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EACVI CONSENSUS PAPER

European Association of Cardiovascular Imaging expert consensus paper: a comprehensive review of cardiovascular magnetic resonance normal values of cardiac chamber size and aortic root in adults and recommendations for grading severity

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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.

Keywords grading • severity • cardiovascular magnetic resonance • position statement • cardiac chambers

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 (CT). 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]

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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.

For CMR measurements, there is no consensus on how to categorize the severity of abnormality. The echocardiography community has published consensus statements to this end.[10,11] Here, we attempt to suggest approaches to grade the severity of abnormality for common and clinically useful CMR parameters. Recommendations on image analysis, including chamber quantification, have been published and are not the scope of this paper.[6] Readers of this expert consensus article should ensure they are aware of the analysis methods used for the original data from which the normal reference ranges are derived, as different analysis approaches can have a clinically relevant impact on results. Between CMR and other imaging modalities that can measure the same phenotype systemic biases may exist. Using the same cut-off values based on different modalities may thus not always be appropriate and even using the same cut-off values for different CMR techniques needs to be interpreted with caution, given documented differences (e.g. between fast gradient echo and steady-state free precession for myocardial mass and volumes).[12]

The authors acknowledge explicitly that the same value on a continuous scale or the same category may not reflect the same degree of abnormality depending on the context. Despite a normal left ventricular ejection fraction (LVEF) value in the context of severe mitral regurgitation, this may still suggest an abnormal systolic function. Similarly, a patient with severe concentric hypertrophy and a 'normal' LVEF may still have abnormal systolic function. Thus, any attempt to categorize the severity of abnormality should not be seen as providing optimal cut-off values in every case. Physicians reporting CMR scans should provide an interpretation that considers the clinical context.

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 complementing the consensus documents on CMR image acquisition, interpretation and analysis, and reporting.[4,6,15] Derived parameter values could be automatically categorized in clinical reporting software or clinical trials for improved interpretation of CMR results.

In the following sections, we present consensus suggestions on the grading severity of abnormality based on the anatomical structure assessed. We do not attempt to provide values for each normal reference paper that exists at the time of publication. Specifically, this consensus paper complements a comprehensive recent systematic review of normal ranges using CMR.[16] Much of what is presented in this paper is derived from published normal ranges with relatively small samples but can be updated in the future, using the same principles, with larger datasets. For example, it would also be ideal to have reference ranges categorized by age as well as gender. However, because of the small number of individuals included in the current studies, the consensus was to delay providing age categorized grading until larger reference ranges are published. This will hopefully provide more accurate ranges. We did not include the recent UK Biobank reference ranges in this consensus document given that the LVEFs were significantly lower than currently accepted normal ranges.[17] Further analysis of the data was considered to be required by the writing group before recommending its use in routine clinical practice. It should also be noted that recent European Society of Cardiology heart failure guidelines now categorize heart failure patients as those having reduced (<40%), mid-range (40–49%), and preserved (>50%) ejection fraction based on transthoracic echocardiographic measures.[18]

Most of the normal range publications did not specify the ethnicity but were derived from a western population and would largely if not all have been Caucasians and predominantly from the UK.[19–25] The approaches here are mostly defining cut-off values based on standard

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

2D, 2-dimensional; 3D, 3-dimensional; AV, atrioventricular; ECG, electrocardiogram; HLA, horizontal long axis; LA, left atrium; LV, left ventricle; PV, pulmonary vein; RA, right atrium; RV, right ventricle; SAX, short axis; SSFP, steady-state free precession; VLA, vertical long axis.

deviations reported in the normal population apart from ejection fraction measurement that are derived from a combination of standard deviation and expert consensus. Using the statistical method, the normal range is defined as ±2 SD from the mean, mildly abnormal from this cut-off to 3 SD, moderately abnormal from the mild cut-off to 4 SD, and severe being more than 4 SD from the population mean. The term 'Opposite' refers to values that are outside the normal range but in the opposite direction of typical thought of as pathology, e.g. smaller LV end-diastolic volumes or supra-normal LVEF. This consensus agreement was to allow commonly used cut-offs that are used for different imaging modalities and avoid confusion. It should be emphasized that these cut-offs are to allow clearer and easier communication of grading. As such, any new or omitted reference range can easily be categorized using the same principles.

Measurements and methods

The summary of measurements and techniques used in deriving the normal values from the published papers that are included in this consensus paper are included in *Table 1* with description of the methodology used in the relevant subsections. *Table 2* provided additional details of the individual studies used to derive the grading parameters. Grading suggestions for left ventricular (*Table 3*), right ventricular (*Table 4*), left atrial (LA, *Table 5*), right atrial (RA, *Table 6*), and aortic parameters (*Table 7*), based mainly on a recent review containing normal ranges, are provided.[16]

Left and right ventricular ejection fraction

Ejection fraction of the left ventricle is one of the most commonly used cardiac imaging parameters in clinical practice. LVEF and right ventricular ejection fraction grades were decided on using a combination of statistical method and consensus consistent with the method used by the European Association of Cardiovascular Imaging (EACVI) echocardiography recommendations.[11] Normal range was based on statistical method (published mean ±2 SD). Mildly reduced systolic function was based on a combination of statistical method (for upper range, mean minus 2 SD) and consensus (for lower range). Grading for moderate and severely reduced left ventricular systolic function was based on consensus between the group and in line with the cut-offs published in the EACVI echocardiography document.[11]

Normalizing or indexing the reference values according to body habitus can be done in many different ways, most commonly values are indexed to body surface area. The principles of categorizing abnormal values to mildly, moderately, or severely abnormal are independent of the indexing approach.

Left and right atria

We would ideally recommend using volume assessment rather than the areas for the atria for increased accuracy. However, there are some discrepancies in the normal reference values for LA volume between some studies and this should be considered when interpreting the results.[19,21] As 3D analysis tools are not readily available and may be more time consuming, our current recommendation would be to use the biplane method of disks/area analysis based on 2D images from four- and two-chamber views. There is need for a future update of the grading cut-offs for LA and RA volumes with larger reference range studies. In the meantime, we have still included the LA area measurements. Similar caution in interpretation should be used when assessing

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 (T)	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	Left ventricle	SSFP cine imaging. Left ventricular short-axis stack. Papillary muscles included in mass and excluded from volumes. Slice thickness of 7 mm. 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 intra-cavity blood pool (*Figure 1*)
Maceira *et al.*[23]						Right ventricle	Included papillary muscles in mass and excluded them from volumes. Slice thickness of 7 mm.
Maceira *et al.*[21]						Left atrium	3-D modelling, including tracking of AV ring. Atrial volumes analysed in two 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 5 mm 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 four-chamber and right two-chamber views. Volume analysis in two steps. (i) Delineation of atrial endocardial border in all cardiac phases. (ii) 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 two-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 5 mm 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	Left ventricle	SSFP cine imaging. Papillary muscles were included in the mass and excluded from the volumes. Slice thickness of 7 mm 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	Left ventricle	SSFP cine imaging. Papillary muscles included in the mass and excluded from the volumes (*Figure 1*). Slice thickness of 7 mm.
						Right ventricle	Included papillary muscles in the RV volume and excluded them from the mass (*Figure 1*).
Sievers *et al.*[27]	70 (38:32)	25–73	Healthy volunteers. No cardiac or pulmonary disease and no cardiovascular risk factors.	Germany	1.5	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: $8 \times (\text{Area1})2/3\pi$ length, included in this paper) from the four-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 BNP levels were in the normal range.	UK	1.5	Aorta	SSFP cines images. Maximum systolic and end-diastolic measurements at three levels in sagittal and coronal left ventricular outflow tract 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 7 mm.

BNP, brain natriuretic peptide; ECG, electrocardiogram; EF, ejection fraction; LV, left ventricle; RV, right ventricle; SSFP, steady-state free precession; UK, United Kingdom.

Table 3 Left ventricle ranges for adults aged 20–80 years[a] 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)[b]	<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

'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.
BSA, body surface area; EC, expert consensus; EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; LV, left ventricular; SM, statistical method.
[a]Combined values from references Alfakih *et al.*[24] (30 males:30 females), Hudsmith *et al.*[19] (63 males:45 females), Maceira *et al.*[20] (60 males:60 females), and unless stated otherwise.
[b]From references Hudsmith *et al.*[19] (63 males:45 females) and Maceira *et al.*[20] (60 males:60 females) only.

Table 4 Right ventricle ranges for adults aged 20–68 years[a] 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)[b]	<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)[b]	<21	21–49	50–56	57–63	>63	<25	25–57	58–65	66–73	>73	SM
Mass/BSA (g/m²)[b]	<12	12–28	29–32	33–36	>36	<13	13–29	30–33	34–37	>37	SM

'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;
BSA, body surface area; EC, expert consensus; EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; RV, right ventricular; SM, statistical method.
[a]Combined values from references Alfakih *et al.*,[24] (30 males:30 females), Hudsmith *et al.*[19] (63 males:45 females).
[b]From reference Hudsmith *et al.* (63 males:45 females) only.

RA volume measurements as discrepancies also exist for normal reference range values for the RA. This is likely in part due to the assumptions made when using the equations to derive volume measurements from a single four-chamber view.

It should be noted that echo assessment predominantly uses the area–length method or the modified Simpson' rule (*Figure 2*). Differences in volumes from 3D CMR measures and from echo will exist due to different techniques, spatial resolution and from the inclusion of the appendages in the volumes measured by CMR. For these reasons, care should be taken to avoid direct comparison of measurements and cut-offs obtained from CMR and echo.

Aortic root indices

Although the proposed acquisition method is relatively simple, correct alignment of the oblique sagittal and coronal imaging planes may be difficult and ensuring reliable measurements can be challenging, as applied in the study of Burman *et al.*[25] A 3D steady-state free precession (SSFP) or a contrast-enhanced magnetic resonance angiography (MRA) may be the more appropriate method for ensuring precise

Table 5 Left atrial maximal volume in the adult based on 3D modelling method and left atrial maximal area in the adult for the SSFP technique[a]

	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/m^2)	<27	27–53	54–60	61–67	>67	<26	26–52	53–59	60–66	>66	SM
Adults											
Area (cm^2) 4Ch	<13	13–27	28–31	32–35	>35	<15	15–29	30–33	34–37	>37	SM
Area/BSA (cm^2/m^2) 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 (cm^2) 2Ch	<10	10–28	29–33	34–38	>38	<12	12–30	31–35	36–40	>40	SM
Area/BSA (cm^2/m^2) 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 (cm^2) 3Ch	<10	10–24	25–28	29–31	>31	<12	12–26	27–30	31–33	>33	SM
Area/BSA (cm^2/m^2) 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

'Opposite' refers to values that outside the normal range but in the opposite direction of typical pathology.
2Ch, two-chamber view; 3Ch, three-chamber view; 4Ch, four-chamber view; BSA, body surface area; LA, left atrium; Max, maximum; SM, statistical method; SSFP, steady-state free precession.
[a]From reference according to reference Maceira 2010 (60 males:60 females) only.[21]

Table 6 Right atrial maximal volume and right atrial maximal area in the adult for the SSFP technique based on Sievers *et al.*[27] and Maceira *et al.*[22] publications[a]

	Adults					Methods and reference
	'Opposite'	Reference range	Mildly abnormal	Moderately abnormal	Severely abnormal	
25–73 years						
Max. RA volume (mL)[a]	<37	37–169	170–202	203–235	>235	SM
Max. RA volume/BSA (mL/m^2)[a]	<18	18–90	91–108	109–126	>126	SM
20–80 years						
Area (cm^2) 4Ch[b]	<14	14–30	31–34	35–38	>38	SM
Area/BSA (cm^2/m^2) 4Ch[b]	<8	8–16	17–18	19–20	>20	SM
Area (cm^2) 2Ch[b]	<14	14–30	31–34	35–38	>38	SM
Area/BSA (cm^2/m^2) 2Ch[b]	<8	8–16	17–18	19–20	>20	SM

'Opposite' refers to values that outside the normal range but in the opposite direction of typical pathology.
2Ch, two-chamber view; 4Ch, four-chamber view; BSA, body surface area; Max, maximum; Min, minimum; RA, right atrium; SM, statistical method; SSFP, steady-state free precession.
[a]From reference Seivers 2007 (38 males:32 females) only.[27]
[b]From reference Maceira 2013 (60 males:60 females) only.[22]

measurements. However, further studies are needed to validate the most accurate and reproducible method of measuring the aorta using CMR and other imaging modalities. Previous guidelines recommended that maximum aneurysm diameter be ideally measured perpendicular to the centre line of the vessel with 3D reconstruction of CT scan images whenever possible. This approach appears to offer more accurate and reproducible measurements of true aortic dimensions compared with axial cross-section diameters. Using sagittal and coronal views in CMR can provide a good estimation of aortic measurements but may be inaccurate in measuring the true maximum diameters in cases where asymmetry exists.

Limitations

The measures for grading are based on currently available normal ranges. These are based on relatively small cohorts of healthy volunteers and there may be some variations between published reference ranges. Utilizing the methodology outlined in this consensus paper

Table 7 Aortic root dimensions reference ranges for based on Burman publication[a]

	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

c, coronal left ventricular outflow plane; F, female; M, male; s, sagittal left ventricular outflow plane; SM, statistical method; STJ, sinotubular junction.
[a]From reference Burman 2008 (60 males:60 females) only.[25]

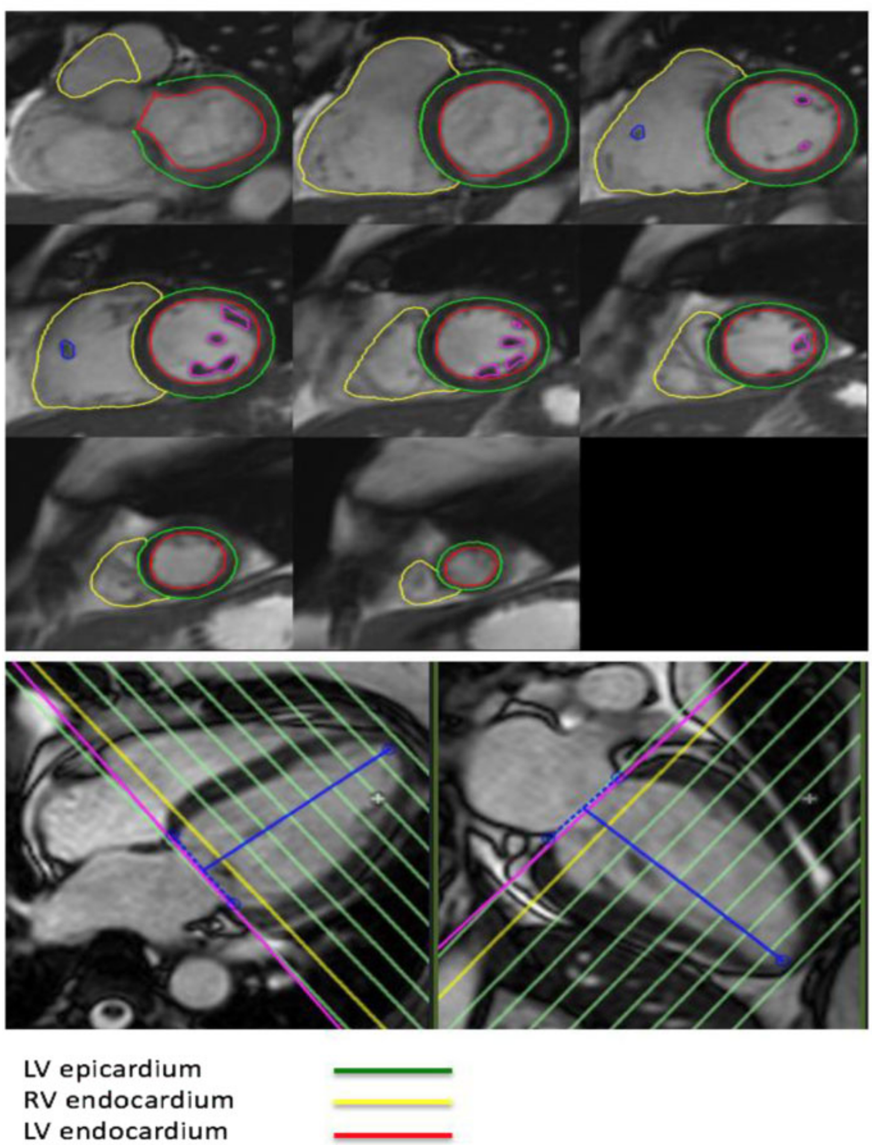

Figure 1 Short-axis slices including left ventricular endocardial and epicardial contours and right ventricular endocardial contours. The four- and two-chamber views show the full coverage of the left and right ventricles required for analysis.

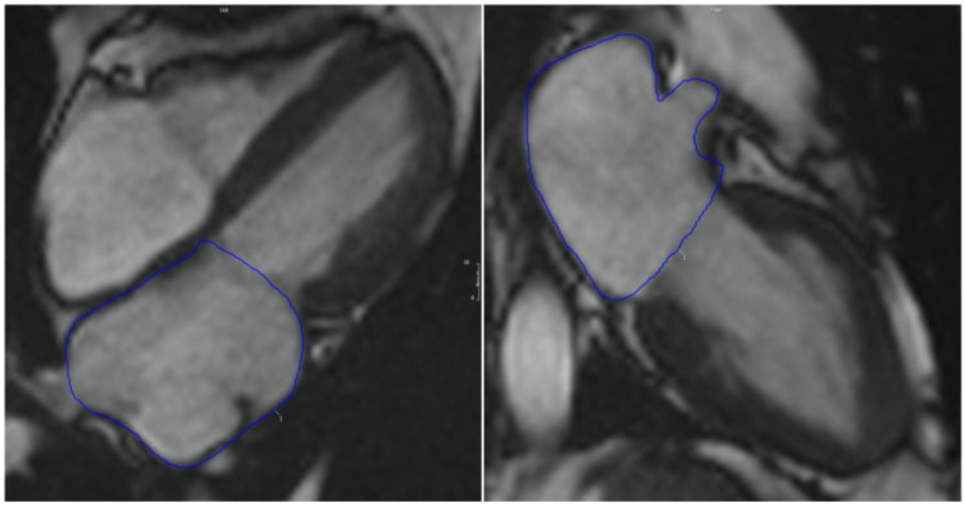

Figure 2 Left atrial contours for area assessment in four and two chambers during atrial end-diastole, measures just before the mitral valve opening for maximum LA volume.

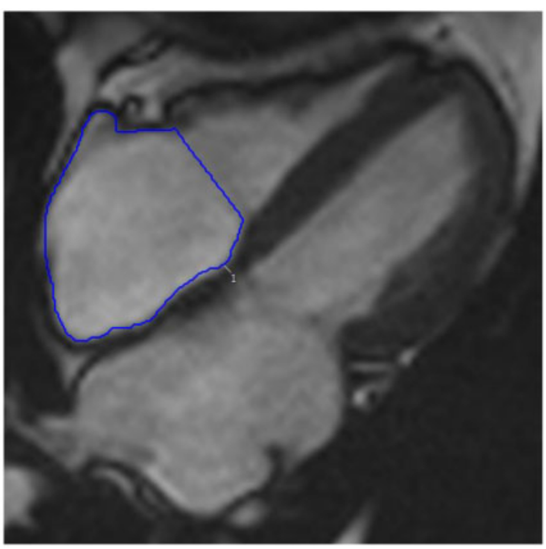

Figure 3 Right atrial contour for area–length measurement during atrial end-diastole for maximal RA volume.

we plan to update this consensus paper using normal ranges of larger cohorts, such as from the UK Biobank study, once further validation work has been completed in order to provide more robust reference ranges. Reference values for LV volumes and mass are influenced by gender and age and thus were presented separately in reference range paper, however, given the small sample sizes in the age categorized tables, we considered it would be more accurate to provide age categorized grading parameters derived from larger data sets in the future.

Indexed measurements may present limitations when considering obese patients, as the increase in chambers volumes/ dimensions is not necessarily proportional to the increase in body surface area and may thus lead to inconsistencies. Unfortunately, this is a common problem for a number of imaging modalities and is not unique to CMR. Ideally, the cut-offs for severity categorization using CMR and other imaging modalities should be linked with their impact on the outcomes. However, data regarding this are currently limited. Direct comparison in large cohorts with echocardiography should be done in the future since CMR and echo measures are not directly comparable (different techniques, different measurements' methods) and cut-offs may not be the same when considering severity categorization. This will have obvious clinical impact such as when deciding on suitability for advanced cardiac device therapy e.g. cardiac resynchronization therapy or implantable cardioverter-defibrillators.

Aortic measurements may be more accurately determined using more advanced CMR techniques (e.g. 3D high resolution non-contrast native MRA with high isotropic resolution); also, the studies quoted were published before the Society for Cardiovascular Magnetic Resonance (SCMR) 2013 Standardized image interpretation and post-processing in CMR paper,[6] so could introduce some variability in measurements reported between the studies quoted, and contemporary practices.

The normal ranges for right ventricular end-diastolic volumes indexed to body surface area using the contemporary SSFP cine imaging approach contain the cut-off values for major or minor criteria as part of the arrhythmogenic right ventricular cardiomyopathy (ARVC) task force criteria.[28] The ARVC task force criteria were developed largely based on gradient echo cine CMR which is known to underestimate volumes due to lower/incomplete endocardial border definition.[12,29] Arguably, the ARVC Task Force criteria may need updating based on contemporary SSFP cine normal ranges provided in this expert consensus document to avoid being too sensitive or lacking specificity.

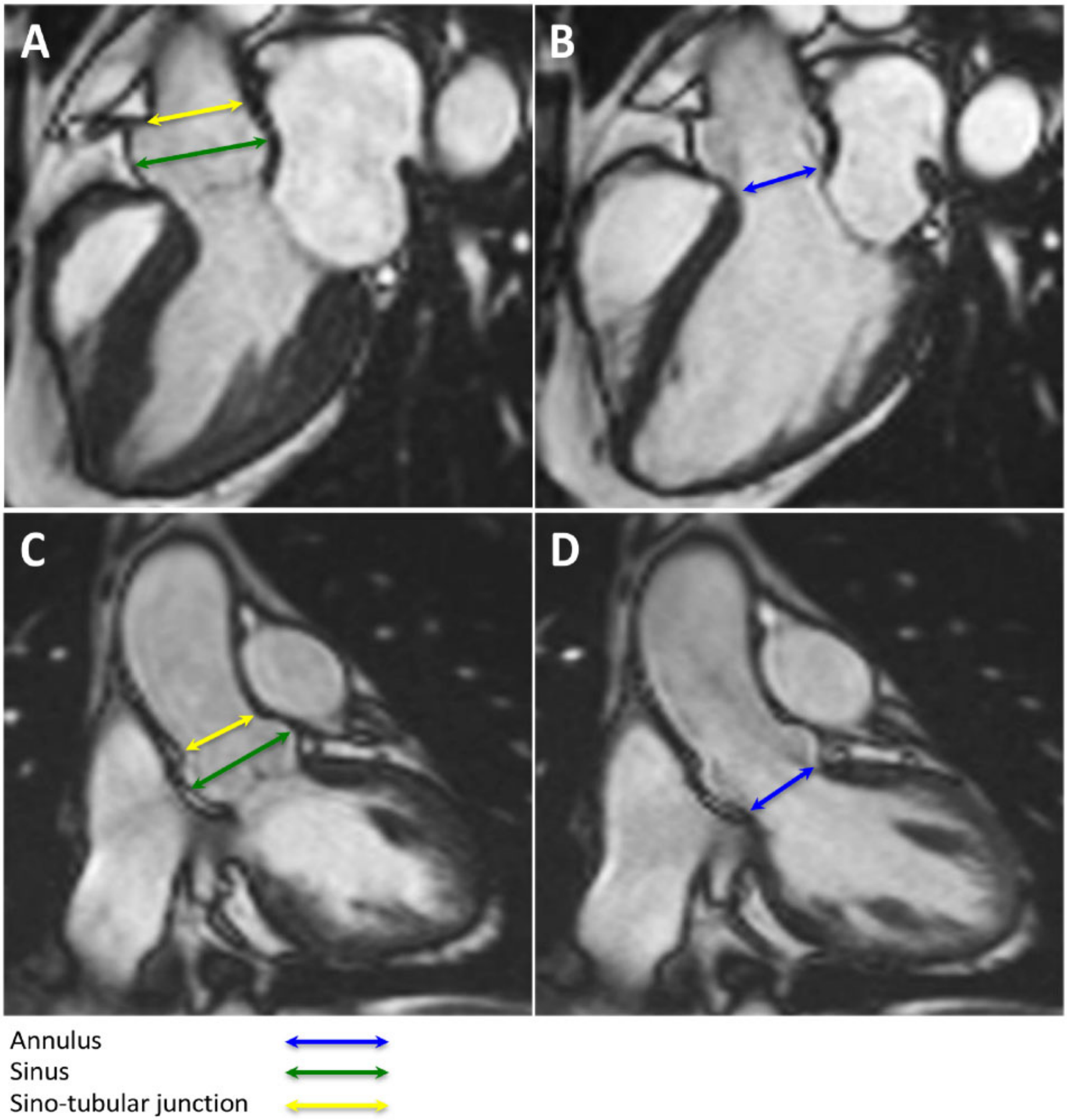

Figure 4 Oblique sagittal[a] (*A* and *B*) and oblique coronal[b] (*C* and *D*) left ventricular outflow views showing the common aortic root measurements. Typically, annulus measured during systole and sinuses of Valsalva and sinotubular junction measured in diastole.[11,26]
[a]Oblique coronal acquisitions were then located orthogonal to the oblique sagittal cine, aligned with the axis of the left ventricular outflow tract.[25]
[b]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.

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