional Imaging (AFI) system automatically tracks the endocardial border with
554 appropriate thickness over the region of interest. After manual adjustment, the
555 system will check the quality of tracking of the six segments. After identifying the time
556 of aortic valve closure by ECG, the system will generate the RV global longitudinal
557 strain (GLS) with the average strain values of the six segments. The Quadrupolar
558 plot can be generated showing strain value of individual segments. RV free wall
559 strain (FWS) is provided by averaging the strain value of the three free RV wall
560 segments.

561

562 **Figure 4.** Cardiac magnetic resonance tissue tracking on the 4-chamber view. The
563 yellow line represents the right ventricular endocardial contour whilst the light blue
564 line is the epicardial contour. The orange line which is an upside down T-shape,
565 pinpoints the tricuspid annulus and the RV apex. This allows the software to

566 determine the extent of the right ventricle. The software then identifies the RV free
567 wall throughout the cardiac cycle to obtain the strain measurements.

568

569 **Figure 5.** Scatter plots demonstrating the correlation between STE and CMR-TT with
570 RVEF. Image A shows the scatter plot and correlation between STE RV free wall
571 longitudinal strain and RVEF. Image B shows STE RV global wall longitudinal strain
572 and RVEF. Image C shows CMR-TT RV free wall longitudinal strain compared to
573 RVEF.

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575 **Figure 6.** Receiver Operator Curve of CMR-TT RV FLS to identify an RVEF<45%.

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577 **Figure 7.** Receiver Operator Curve of STE RV FLS to identify an RVEF<45%.

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580 **Figure 8.** Receiver Operator Curve of STE RV GLS to identify an RVEF<45%.

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