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European Association of Cardiovascular Imaging (EACVI) Expert Consensus Paper: Comprehensive Review of Cardiovascular Magnetic Resonance (CMR) Normal Values of Cardiac Chamber Size and Aortic Root in Adults and Recommendations for Grading Severity
--Manuscript Draft--

Abstract

Preamble

This consensus paper provides a framework for grading of severity of cardiovascular magnetic resonance (CMR) imaging-based assessment of chamber size, function and aortic measurements. This does not currently exist for CMR measures. Differences exist in the normal reference values between echocardiography and CMR along with differences in methods used to derive these. We feel that this document will significantly complement the current literature and provide a practical guide for clinicians in daily reporting and interpretation of CMR scans.

This manuscript aims to complement a recent comprehensive review of CMR normal value publications to recommend cut-off values required for severity grading. Standardization of severity grading for clinically useful CMR parameters is encouraged to lead to clearer and easier communication with referring clinicians and may contribute to better patient care. To this end, the European Association of Cardiovascular Imaging (EACVI) has formed this expert panel that has critically reviewed the literature and has come to a consensus on approaches to severity grading for commonly quantified CMR parameters.

European Association of Cardiovascular Imaging (EACVI) Expert Consensus Paper:

Comprehensive Review of Cardiovascular Magnetic Resonance (CMR) Normal Values of

Cardiac Chamber Size and Aortic Root in Adults and Recommendations for Grading Severity

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Key words

Grading, severity, cardiovascular magnetic resonance, position statement, cardiac chambers

1   **European Association of Cardiovascular Imaging (EACVI) Expert Consensus Paper:**

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for commonly quantified CMR parameters.

Introduction

Cardiovascular Magnetic Resonance (CMR) imaging is now firmly established in clinical practice as a cardiac imaging modality, which complements other non-invasive techniques, such as echocardiography, nuclear cardiac imaging and cardiac computed tomography. CMR has an important role in a wide range of clinical indications and scenarios.[1-3]

Patient impact is dependent on the quality of the clinical CMR service provision. Efforts to standardize CMR image acquisition,[4,5] CMR image analysis and CMR image reporting contribute to raising overall CMR service quality.[6] Certification of individuals in CMR sets minimum standards of expertise and provides evidence to those that can demonstrate it.[7]

Communication of CMR and other imaging modality findings is a key component to ensure that they positively impact patient management.[8] Complementing a description of a parameter as being normal or abnormal (reference values), clinical imaging physicians most often qualify the extent of abnormalities using terms such as 'mild', 'moderate' or 'severe'. Such descriptions allow the clinician not only to understand that the parameter is abnormal but also the extent to which their patient's measurements deviate from normal. As well as providing normative data it would be beneficial to standardize cut-offs for severity of abnormality across centres, such that moderately abnormal has the same implication in all. The association of continuous information with prognosis may be stronger than between the categories of normal, mildly, moderately and severely abnormal and prognosis.[9] However, communication of the degree of abnormality in categories may be clearer to the referring physician and thus may lead to more rapid and consistent clinical decisions.

4

100   For CMR measurements there is no consensus on how to categorize the severity of abnormality.

101   The echocardiography community has published consensus statements to this end.[10,11] Here, we

102   attempt to suggest approaches to grade the severity of abnormality for common and clinically

103   useful CMR parameters. Recommendations on image analysis, including chamber quantification,

104   have been published and are not the scope of this paper.[6] Readers of this expert consensus article

105   should ensure they are aware of the analysis methods used for the original data from which the

106   normal reference ranges are derived, as different analysis approaches can have a clinically

107   relevant impact on results. Between CMR and other imaging modalities that can measure the

108   same phenotype systemic biases may exist. Using the same cut-off values based on different

109   modalities may thus not always be appropriate and even using the same cut-off values for

110   different CMR techniques needs to be interpreted with caution given documented differences

111   (e.g. between fast gradient echo and steady state free procession for myocardial mass and

112   volumes).[12]

113   The authors acknowledge explicitly that the same value on a continuous scale or the same

114   category may not reflect the same degree of abnormality depending on the context. Despite a

115   normal left ventricular ejection fraction value in the context of severe mitral regurgitation this may

116   still suggest an abnormal systolic function. Similarly, a patient with severe concentric hypertrophy

117   and a 'normal' left ventricular ejection fraction may still have abnormal systolic function. Thus, any

118   attempt to categorize the severity of abnormality should not be seen as providing optimal cut-off

119   values in every case. Physicians reporting CMR scans should provide an interpretation that

120   considers the clinical context.

121

122

Methodology for severity grading

The writing group considered several different approaches to define the cut-off values for mild,

moderate and severely abnormal measurements. Multiple statistical techniques exist for

determining threshold values, all of which have limitations.[13] The first approach would be to

define these cut-offs for abnormalities based on standard deviations below and above the normal

reference limit derived from a group of healthy subjects. These data exist for most CMR

parameters. However, not all cardiac parameters are normally distributed, such as aortic valve

regurgitant fraction, making the use of standard deviation as a measure of spread potentially

problematic.

The second approach would be to define abnormalities based on percentile values (95th, 99th,

etc.) of measurements. These are derived from a population that would include normal subjects

along with individuals with disease states.[14] They would consider asymmetric distribution and

range of abnormality present within the general population. A limiting factor for this approach is

that large enough population data sets do not exist for most CMR variables. Ideally, an approach

could classify outcomes directly. A moderately abnormal variable would imply a moderate risk of a

particular adverse outcome for that patient. Risk data are still sparse for some CMR measures and

a moderate degree of deviation from normal may have differential effects on different important

outcomes (e.g. morbidity and mortality). The third approach defines cut-off values based on

expert opinion. Although scientifically least rigorous, this method considers the collective

experience of a panel of experienced CMR experts. We used expert consensus mainly when the

statistical methods would not provide equally distributed value ranges between the severity

categories and to provide some consistency if well-established cut-offs exist for other imaging

modalities (e.g. LVEF grading). Despite the limitations, this categorization of CMR parameters in

the abnormal range represents another step towards the standardization of clinical CMR

148 complementing the consensus documents on CMR image acquisition, interpretation and analysis

149 and reporting.[4,6,15] Derived parameter values could be automatically categorized in clinical

150 reporting software or in clinical trials for improved interpretation of CMR results.

151

152 In the following sections we present consensus suggestions on the grading severity of abnormality

153 based on the anatomical structure assessed. We do not attempt to provide values for each normal

154 reference paper that exists at the time of publication. Specifically, this consensus paper

155 complements a comprehensive recent systematic review of normal ranges using CMR.[16] Much of

156 what is presented in this paper is derived from published normal ranges with relatively small

157 samples but can be updated in the future, using the same principles, with larger datasets. For

158 example, it would also be ideal to have reference ranges categorized by age as well as gender.

159 However, because of the small number of individuals included in the current studies, the

160 consensus was to delay providing age categorised grading until larger reference ranges are

161 published. This will hopefully provide more accurate ranges. We did not include the recent UK

162 Biobank reference ranges in this consensus document given that the LV ejection fractions were

163 significantly lower than currently accepted normal ranges.[17] Further analysis of the data was

164 considered to be required by the writing group before recommending its use in routine clinical

165 practice. It should also be noted that recent European Society of Cardiology heart failure

166 guidelines now categorise heart failure patients as those having reduced (<40%), mid-range (40-

167 49%) and preserved (>50%) ejection fraction based on transthoracic echocardiographic

168 measures.[18]

169

170 Most of the normal range publications did not specify the ethnicity but were derived from a

171 Western population and would largely if not all have been Caucasians and predominantly from the

172 United Kingdom.[19-25] The approaches here are mostly defining cut-off values based on standard

173 deviations reported in the normal population apart from ejection fraction measurement that are

174 derived from a combination of standard deviation and expert consensus. Using the statistical

175 method, the normal range is defined as +/- 2 standard deviations from the mean, mildly abnormal

176 from this cut-off to 3 SD, moderately abnormal from the mild cut-off to 4 SD and severe being

177 more than 4 SD from the population mean. The term "Opposite" refers to values that are outside

178 the normal range but in the opposite direction of typical thought of as pathology, e.g. smaller LV

179 end-diastolic volumes or supra-normal LV ejection fraction. This consensus agreement was to

180 allow commonly used cut-offs that are used for different imaging modalities and avoid confusion.

181 It should be emphasized that these cut-offs are to allow clearer and easier communication of

182 grading. As such, any new or omitted reference range can easily be categorized using the same

183 principles.

184

185 ***Measurements and methods***

186

187 The summary of measurements and techniques used in deriving the normal values from the

188 published papers that are included in this consensus paper are included in Table 1 with description

189 of the methodology used in the relevant subsections. Table 2 provided additional details of the

190 individual studies used to derive the grading parameters. Grading suggestions for left ventricular

191 (Table 3), right ventricular (Table 4), left atrial (Table 5), right atrial (Table 6) and aortic parameters

192 (Table 7), based mainly on a recent review containing normal ranges, are provided.[16]

193

194 **Left and right ventricular ejection fraction**

195 Ejection fraction of the left ventricle is one of the most commonly used cardiac imaging

196 parameters in clinical practice. Left and right ventricular ejection fraction grades were decided on

197 using a combination of statistical method and consensus consistent with the method used by the

8

198   EACVI echocardiography recommendations.[11] Normal range was based on statistical method

199   (published mean +/- 2 standard deviation). Mildly reduced systolic function was based on a

200   combination of statistical method (for upper range, mean - 2 standard deviations) and consensus

201   (for lower range). Grading for moderate and severely reduced left ventricular systolic function was

202   based on consensus between the group and in line with the cut offs published in the EACVI

203   echocardiography document.[11]

204   Normalizing or indexing the reference values according to body habitus can be done in many

205   different ways, most commonly values are indexed to body surface area. The principles of

206   categorizing abnormal values to mildly, moderately or severely abnormal are independent of the

207   indexing approach.

208

237   **Left and right atria**

238

239   We would ideally recommend using volume assessment rather than the areas for the atria for

240   increased accuracy. However, there are some discrepancies in the normal reference values for LA

241   volume between some studies and this should be considered when interpreting the results.[19,21] As

242   3-dimensional analysis tools are not readily available and may be more time consuming, our

243   current recommendation would be to use the biplane method of disks/ area analysis based on 2-

244   dimensional images from 4 and 2 chamber views. There is need for a future update of the grading

245   cut-offs for LA and RA volumes with larger reference range studies. In the meantime, we have still

246   included the LA area measurements. Similar caution in interpretation should be used when

247   assessing RA volume measurements as discrepancies also exist for normal reference range values

248   for the RA. This is likely in part due to the assumptions made when using the equations to derive

249   volume measurements from a single 4 chamber view.

250

251 It should be noted that echo assessment predominantly uses the area-length method or the

252 modified Simpson' rule (Figure 2). Differences in volumes from 3D CMR measures and from echo

253 will exist due to different techniques, spatial resolution and from the inclusion of the appendages

254 in the volumes measured by CMR. For these reasons care should be taken to avoid direct

255 comparison of measurements and cut-offs obtained from CMR and echo.

256

257 ***Aortic root indices***

258 Although the proposed acquisition method is relatively simple, correct alignment of the oblique

259 sagittal and coronal imaging planes may be difficult and ensuring reliable measurements can be

260 challenging, as applied in the study of Burman et al.[25] A 3-dimensional SSFP or a contrast enhanced

261 magnetic resonance angiography may be the more appropriate method for ensuring precise

262 measurements. However, further studies are needed to validate the most accurate and

263 reproducible method of measuring the aorta using CMR and other imaging modalities. Previous

264 guidelines recommended that maximum aneurysm diameter be ideally measured perpendicular to

265 the centre line of the vessel with 3-dimensional reconstruction of CT scan images whenever

266 possible. This approach appears to offer more accurate and reproducible measurements of true

267 aortic dimensions compared with axial cross-section diameters. Using sagittal and coronal views in

268 CMR can provide a good estimation of aortic measurements but may be inaccurate in measuring

269 the true maximum diameters in cases where asymmetry exists.

270
271 **Limitations**
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274 The measures for grading are based on currently available normal ranges. These are based on

275 relatively small cohorts of healthy volunteers and there may be some variations between

276 published reference ranges. Utilizing the methodology outlined in this consensus paper we plan to

277 update this consensus paper using normal ranges of larger cohorts, such as from the UK Biobank

278   study, once further validation work has been completed in order to provide more robust reference

279   ranges. Reference values for LV volumes and mass are influenced by gender and age and thus

280   were presented separately in reference range paper, however, given the small sample sizes in the

281   age categorized tables we considered it would be more accurate to provide age categorized

282   grading parameters derived from larger data sets in the future.

283   Indexed measurements may present limitations when considering obese patients, as the increase

284   in chambers volumes/dimensions is not necessarily proportional to the increase in body surface

285   area and may thus lead to inconsistencies. Unfortunately, this is a common problem for a number

286   of imaging modalities and is not unique to CMR. Ideally the cut-offs for severity categorization

287   using CMR and other imaging modalities should be linked with their impact on the outcomes.

288   However, data regarding this are currently limited. Direct comparison in large cohorts with

289   echocardiography should be done in the future since CMR and echo measures are not directly

290   comparable (different techniques, different measurements' methods) and cut-offs may not be the

291   same when considering severity categorization. This will have obvious clinical impact such as when

292   deciding on suitability for advanced cardiac device therapy e.g. cardiac resynchronization therapy

293   or implantable cardioverter defibrillators.

294

295   Aortic measurements may be more accurately determined using more advanced CMR techniques

296   (e.g. 3D high resolution non-contrast native MRA with high isotropic resolution); also, the studies

297   quoted were published before the SCMR 2013 Standardized image interpretation and post

298   processing in CMR paper,[6] so could introduce some variability in measurements reported between

299   the studies quoted, and contemporary practices.

300

301   The normal ranges for right ventricular end-diastolic volumes indexed to body surface area using

302   the contemporary steady state free precession cine imaging approach contain the cut-off values

303   for major or minor criteria as part of the ARVC task force criteria.[26] The ARVC task force criteria

304   were developed largely based on gradient echo cine CMR which is known to underestimate

305   volumes due to lower/incomplete endocardial border definition.[12,27] Arguably, the ARVC Task

306   Force criteria may need updating based on contemporary SSFP cine normal ranges provided in this

307   expert consensus document to avoid being too sensitive or lacking specificity.

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Table 1: Summary of measurements and techniques used in the normal values published papers included in this

consensus paper.

Parameter/Method	Technique	Advantages	Limitations
LV mass and volumes[19,20] **(Figure 1)**	Papillary muscles included in the mass and excluded from the volumes (Figure 1)	More accurate assessment of mass	More time consuming. Often not followed in clinical practice
RV mass and volumes[19,20] **(Figure 1)**	Papillary muscles included in the mass and excluded from the volumes (Figure 1)	More accurate assessment of mass	More time consuming
LA volumes[19] **(Figure 2)**	Biplane area-length method in HLA and VLA. LA appendage included in LA area but not PVs (Figure 2)	Available from standard imaging SSFP	Not as accurate as SAX contours or 3D analysis
LA volumes[21]	3D modelling, including tracking of AV ring. At phase in which LA size maximal. LA appendage included in LA area but not PVs	More accurate than biplane area length method	Requires 3D modelling software for SSFP image analysis
RA volumes[22] **(Figure 3)**	3D modelling, including tracking of AV ring and time volume curves. At phase in which RA size maximal.	More accurate than area length method (Figure 3)	Requires 3D modelling software for SSFP image analysis
Aortic root dimensions[25] **(Figure 4)**	SSFP images endo-endo from oblique coronal and oblique sagittal views in late diastole (Figure 4)	Accurate assessment of aortic dimensions in 2D	Requires ECG gating. Not as accurate as 3D assessment

433

434 Abbreviations: AV= Atrioventricular; HLA= Horizontal long axis; LA= Left atrium; LV= Left ventricle;
435 PV= Pulmonary vein; RA= Right atrium; RV= Right ventricle; SAX= Short axis; SSFP= Steady state
436 free precession; VLA= Vertical long axis; 2D= 2-dimensional; 3D= 3- dimensional

Table 2. Details of individual studies used to derive the grading parameters in this consensus document.

Study author	Subjects (M:F)	Age range, years	Subjects details	Country	Field strength	Chamber	Measurement methods
Maceira et al[20]	120 (60:60) 10 M and 10 F in 6 age deciles from 20 to 80 years	20-80	Healthy volunteers. Asymptomatic, no known cardiovascular risk factors or history of cardiac disease. Normal physical examination and ECG. Normal BNP levels.	UK	1.5 Tesla	Left Ventricle	SSFP cine imaging. Left ventricular short axis stack. Papillary muscles included in mass and excluded from volumes. Slice thickness of 7mm. Basal slices for end-diastole and end-systole had at least 50% of blood volume surrounded by myocardium. The apical slice defined as last slice showing intracavity blood pool (Figure 1)
Maceira et al[23]						Right Ventricle	Included papillary muscles in mass and excluded them from volumes. Slice thickness of 7mm.
Maceira et al[21]						Left atrium	3-D modelling, including tracking of AV ring. Atrial volumes analysed in 2 steps. Endocardial borders included atrial appendage included in the volume. Systolic descent and twist of the mitral valve was calculated from the tracking of the valve motion on the long axis cine to allow for correction for increase in LA volume due to AV ring descent. LA diameters and areas were measured at end systole. Left atrial appendage included in the atrial volume, but pulmonary veins were not. Slice thickness of 5mm with no inter-slice gap.
Maceira et al[22]						Right atrium	3-D modelling, including tracking of AV ring and time-volume curve analysis. RA maximum volume and maximum diameter measured in the 4-chamber and right 2-chamber views. Volume analysis in 2 steps. 1) Delineation of atrial endocardial border in all cardiac phases. 2) Systolic descent and twist of the tricuspid valve calculated from tracking valve motion in long axis cines, to correct for the increase in atrial volumes due to AV ring descent. Atrial appendage included in volumes, vena cava excluded. Diameters and areas from 2D images measured in the phase and corresponding cines where atrial size and volumes were at a maximum. Longitudinal diameter measured from the midpoint of a line between the septal and lateral (superior and inferior pertaining to the 2-chamber view) insertion of the tricuspid valve to the roof of the right atrium. Transverse diameter measured perpendicular to the midpoint of the longitudinal diameter. Slice thickness of 5mm with no inter-slice gap.

Hudsmith et al[19]	108 (63:45)	21-68	Healthy volunteers. No history of cardiac disease, hypertension or cardiac risk factors and had a normal baseline electrocardiogram	UK	1.5 Tesla	Left Ventricle	SSFP cine imaging. Papillary muscles were included in the mass and excluded from the volumes. Slice thickness of 7mm was used for scanning (Figure 1).
						Right Ventricle	RV volumes below the pulmonary valve. RV volumes were excluded if the surrounding muscle was thin and not trabeculated, suggestive of right atrium. Papillary muscles were included in the mass and excluded from the volume calculation.
						Left atrium	Left atrial volumes, ejection fraction and stroke volumes using the biplane area-length method in the horizontal and vertical long axis. Left atrial appendage included in the atrial volume, but the pulmonary veins were excluded
Alfakih et al[24]	60 (30:30)	20-65	Healthy volunteers. with no history of cardiovascular disease or hypertension, with a normal blood pressure, normal cardiovascular examination and normal resting electrocardiogram. Subjects with arrhythmia, who were pregnant or elite athletes were excluded.	UK	1.5 Tesla	Left Ventricle	SSFP cine imaging. Papillary muscles included in the mass and excluded from the volumes (Figure 1). Slice thickness of 7mm.
						Right ventricle	Included papillary muscles in the RV volume and excluded them from the mass (Figure 1).
Sievers et al[28]	70 (38:32)	25-73	Healthy volunteers. No cardiac or pulmonary disease and no cardiovascular risk factors.	Germany	1.5 Tesla	Right atrium	SSFP cine images. Atrial parameters from both short axis (atrial appendage was included in the volume, vena cava excluded, not included in this paper) and area length method (right atrial volumes and EF were then calculated using the area length method for ellipsoid bodies using formula: 8 x (Area1)2 /3π Length, included in this paper) from the 4-chamber view (Figure 3).
Burman et al[25]	120 (60:60)	20-80	Healthy volunteers. Asymptomatic, had no known cardiovascular risk factors or history of cardiac disease. Physical examination was normal and the ECG was unremarkable. All brain natriuretic peptides (BNP) levels were in the normal range.	UK	1.5 Tesla	Aorta	SSFP cines images. Maximum systolic and end diastolic measurements at 3 levels in sagittal and coronal LVOT planes: at level of the aortic annulus, at level of the maximum diameter across the sinuses, and at sinotubular junction (Figure 4). Slice thickness of 7mm.

438 Abbreviations: BNP = brain naturetic peptide; ECG = electrocardiogram; EF = ejection fraction; LV = left ventricle; RV = right ventricle; SSFP = steady state free precession; UK =
439 United Kingdom;
440

Table 3 – Left ventricle ranges for adults aged 20-80 years* based on Kawel-Boehm **meta-analysis.**[16]

	Women					Men					Methods and Reference
	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	
20-80 years											
EDV [ml]	<86	86 - 178	179 - 201	202 - 224	>224	<106	106 - 214	215 - 241	242 - 268	>268	SM
EDV /BSA [ml/m2]	<56	56 - 96	97 - 106	107 - 116	>116	<57	57 - 105	106 - 117	118 - 129	>129	SM
ESV [ml]	<22	22 - 66	67 - 77	78 - 88	>88	<26	26 - 82	83 - 96	97 - 110	>110	SM
ESV/BSA [ml/m2]#	<14	14 - 34	35 - 39	40 - 44	>44	<14	14 - 38	39 - 44	45 - 50	>50	SM
EF [%]	>78	57 - 77	41 - 56	30 - 40	<30	>78	57 - 77	41 - 56	30 - 40	<30	SM, EC
Mass [g]	<56	56 - 140	141 - 161	162 - 182	>182	<92	92 - 176	177 - 197	198 - 218	>218	SM
Mass/BSA [g/m2]	<41	41 - 81	82 - 91	92 - 101	>101	<49	49 - 85	86 - 94	95 - 103	>103	SM

Abbreviations: BSA = Body surface area; EC = Expert consensus; EDV = End-diastolic volume; EF = Ejection fraction; ESV = End-systolic volume; LV= Left ventricular; "Opposite" refers to values that outside the normal range but in the opposite direction of typical pathology, e.g. smaller LV end-diastolic volumes or supra-normal LV ejection fraction; SM = Statistical method.

*Combined values from references Alfakih[24] (30 Males:30 Females), Hudsmith[19] (63 Males:45 Females), Maceira[20] (60 Males:60 Females), unless stated otherwise.

#From references Hudsmith[19] (63 Males:45 Females) and Maceira[20] (60 Males:60 Females) only.

451 **Table 4 – Right Ventricle ranges for adults aged 20-68 years* based on** Kawel-Boehm **meta-analysis.**[16]

	Women					Men					Methods and Reference
	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	
20-68 years											
EDV [ml]	<77	77-201	202-232	233-263	>263	<118	118-250	251-283	284-316	>316	SM
EDV /BSA [ml/m2]	<48	48-112	113-128	129-144	>144	<61	61-121	122-136	137-151	>151	SM
ESV [ml]	<24	24-84	85-99	100-114	>114	<41	41-117	118-136	137-155	>155	SM
ESV/BSA [ml/m2]#	<12	12-52	53-62	63-72	>72	<19	19-59	60-69	70-79	>79	SM
EF [%]	>71	51-71	41-51	30-40	<30	>72	52-72	41-52	30-40	<30	SM, EC
Mass [g]#	<21	21-49	50-56	57-63	>63	<25	25-57	58-65	66-73	>73	SM
Mass/BSA [g/m2]#	<12	12-28	29-32	33-36	>36	<13	13-29	30-33	34-37	>37	SM

452 Abbreviations: BSA = Body surface area; EC = Expert consensus; EDV = End-diastolic volume; EF = Ejection fraction; ESV = End-systolic volume; RV=
453 right ventricular; "Opposite" refers to values that outside the normal range but in the opposite direction of typical pathology, e.g. smaller LV end-
454 diastolic volumes or supra-normal LV ejection fraction; SM = Statistical method.
455 *Combined values from references Alfakih[24] (30 Males:30 Females), Hudsmith[19] (63 Males:45 Females).
456 #From references Hudsmith (63 Males:45 Females) only.

457

458

459   **Table 5 – Left atrial** maximal volume in the adult based on 3D modeling method and **left atrial maximal** area in the adult for the SSFP technique*.[21]

	Women					Men					Methods and Reference
	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	
20-80 years											
Max. LA volume (ml)	<38	38-98	99-113	114-128	>128	<47	47-107	108-122	123-137	>137	SM
Max. LA volume/ BSA (ml/m²)	<27	27-53	54-60	61-67	>67	<26	26-52	53-59	60-66	>66	SM
Adults											
Area (cm2) 4Ch	<13	13-27	28-31	32-35	>35	<15	15-29	30-33	34-37	>37	SM
Area/BSA (cm2/ m2) 4Ch	<8.4	8.4-15.6	15.7-17.4	17.5-19.2	>19.2	<7.4	7.4-14.6	14.7-16.4	16.5-18.2	>18.2	SM
Area (cm2) 2Ch	<10	10-28	29-33	34-38	>38	<12	12-30	31-35	36-40	>40	SM
Area/BSA (cm2/ m2) 2Ch	<6.2	6.2-15.8	15.9-18.2	18.3-20.6	>20.6	<6.2	6.2-15.8	15.9-18.2	18.3-20.6	>20.6	SM
Area (cm2) 3Ch	<10	10-24	25-28	29-31	>31	<12	12-26	27-30	31-33	>33	SM
Area/BSA (cm2/ m2) 3Ch	<6.4	6.4-13.6	13.7-15.4	15.5-17.2	>17.2	<6.4	6.4-13.6	13.7-15.4	15.5-17.2	>17.2	SM

460   Abbreviations: BSA – Body surface area; LA – Left atrium; Max – Maximum; "Opposite" refers to values that outside the normal range but in the
461   opposite direction of typical pathology; SM = Statistical method; 2Ch = 2 chamber view; 3Ch = 3 chamber view; 4Ch = 4 Chamber view; SSFP= Steady
462   state free precession.
463   *From reference according to reference Maceira, 2010 (60 Males:60 Females) only.[21]
464

465 **Table 6 – Right atrial** maximal volume and **right atrial maximal** area in the adult for the SSFP technique based on Sievers[28] and Maceira

466 publications*.[22]

	Adults					
	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	**Methods and Reference**
25-73 years						
Max. RA volume (ml)*	<37	37-169	170-202	203-235	>235	SM
Max. RA volume/BSA (ml/m2)*	<18	18-90	91-108	109-126	>126	SM
20-80 years						
Area (cm2) 4Ch#	<14	14-30	31-34	35-38	>38	SM
Area/BSA (cm2/ m2) 4Ch#	<8	8-16	17-18	19-20	>20	SM
Area (cm2) 2Ch#	<14	14-30	31-34	35-38	>38	SM
Area/BSA (cm2/ m2) 2Ch#	<8	8-16	17-18	19-20	>20	SM

467 Abbreviations: BSA = Body surface area; Max = Maximum; Min = Minimum; "Opposite" refers to values that outside the normal range but in the
468 opposite direction of typical pathology; RA = Right atrium; SM = Statistical method; 2Ch = 2 chamber view; 4Ch = 4 Chamber view; SSFP= Steady state
469 free precession.
470 *From reference a Seivers 2007 (38 Males:32 Females) only.[28]
471 #From reference Maceira 2013 (60 Males:60 Females) only.[22]
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474

475 **Table 7: Aortic root dimensions reference ranges for based on Burman publication*.**[25]

	Women					Men					Methods and Reference
	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	"Opposite"	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	
20 – 80 years											
Annulus (s) (mm)	<16.	16 - 23	24 - 25	26 - 28	>28	<17	17 - 27	28 - 29	30 - 32	>32	SM
Annulus (c) (mm)	<19	19 - 27	28 - 29	30 - 32	>32	<21	21 - 30	31 - 33	34 - 36	>36	SM
Aortic sinus(s) (mm)	<22	22 - 35	36 - 39	40 - 42	>42	<24	24 - 40	41 - 45	46 - 50	>50	SM
Aortic sinus(c) (mm)	<24	24 - 36	37 - 40	41 - 43	>43	<25	25 - 42	43 - 47	48 - 52	>52	SM
STJ (s) (mm)	<18	18 - 30	31 - 33	34 - 36	>36	<17	17 - 33	34 - 37	38 - 42	>42	SM
STJ (c) (mm)	<18	18 - 28	29 - 31	32 - 34	>34	<18	18 - 32	33 - 36	37 - 40	>40	SM

476 Abbreviations: c = Coronal left ventricular outflow plane; F = Female; M = Male; STJ = Sino tubular junction; s = Sagittal left ventricular outflow plane;

477 SM = Statistical method

478 *From reference Burman 2008 (60 Males:60 Females) only.[25]

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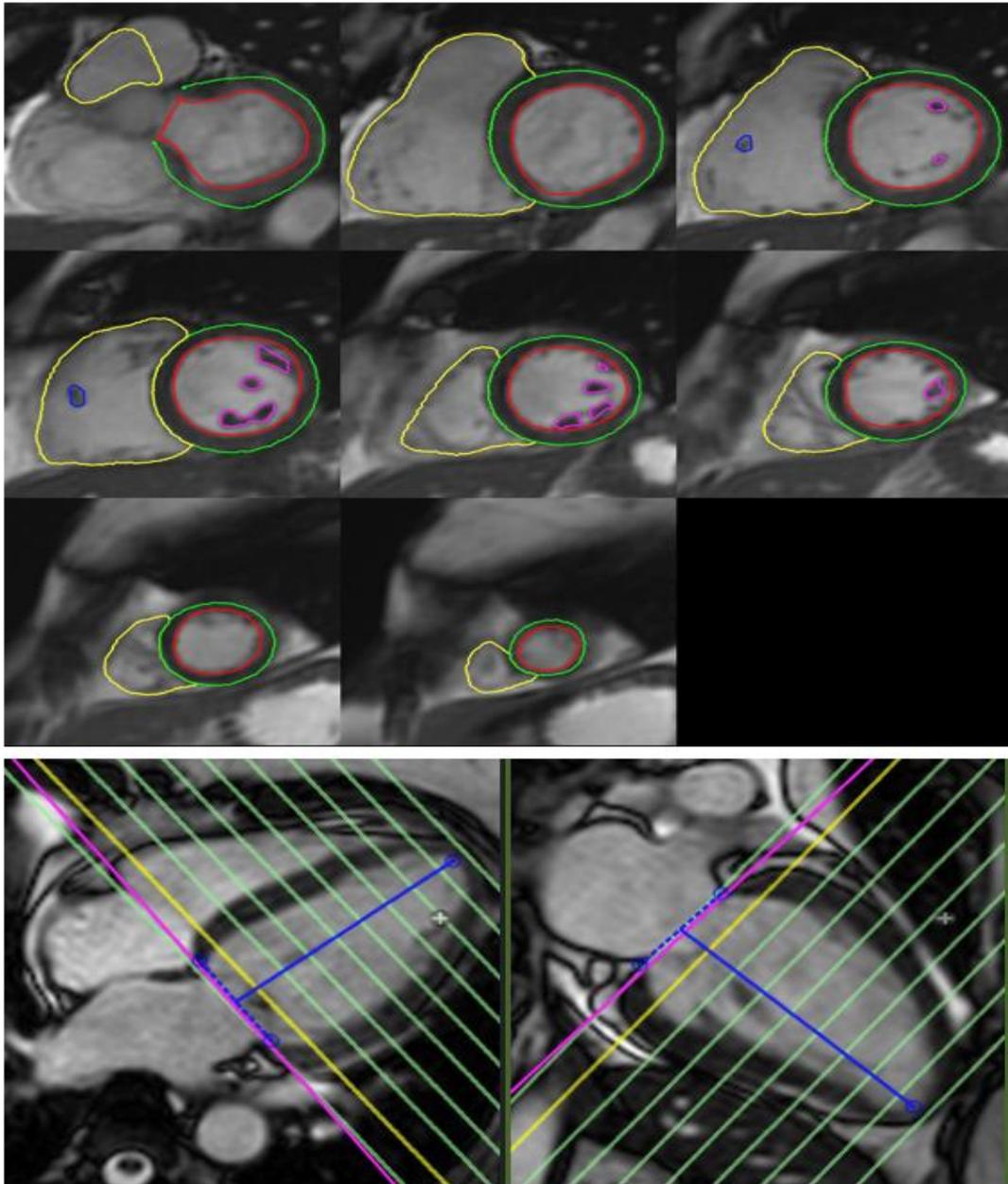
LV epicardium ████████ (green)
RV endocardium ████████ (yellow)
LV endocardium ████████ (red)

Figure 1: Short axis slices including left ventricular endocardial and epicardial contours and right ventricular endocardial contours. The 4 and 2 chamber views show the full coverage of the left and right ventricles required for analysis.

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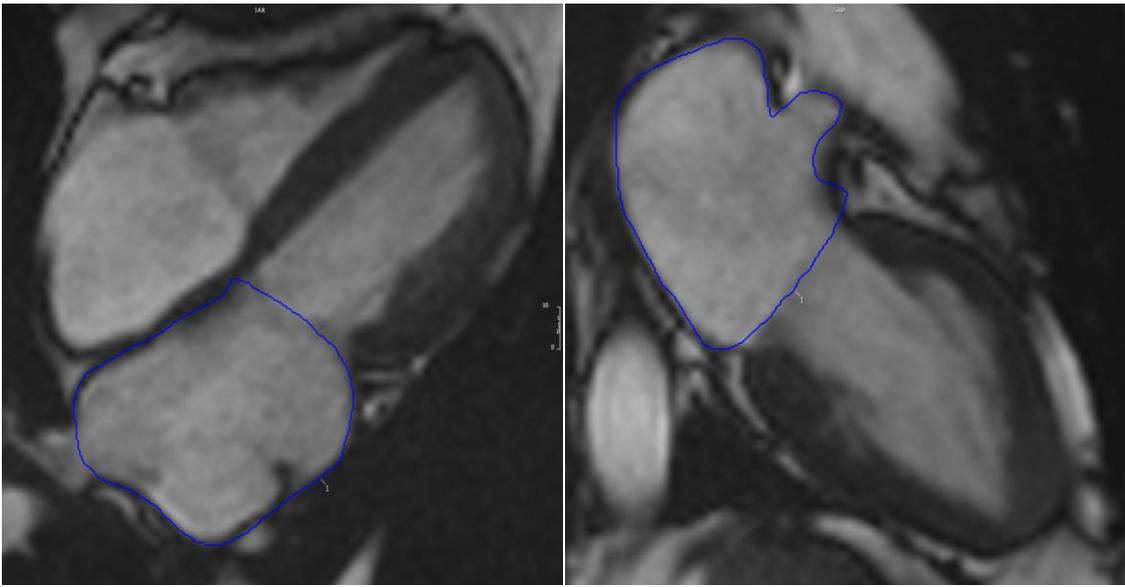
Figure 2: Left atrial contours for area assessment in 4 and 2 chambers during atrial end diastole, measures just before the mitral valve opening for maximum LA volume.

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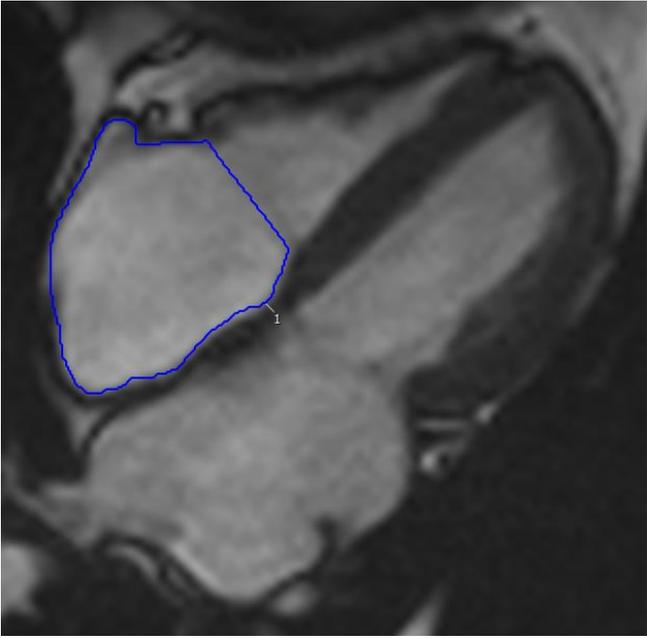
Figure 3: Right atrial contour for area length measurement during atrial end diastole for maximal RA volume.

495

496

Annulus	←→ (blue)
Sinus	←→ (green)
Sino-tubular junction	←→ (yellow)

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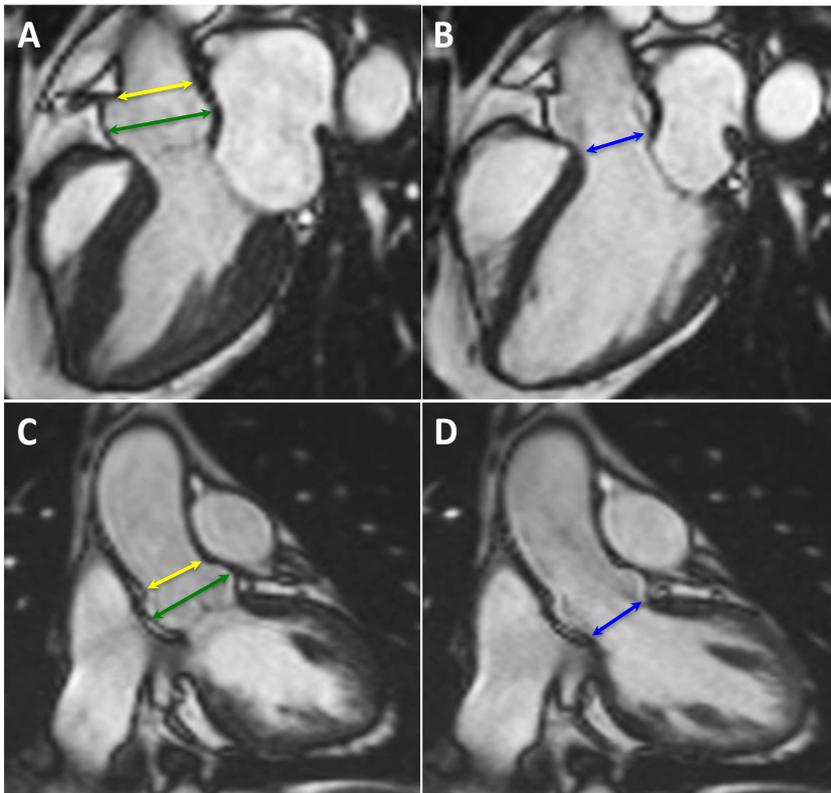
Figure 4: Oblique sagittal# (A, B) and oblique coronal* (C, D) left ventricular outflow views showing the common aortic root measurements. Typically, annulus measured during systole and sinuses of Valsalva and sino-tubular junction measured in diastole. [11,29]

*Oblique sagittal images were obtained by aligning orthogonal to the coronal scouts in the axis of the left ventricular outflow tract and proximal ascending aorta.
#Oblique coronal acquisitions were then located orthogonal to the oblique sagittal cine, aligned with the axis of the left ventricular outflow tract.[25]

Wordcount

Word count including references, tables, figure legends

6793