Reference ranges (“normal values”) for cardiovascular magnetic resonance (CMR) in adults and children: 2020 update

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Abstract
Cardiovascular magnetic resonance (CMR) enables assessment and quantification of morphological and functional parameters of the heart, including chamber size and function, diameters of the aorta and pulmonary arteries, flow and myocardial relaxation times. Knowledge of reference ranges (“normal values”) for quantitative CMR is crucial to interpretation of results and to distinguish normal from disease. Compared to the previous version of this review published in 2015, we present updated and expanded reference values for morphological and functional CMR parameters of the cardiovascular system based on the peer-reviewed literature and current CMR techniques. Further, databases and references for deep learning methods are included.

Keywords: Normal values, Reference range, Cardiac magnetic resonance

Background
Cardiovascular magnetic resonance (CMR) provides a wealth of information to help distinguish health from disease. In addition to non-invasively defining chamber sizes and global function, CMR can also assess regional cardiac function as well as tissue composition (myocardial T1, T2 and T2* relaxation time). Advantages of quantitative evaluation of CMR images are objective differentiation between pathology and normal conditions, grading of disease severity, monitoring changes during therapy and evaluating prognosis [1].

Knowledge of the range of normal structure and function is required to interpret abnormal cardiac conditions. Thus, the aim of this review is to provide reference intervals (“normal values”) for morphological and functional CMR parameters of the cardiovascular system based on a systematic review of the literature using current CMR techniques and sequences.

Since the initial publication of the “normal value review” in 2015 [1], new research related to CMR reference values have been published and are now integrated in this update. Previous topics were expanded with new sections including morphological and functional parameters in athletes, myocardial T2 mapping, myocardial perfusion, left-ventricular (LV) trabeculation and normal dimensions of the pulmonary arteries in adults and children. Further, feature tracking is increasingly used to assess myocardial strain and reference intervals are now available for that technology. Deep learning methods are rapidly being incorporated into clinical software analysis packages [2, 3]. These new analytic methods are expected to accelerate quantification of myocardial function from CMR images. To date, reference ranges based on cohorts of healthy subjects using deep learning methods have not
been presented. However due to the potential importance of this topic, we present algorithms and major references related to CMR on these methods.

Methods
A literature search was performed in PubMed to identify publications of CMR reference intervals for each section. When feasible (discussed further below), we sought to provide weighted means calculated based on these published normal values in healthy individuals. General criteria used for inclusion of data in this review are as follows:

a) Sample size of at least 40 subjects. 40 subjects is accepted as the smallest sample size that allows calculation of reference ranges using a parametric method for data with a Gaussian distribution [4]. In some circumstances, separate reference ranges need to be provided by gender. In that case, the sample size of included studies were at least a minimum of 40 subjects per gender. Exceptions to sample size of 40 subjects per group were made for clinically relevant parameters where no publication was available with sufficient sample size for certain parameters. However, reference ranges based on a smaller sample size are of limited validity and should be applied with caution.
b) Only values of “healthy” reference cohorts were included. In particular, reference cohorts that included subjects with a disease or condition known to affect the measured parameter (e.g. hypertension and diabetes) were excluded. For publications that described population statistics (e.g., the MESA study, UK Biobank), we used data only from subgroups of individuals without risk factors or conditions known to affect the CMR parameter. In cases where the original manuscript did not provide sufficient information to allow upper and lower limits to be calculated, authors were contacted for clarification.
c) If two or more publications were determined to refer to the same healthy reference cohort, the values of the cohort were included only once.

Manuscripts were then excluded from consideration as follows: (a) obsolescent CMR technique, (b) missing data that were not provided by the authors of the original publication on request and/ or (c) insufficient or inconsistent description of methods and/or (d) methods of analysis that were not consistent with current Society for Cardiovascular Magnetic Resonance (SCMR) guidelines [5] as of the time of this review.

Technical factors such as sequence parameters are relevant for CMR, and these factors are provided in relationship to the reference values. In addition, factors related to post processing will affect the CMR analysis and these factors are also described. Finally, when available, the relationship of demographic factors (e.g. age, gender, and ethnicity) to reference values are described in each section.

Statistical methods
Statistical analyses were performed with R for statistical computing (version 3.5, R Core Team, Vienna, Austria). Results from multiple studies reporting normal values for the same CMR parameters were combined using a random effects meta-analysis model as implemented by the metamean function in the meta library in R. This produced a weighted, pooled estimate of the population mean of the CMR parameters in the combined studies. Upper and lower limits of normal values were calculated as ±2SDp, where SDp is the pooled standard deviation calculated from the standard deviations reported in each study. Mean values and limits of normal values were “rounded up” to avoid excess digits beyond the measurement capability of CMR.

Left ventricular dimensions and functions in the adult
CMR acquisition parameters
The primary method used to assess the LV is balanced steady-state free precession (bSSFP) technique at 1.5 or 3 T CMR (Table 1). bSSFP technique yields improved blood-myocardial contrast compared to its predecessor, fast gradient echo (FGRE) sequence.

CMR analysis methods
Papillary muscle mass has been shown to significantly affect LV volumes and mass [6–8]. No uniformly accepted convention has been used for analyzing trabeculation and papillary muscle mass. Post-processing recommendations by the SCMR [9] stipulate that papillary muscles should either be consistently included in the LV volume or in the LV mass, but not in both. Tables of normal values should specify the status of the papillary muscles in the CMR analysis.

The majority of published articles used semi-automatic software for analysis of LV function and structure [10–16]. Short-axis images are most commonly analyzed on a per-slice basis, deriving LV mass and volume by applying the Simpson’s method (“stack of disks”) [17]. An example of LV contouring is shown in Fig. 1. Automated CMR analysis facilitated by machine learning is rapidly making inroads in LV volume and mass quantification [3]. The primary focus of early manuscripts has been on agreement between manual and automatic contouring [2]. However, to date, CMR variables for healthy cohorts have not been reported using machine learning methods.
Measurements of LV diameter obtained on cine bSSFP images at diastole and systole on a 4 chamber view and short axis view are shown in Fig. 2.

### Demographic parameters

Gender is independently related to ventricular volumes and mass. Absolute and normalized volumes decrease

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**Table 1** References, normal adult left ventricular volumes, function and dimensions

| First author, year | CMR technique | n, male:female | Age range (years) |
|-------------------|---------------|----------------|------------------|
| Hudsmith, 2005 [22] | 1.5 T, short axis bSSFP, papillary muscles included in LV mass | 63:45 | 21–68 |
| Maceira, 2006 [10] | 1.5 T, short axis bSSFP, papillary muscles included in LV mass | 60:60 | 20–80 |
| Chang, 2012 [23] | 1.5 T, short axis bSSFP, papillary muscles included in LV volume | 64:60 | 20–70 |
| Macedo, 2013 [24] | 1.5 T, short axis bSSFP, papillary muscles included in LV mass | 54:53 | 20–80 |
| Yeon, 2015 [25] | 1.5 T, short axis bSSFP, papillary muscles included in LV volume | 512:340 (61 ± 9)a | 20–70 |
| Le, 2016 [11] | 3 T, short axis bSSFP, papillary muscles included in LV mass | 91:89 | 20–69 |
| Le Ven, 2016 [14] | 1.5 T, Short axis bSSFP, papillary muscles included in LV mass | 196:238 | 18–36 |
| Lei, 2017 [15] | 3 T, short axis bSSFP, papillary muscles included in LV volume | 60:60 | 20–80b |
| Petersen, 2017 [16] | 1.5 T, short axis bSSFP, papillary muscles included in LV volume | 368:432 | 45–74 |
| Bentatou, 2018 [12] | 1.5 T, short axis bSSFP, papillary muscles included in LV mass | 70:70 | 20–69 |
| Buelow, 2018 [13] | 1.5 T, short axis bSSFP, papillary muscles included in LV mass | 291:326 | 20–80b |
| Liu, 2018 [26] | 1.5 T, short axis bSSFP, papillary muscles included in LV mass | 50:50 | 20–70 |

**n** number of study subjects, **bSSFP** balanced steady-state free precession, **LV** left ventricle

*a* Mean ± SD (age-range not provided in original publication)

*b* 6 subjects > 80 years included

**Fig. 1** Contouring of the left ventricle (LV) and right ventricle (RV). Note that LV papillary muscle mass has been isolated and added to LV mass. RV papillary muscles and trabeculations were included in the RV volume
in relationship to age in adults [10] in a continuous manner. For convenience, both average, and values per age decile are given in Tables 2, 3, 4 and 5 based on the peer-reviewed literature.

**Studies included in this review**

Multiple studies have presented cohorts of normal individuals for determining normal LV dimensions. For the purpose of this review, only cohorts of 40 or more normal subjects stratified by gender using bSSFP CMR technique at 1.5 or 3 T have been included. In addition, a full description of the subject cohort (including the analysis methods used), age and gender of subjects was required to be included for this review. Two studies [18, 19] included papillary muscles in LV volume except if directly attached to the LV wall, in which case they were included in LV mass (LVM) instead. Since this approach was inconsistent with post-processing recommended by SCMR [9] and other manuscripts on the topic, both studies were excluded from the current analysis. Data at 1.5 and 3 T is now available for normal subjects using bSSFP short axis imaging. Since it has been shown that parameters of LV volumes and function do not vary by field strength, calculation of the weighted means of these parameters include studies performed at 1.5 T and 3 T [20]. Information on ethnicity in relationship to LV parameters is not available for the majority of papers reporting the bSSFP technique and is therefore not reported in this review. However, small differences in LV parameters by ethnicity have been reported in the Multi-ethnic Study of Atherosclerosis (MESA) study; for further information on the magnitude of such

![Fig. 2](Figure2.png)

**Fig. 2** Measurements of LV diameters obtained on cine bSSFP images during diastole (a, b) and systole (c, d) on the 4 chamber view (a, c) and short axis view (b, d). The longitudinal diameter of the LV was measured on the 4 chamber view as the distance between the mitral valve plane and the LV apex (a, c). On the 4 chamber view the transverse diameter was defined as the distance between the septum and the lateral wall at the basal level [18]. On the short axis view the transverse diameter was obtained at the level of the basal papillary muscles (b, d) [15]
differences, the reader is referred to the work by Natori S et al. [21]. Normal adult values for LV dimensions and functions according to those studies that consistently included papillary muscles in the LVM are presented in Tables 2, 3, 4, whereas those that consistently included papillary muscles in the LV volume are presented in Table 5. For parameters with sufficient sample size, values are also presented per age decile (Tables 3, 4).

Additional left ventricular function parameters

In addition to left ventricular ejection fraction (LVEF), Maceira et al. have provided additional functional parameters that may be useful in some settings [10]. These are summarized in Table 6. For diastolic function, the derivative of the time/volume filling curve expresses the peak filling rate (PFR). Both early (E) and active (A) transmitral filling rates are provided. In addition, longitudinal atrioventricular plane descent (AVPD) and sphericity index (volume observed/volume of sphere using long axis as diameter) at end diastole and end systole are given. These latter parameters are not routinely used for clinical diagnosis. A number of publications have also reported LV end-diastolic and end-systolic diameters by CMR; these parameters are summarized in Table 7.

Right ventricular dimensions and functions in the adult

CMR acquisition parameters

For measurement of right ventricular (RV) volumes, a stack of cine bSSFP images is acquired either in the short axis plane or transaxial plane [9].

CMR analysis methods

Similar to the LV, analysis of the RV is usually performed on a per slice basis by manual contouring of the endocardial and epicardial borders. Volumes are calculated based on the Simpson’s method [17]. The RV volumes and mass are significantly affected by inclusion or exclusion of trabeculations and papillary muscles [27, 28]. For manual contouring, inclusion of trabeculations and papillary muscles as part of the RV volume will achieve higher reproducibility [9, 27, 28]. However, semiautomatic software is increasingly used for volumetric analysis, enabling automatic delineation of papillary muscles [29]. Therefore, normal values for both methods are provided. An example for RV contouring is shown in Fig. 1.

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### Table 2

Left ventricular parameters in the adult for men and women (ages 18–83), papillary muscles included in left ventricular mass

| Parameter                  | Men                          | Women                         |
|----------------------------|------------------------------|-------------------------------|
|                            | n   | Mean<sub>p</sub> | SD<sub>p</sub> | LL–UL<sup>h</sup> | n   | Mean<sub>p</sub> | SD<sub>p</sub> | LL–UL<sup>h</sup> |
| LVEDV (ml)<sup>a</sup>     | 464 | 155   | 30      | 95–215          | 485 | 123   | 22      | 78–167          |
| LVEDV/BSA (ml/m<sup>2</sup>)<sup>b</sup> | 875 | 79    | 15      | 50–108          | 931 | 73    | 12      | 50–96           |
| LVESV (ml)<sup>a</sup>     | 464 | 55    | 15      | 25–85           | 485 | 43    | 11      | 21–64           |
| LVESV/BSA (ml/m<sup>2</sup>)<sup>b</sup> | 875 | 29    | 9       | 11–47           | 931 | 25    | 7       | 10–40           |
| LSV (ml)<sup>c</sup>       | 410 | 103   | 21      | 61–145          | 432 | 83    | 16      | 52–114          |
| LSV/BSA (ml/m<sup>2</sup>)<sup>d</sup> | 701 | 52    | 10      | 33–72           | 758 | 49    | 8       | 33–64           |
| LVEF (%)<sup>e</sup>       | 875 | 64    | 8       | 49–79           | 931 | 66    | 7       | 52–79           |
| LVM (g)<sup>f</sup>        | 464 | 121   | 28      | 66–176          | 485 | 83    | 21      | 41–125          |
| LVM/BSA (g/m<sup>2</sup>)<sup>f</sup> | 805 | 62    | 11      | 39–85           | 861 | 49    | 10      | 30–68           |
| LVCO (l/min)<sup>g</sup>   | 91  | 5.6   | 1.1     | 3.4–7.8         | 89  | 4.5   | 0.9     | 2.7–6.3         |
| LVCI (l/min/m<sup>2</sup>)<sup>g</sup> | 91  | 3.0   | 0.6     | 1.8–4.2         | 89  | 2.9   | 0.5     | 1.9–3.9         |
| LVM/LVEDV (g/ml)<sup>h</sup> | 287 | 0.7   | 0.1     | 0.4–0.9         | 327 | 0.6   | 0.1     | 0.3–0.8         |

<sup>a</sup> Pooled weighted values from references [10, 11, 14, 22, 24]
<sup>b</sup> Pooled weighted values from references [10–14, 22, 24, 26]
<sup>c</sup> Pooled weighted values from references [10, 11, 14, 22]
<sup>d</sup> Pooled weighted values from references [10, 11, 13, 14, 22]
<sup>e</sup> Values from reference [11]
<sup>f</sup> Pooled weighted values from references [11, 14]
<sup>g</sup> Values calculated as mean±2SD<sub>p</sub>

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*BSA* body surface area
Table 3  Left ventricular parameters for adult men by age group, papillary muscles included in left ventricular mass

| Parameter            | 20–29 years | 30–39 years | 40–49 years | 50–59 years | 60–69 years |
|----------------------|-------------|-------------|-------------|-------------|-------------|
|                      | n           | Mean ± SD (LL–UL) | n           | Mean ± SD (LL–UL) | n           | Mean ± SD (LL–UL) | n           | Mean ± SD (LL–UL) | n           | Mean ± SD (LL–UL) |
| LVEDV/BSA (mL/m²)    | 51<sup>a</sup> | 86 ± 13 (61–112) | 105<sup>a</sup> | 81 ± 11 (59–103) | 110<sup>a</sup> | 83 ± 14 (55–110) | 78<sup>a</sup> | 77 ± 14 (49–105) | 34<sup>b</sup> | 78 ± 11 (57–99) |
| LVESV/BSA (mL/m²)    | 51<sup>a</sup> | 34 ± 10 (14–53) | 105<sup>a</sup> | 30 ± 8 (15–46) | 110<sup>a</sup> | 32 ± 9 (13–50) | 78<sup>a</sup> | 29 ± 8 (12–45) | 34<sup>b</sup> | 30 ± 8 (13–46) |
| LVSV/BSA (mL/m²)     | 41<sup>b</sup> | 54 ± 7 (40–68) | 93<sup>b</sup> | 51 ± 8 (34–67) | 101<sup>b</sup> | 52 ± 8 (36–68) | 63<sup>b</sup> | 49 ± 10 (30–69) | 34<sup>b</sup> | 48 ± 8 (34–63) |
| LVEF (%)             | 51<sup>a</sup> | 60 ± 7 (46–74) | 105<sup>a</sup> | 63 ± 7 (49–77) | 110<sup>a</sup> | 62 ± 7 (48–76) | 78<sup>a</sup> | 63 ± 7 (49–78) | 34<sup>b</sup> | 62 ± 7 (48–76) |
| LVM/BSA (g/m²)       | 51<sup>a</sup> | 66 ± 11 (44–87) | 105<sup>a</sup> | 64 ± 11 (41–86) | 110<sup>a</sup> | 64 ± 10 (43–84) | 78<sup>a</sup> | 62 ± 10 (42–83) | 34<sup>b</sup> | 62 ± 12 (38–87) |

<sup>a</sup> Pooled weighted values from references [10, 13, 24]

<sup>b</sup> Pooled weighted values from references [10, 13]

<sup>c</sup> Calculated as mean ± 2*SD.
Table 4: Left ventricular parameters for adult women by age group, papillary muscles included in left ventricular mass

| Parameter          | 20–29 years | 30–39 years | 40–49 years | 50–59 years | 60–69 years |
|--------------------|-------------|-------------|-------------|-------------|-------------|
|                    | n           | Mean$_p$ ± SD$_p$ (LL–UL)$^c$ | n           | Mean$_p$ ± SD$_p$ (LL–UL)$^c$ | n           | Mean$_p$ ± SD$_p$ (LL–UL)$^c$ | n           | Mean$_p$ ± SD$_p$ (LL–UL)$^c$ | n           | Mean$_p$ ± SD$_p$ (LL–UL)$^c$ |
| LVEDV/BSA (ml/m²)  | 43$^a$      | 77 ± 12 (54–100) | 110$^b$     | 77 ± 13 (52–102) | 127$^b$     | 73 ± 12 (50–96) | 93$^a$      | 68 ± 10 (48–89) | 41$^b$     | 68 ± 8 (51–84)  |
| LVESV/BSA (ml/m²) | 43$^a$      | 29 ± 7 (16–43)  | 110$^b$     | 29 ± 10 (9–49)  | 127$^b$     | 27 ± 7 (12–42)  | 93$^a$      | 24 ± 7 (10–38)  | 41$^b$     | 25 ± 5 (14–35)  |
| LSVV/BSA (ml/m²)  | 33$^b$      | 50 ± 6 (38–63)  | 92$^b$      | 49 ± 7 (34–64)  | 110$^b$     | 48 ± 8 (32–64)  | 84$^b$      | 47 ± 6 (34–59)  | 41$^b$     | 44 ± 7 (31–58)  |
| LVEF (%)           | 43$^a$      | 62 ± 6 (50–73)  | 110$^b$     | 64 ± 6 (52–77)  | 127$^b$     | 63 ± 7 (50–76)  | 93$^a$      | 65 ± 6 (52–78)  | 41$^b$     | 65 ± 6 (53–77)  |
| LVM/BSA (g/m²)     | 43$^a$      | 51 ± 11 (29–72) | 110$^b$     | 50 ± 9 (32–68)  | 127$^b$     | 49 ± 9 (32–66)  | 93$^a$      | 51 ± 10 (31–70) | 41$^b$     | 52 ± 11 (31–74) |

$n$: number of study subjects included in the weighted mean values; $\text{Mean}_p$: pooled weighted mean; $\text{SD}_p$: pooled standard deviation; $\text{LL}$: lower limit; $\text{UL}$: upper limit; $\text{LVEF}$: ejection fraction; $\text{LVM}$: left ventricular mass; $\text{BSA}$: body surface area

$^a$: Pooled weighted values from references [10, 13, 24]
$^b$: Pooled weighted values from references [10, 13]
$^c$: Calculated as $\text{Mean}_p ± 2\times\text{SD}_p$
Detailed recommendations for RV acquisitions and post processing have been published [9].

**Demographic parameters**

RV mass and volumes are dependent on body surface area (BSA) [14, 29]. Absolute and RV volumes indexed by BSA are significantly larger in males compared to females [11, 14, 16, 18, 22, 29]. Further, RV volumes decrease with greater age [11, 14, 16, 18, 22, 29].

**Studies included in this review**

Criteria regarding study inclusion are identical compared to the LV. Nine studies based on bSSFP imaging were included (Table 8). In one study, papillary muscles were included as part of the RV mass and excluded from the RV volume [29] with results presented for men and women (Table 9). In the remaining eight studies, the papillary muscles were included as part of the RV cavity volume rather than included in the RV mass [11, 14–16, 18, 22–24] with pooled weighted mean values presented for men and women (Table 10). For a subset of three of these studies [18, 23, 24], for parameters with a sufficient sample size pooled weighted mean values are presented based on age deciles between 20 and 59 years of age for both men (Table 11) and women (Table 12).

### Additional RV function parameters

Similar to the LV, Maceira et al. have provided additional functional parameters, including early and active peak filling rate and the longitudinal AVPD, that may have relevance to specific applications and can be found in the original publication [29].

### Left atrial dimensions and functions in the adult CMR acquisition parameters

There is limited consensus in the literature about how to measure left atrial (LA) volume. The most common methods to measure LA volume are the modified Simpson’s method (analogous to that used to measure LV and RV volumes) and the biplane area-length method [30]. Dedicated 3-dimensional modeling software has also been employed [31].

In the Simpson’s method, a stack of cine bSSFP images either in the SAX, the horizontal long axis or transverse view, is required. For 3-dimensional modeling a stack of SAX images has been used [31]. Evaluation by the biplane area-length method is based on a 2 and 4 chamber view [11, 16, 32–34].

LA longitudinal and transverse diameters and area have been measured on 2, 3, and 4 chamber cine bSSFP images [31, 33, 35] (Fig. 3).

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**Table 5** Left ventricular parameters in the adult for men and women (ages 16–83), papillary muscles included in left ventricular volume

| Parameter | Men | | | Women | | | |
|-----------|-----|---|---|--------|---|---|---|
|          | n  | Meanp | SDp | LL–ULg | n  | Meanp | SDp | LL–ULg |
| LVEDV (ml) | 832 | 145 | 31 | 83–207 | 1064 | 112 | 21 | 70–155 |
| LVEDV/BSA (ml/m²) | 832 | 77 | 15 | 47–107 | 1064 | 69 | 12 | 45–93 |
| LVESV (ml) | 832 | 53 | 18 | 19–88 | 1064 | 39 | 12 | 15–64 |
| LVESV/BSA (ml/m²) | 832 | 29 | 9 | 11–47 | 1064 | 24 | 7 | 10–38 |
| LSV (ml) | 832 | 91 | 18 | 55–127 | 1064 | 73 | 13 | 47–99 |
| LSV/BSA (ml/m²) | 772 | 48 | 9 | 30–66 | 1004 | 45 | 7 | 30–59 |
| LVEF (%) | 832 | 63 | 6 | 51–76 | 1064 | 66 | 7 | 52–79 |
| LVM (g) | 832 | 105 | 24 | 57–152 | 1064 | 73 | 15 | 43–103 |
| LVM/BSA (g/m²) | 832 | 56 | 10 | 36–75 | 1064 | 45 | 7 | 30–59 |
| LVCO (l/min) | 464 | 6.1 | 1.1 | 3.9–8.3 | 632 | 4.9 | 1.0 | 3.0–6.9 |
| LVCI (l/min/m²) | 404 | 3.2 | 0.6 | 2.1–4.3 | 572 | 2.9 | 0.5 | 1.9–4.0 |
| LVM/LVEDV (g/ml) | 708 | 0.7 | 0.2 | 0.3–1.2 | 944 | 0.7 | 0.1 | 0.4–1.0 |

* n number of study subjects included in the weighted mean values, meanp pooled weighted mean, SDp pooled standard deviation, LV left ventricular, EDV end-diastolic volume, ESV end-systolic volume, SV stroke volume, EF ejection fraction, LVM left ventricular mass, CO cardiac output, CI cardiac index, BSA body surface area
* a Pooled weighted values from references [15, 16, 19, 23, 25]
* b Pooled weighted values from references [15, 16, 18, 19, 23, 25]
* c Pooled weighted values from references [16, 18, 19, 23, 25]
* d Pooled weighted values from references [15, 23, 25]
* e Pooled weighted values from references [23, 25]
* f Pooled weighted values from references [16, 25]
* g Calculated as meanp ± 2*SDp
### Table 6
Functional and geometric parameters of the normal left ventricle in the adult, from reference [10]

| Parameter                        | Men (n = 60) | Women (n = 60) |
|----------------------------------|-------------|---------------|
|                                 | Mean | SD    | LL–ULa | Mean | SD   | LL–ULa |
| PWRE (ml/s)                     | 527  | 140   | 247–807| 477  | 146  | 185–769 |
| PWRE /BSA (ml/m²)               | 270  | 70    | 130–410| 279  | 81   | 117–441 |
| PWRE /EDV (/s)                  | 3.4  | 0.7   | 2.0–4.8| 3.8  | 0.8  | 2.2–5.4 |
| PWRA (ml/s)                     | 373  | 82    | 209–537| 283  | 69   | 145–421 |
| PWRA /BSA (ml/m²)               | 193  | 44    | 105–281| 168  | 44   | 80–256 |
| PWRA /EDV (/s)                  | 2.6  | 0.6   | 1.4–3.8| 2.3  | 0.5  | 1.3–3.3 |
| PWRE /PWRA                      | 1.4  | 0.3   | 0.8–2.0| 1.7  | 0.3  | 1.1–2.3 |
| Septal AVPD (mm)                | 15   | 4     | 7–23   | 14   | 3    | 8–20 |
| Septal AVPD /long length (%)    | 15   | 3     | 9–21   | 16   | 4    | 8–24 |
| Lateral AVPD (mm)               | 18   | 4     | 10–26  | 17   | 3    | 11–23 |
| Lateral AVPD /long length (%)   | 17   | 3     | 11–23  | 19   | 3    | 13–25 |
| Sphericity index, diastoleb     | 0.31 | 0.07  | 0.20–0.48| 0.34 | 0.07 | 0.20–0.48 |
| Sphericity index, systole       | 0.20 | 0.05  | 0.1–0.3| 0.23 | 0.07 | 0.09–0.37 |

a number of study subjects, SD standard deviation, LL lower limit, UL upper limit, BSA body surface area, PW peak filling rate, E early, A active, AVPD atrioventricular plane descent

b Calculated as mean ± 2*SD

### Table 7
Left ventricular diameters in the adult for men and women, bSSFP technique

| Parameter                        | Men | Women |
|----------------------------------|-----|-------|
|                                 | n   | Meanp | SDp | LL–ULe |
| LV end-diastolic diameter 4Ch (mm)a | 227 | 52    | 5   | 42–62 |
| LV end-diastolic diameter 4Ch (mm)b | 400 | 53    | 5   | 44–62 |
| LV end-systolic diameter 4Ch (mm)c | 54  | 32    | 3   | 26–38 |
| LV end-systolic diameter 4Ch (mm)d | 60  | 34    | 3   | 28–40 |

bSSFP balanced steady-state free precession, n number of study subjects included in the weighted mean values, meanp pooled weighted mean, SDp pooled standard deviation, LL lower limit, UL upper limit, LV left ventricular, 4Ch 4 chamber view, SAx short axis

a Pooled weighted values from references [18, 24]
b Pooled weighted values from references [15, 25]
c Values from reference [24]
d Values from reference [15]

### Table 8
References, normal right ventricular volumes, function and dimensions in the adult

| First author, year | CMR technique | n, male:female | Age range (years) |
|--------------------|---------------|----------------|-------------------|
| Hudsmith, 2005 [22]| 1.5 T, short axis bSSFP, papillary muscles included in RV volume | 63:45 | 21–68 |
| Maceira, 2006 [29]| 1.5 T, short axis bSSFP, papillary muscles included in RV mass | 60:60 | 20–80 |
| Chang, 2012 [23] | 1.5 T, short axis bSSFP, papillary muscles included in RV volume | 64:60 | 20–70 |
| Macedo, 2013 [24] | 1.5 T, short axis bSSFP, papillary muscles included in RV volume | 54:53 | 20–80 |
| Le Ven, 2015 [14] | 1.5 T, short axis bSSFP, papillary muscles included in RV volume | 196:238 | 18–36 |
| Lei, 2016 [15]   | 3 T, short axis bSSFP, papillary muscles included in RV volume | 60:60 | 23–83 |
| Le, 2016 [11]    | 3 T, short axis bSSFP, papillary muscles included in RV volume | 91:89 | 20–69 |
| Aquaro, 2017 [18] | 1.5 T, short axis bSSFP, papillary muscles included in RV volume | 173:135 | 16– > 60 |
| Petersen, 2017 [16] | 1.5 T, short axis bSSFP, papillary muscles included in RV volume | 368:432 | 45–74 |

n number of study subjects, bSSFP balanced steady-state free precession, RV right ventricular
CMR analysis methods
In many studies the LA appendage has been included as part of the LA volume and pulmonary veins are excluded [14, 31], but the practice of excluding both structures from the LA volume is increasingly gaining acceptance [11, 16, 32, 34].

The maximal LA volume is achieved during ventricular systole. In a cine acquisition, the maximum volume image can be defined as last image immediately before opening of the mitral valve. Accordingly the minimal LA volume image can be defined as the first image after closure of the mitral valve [36].

### Table 9
Right ventricular parameters in the adult for men and women (ages 20–79), papillary muscles included in right ventricular mass, from reference [29]

| Parameter          | Men (n = 60) | Women (n = 60) |
|--------------------|--------------|----------------|
|                    | Mean SD LL–UL | Mean SD LL–UL |
| RVEDV (ml)         | 163 27 109–217 | 127 24 79–175 |
| RVEDV/BSA (ml/m²)  | 83 13 58–109   | 74 12 51–97    |
| RVESV (ml)         | 57 17 23–91    | 44 15 13–75    |
| RVESV/BSA (ml/m²)  | 29 9 12–46     | 26 8 9–42      |
| RVSV (ml)          | 106 18 71–141  | 83 13 56–110   |
| RVSV/BSA (ml/m²)   | 54 8 38–71     | 48 7 35–61     |
| RVEF (%)           | 66 7 51–80     | 66 7 52–80     |
| RVM (g)            | 66 15 37–95    | 48 11 26–71    |
| RVM/BSA (g/m²)     | 34 7 20–48     | 28 6 16–40     |

n number of study subjects, SD standard deviation, LL lower limit, UL upper limit, RV right ventricular, EDV end-diastolic volume, ESV end-systolic volume, SV stroke volume, EF ejection fraction, RVM right ventricular mass, BSA body surface area

### Table 10
Right ventricular parameters in the adult for men and women (ages 20–83), papillary muscles included in right ventricular volume

| Parameter          | Men | Women |
|--------------------|-----|-------|
|                    | n   | Meanp SDp LL–ULg | n   | Meanp SDp LL–ULg |
| RVEDV (ml)         | 896 | 166 39 87–244      | 977 | 122 27 68–176     |
| RVEDV/BSA (ml/m²)  | 1069| 88 17 53–123       | 1112| 76 14 48–104      |
| RVESV (ml)         | 896 | 73 22 29–117       | 977 | 50 15 20–80       |
| RVESV/BSA (ml/m²)  | 1069| 38 11 17–59        | 1112| 30 9 13–48        |
| RVSV (ml)          | 842 | 95 26 43–146       | 924 | 74 18 39–109      |
| RVSV/BSA (ml/m²)   | 955 | 52 12 28–75        | 999 | 48 9 29–66        |
| RVEF (%)           | 1069| 57 8 42–72         | 1112| 60 7 46–74        |
| RVM (g)            | 117 | 36 9 17–54         | 98  | 30 9 13–48        |
| RVM/BSA (g/m²)     | 117 | 19 4 10–28         | 98  | 17 5 7–28         |
| RVCO (l/min)       | 155 | 5.6 1.4 2.8–8.3    | 149 | 4.4 1.0 2.4–6.4   |
| RVCI (l/min/m²)    | 155 | 3.0 0.7 1.5–4.5    | 149 | 2.8 0.6 1.6–4.0   |

n number of study subjects included in the weighted mean values, meanp pooled weighted mean, SDp pooled standard deviation, LL lower limit, UL upper limit, RV right ventricular, EDV end-diastolic volume, ESV end-systolic volume, SV stroke volume, EF ejection fraction, RVM right ventricular mass, CO cardiac output, CI cardiac index, BSA body surface area

| a Pooled weighted values from references [11, 14–16, 22–24]  |
| b Pooled weighted values from references [11, 14–16, 18, 22–24]  |
| c Pooled weighted values from references [11, 14–16, 22, 23]  |
| d Pooled weighted values from references [11, 14, 16, 18, 22, 23]  |
| e Pooled weighted values from references [22, 24]  |
| f Pooled weighted values from references [11, 23]  |
| g Calculated as meanp ± 2*SDp  |
Demographic parameters

Body surface area (BSA) has been shown to have a significant independent influence on LA volume and most diameters [31]. Per Sievers et al. [35], age was not an independent predictor of LA maximal volume or diameter in normal individuals. Men have a larger maximal LA volume compared to women [31, 35].

Studies included in this review

There are nine publications for reference values of the adult LA (volume and/or diameter and/or area) based on normal subjects. Studies included in this review are as follows:

1. Kawel-Boehm et al. [31]
2. Sievers et al. [35]
3. Similar studies from other researchers

Table 11: Right ventricular parameters for adult men by age group, papillary muscles included in right ventricular volume

| Parameter | 20–29 years | 30–39 years | 40–49 years | 50–59 years |
|-----------|-------------|-------------|-------------|-------------|
| n | Mean ± SD (LL–UL) | n | Mean ± SD (LL–UL) | n | Mean ± SD (LL–UL) | n | Mean ± SD (LL–UL) |
| RVEDV/BSA (ml/m²) | 50 | 94 ± 15 (63–124) | 55 | 83 ± 13 (57–109) | 49 | 81 ± 16 (50–112) | 55 | 80 ± 16 (48–111) |
| RVESV/BSA (ml/m²) | 50 | 44 ± 11 (23–66) | 55 | 38 ± 8 (22–53) | 49 | 34 ± 8 (18–49) | 55 | 35 ± 10 (16–54) |
| RVSV/BSA (ml/m²) | 40 | 51 ± 13 (26–77) | 43 | 46 ± 10 (27–65) | 40 | 44 ± 11 (23–65) | 40 | 51 ± 13 (24–78) |
| RVEF (%) | 50 | 52 ± 8 (36–69) | 55 | 55 ± 7 (41–68) | 49 | 57 ± 8 (40–73) | 55 | 57 ± 8 (41–74) |

Table 12: Right ventricular parameters for adult women by age group, papillary muscles included in right ventricular volume

| Parameter | 20–29 years | 30–39 years | 40–49 years | 50–59 years |
|-----------|-------------|-------------|-------------|-------------|
| n | Mean ± SD (LL–UL) | n | Mean ± SD (LL–UL) | n | Mean ± SD (LL–UL) | n | Mean ± SD (LL–UL) |
| RVEDV/BSA (ml/m²) | 47 | 78 ± 12 (55–101) | 51 | 76 ± 12 (51–100) | 46 | 74 ± 14 (46–102) | 46 | 69 ± 13 (42–95) |
| RVESV/BSA (ml/m²) | 47 | 33 ± 12 (10–56) | 51 | 31 ± 8 (15–48) | 46 | 29 ± 8 (13–45) | 46 | 28 ± 8 (11–44) |
| RVSV/BSA (ml/m²) | 37 | 46 ± 9 (28–63) | 33 | 45 ± 12 (22–69) | 35 | 47 ± 11 (24–69) | 37 | 42 ± 10 (22–62) |
| RVEF (%) | 47 | 56 ± 11 (34–78) | 51 | 58 ± 9 (39–77) | 46 | 60 ± 8 (44–76) | 46 | 61 ± 8 (44–78) |

Fig. 3 Measurement of left atrial area (A2Ch, A4Ch, A3C), longitudinal (L2Ch, L4Ch), transverse (T2Ch, T4Ch) and anteroposterior (APD) diameters on the 2-, 4- and 3-chamber views according to reference [31].
on bSSFP imaging with sufficient sample size (n > 40) and these are reported in Table 13. Four of these publications used the biplane area-length method, one used the Simpson’s method, one used both, one used a 3D modeling technique and the remainder measured diameters or areas. Publications reporting population-based cohort data rather than true normal data have been excluded from the current analysis as have publications that incompletely describe the measurement method used [22] or the manner in which pulmonary veins/LA appendage were handled. Normal values for LA volumes and function are presented in Table 14, and normal values for LA diameters in Table 15.

### Right atrial dimensions and functions in the adult CMR acquisition parameters

There is no consensus in the literature regarding acquisition and measurement method for the right atrium (RA). Published methods for RA volume include the modified Simpson’s method, the biplane area-length method and 3D-modeling [23, 24, 37]. For Simpson’s method and 3D modeling, a stack of cine bSSFP images in the SAX view are analyzed. For the biplane area-length method, a 4-chamber view and a RV 2-chamber view are utilized [33] (Fig. 4).

### CMR analysis methods

The inferior and superior vena cava are excluded from the RA volume but there is variability in the inclusion [14, 37] or exclusion [33] of the RA appendage.

The maximal RA volume is achieved during ventricular systole and can be defined as the last cine image before opening of the tricuspid valve. The minimal RA volume can be defined as the first cine image after closure of the tricuspid valve.

#### Demographic parameters

Maceira et al. demonstrated the relationship of most RA parameters to BSA, but there was no influence of age on atrial parameters and no influence of gender on atrial volumes [37]. Other studies have demonstrated an influence of gender [14, 33] and age [11, 33] on some RA parameters. In the study by LeVen et al. gender was independently associated with RA end-diastolic volume and RA end-systolic volume with men having greater values compared to women [14]. In the study by Li et al. the longitudinal RA diameter measured in the 2 chamber and 4 chamber view indexed to BSA and the indexed transverse diameter measured on the 4 chamber view were greater in women than in men [33]. Further, the RA volume indexed to BSA was larger in males than in females [33]. Le et al. found a week correlation between the RA area indexed to BSA with age [11].

#### Studies included in this review

There are five publications with reference values for the RA based on bSSFP imaging with sufficient sample size to be included [11, 14, 18, 33, 37] (Table 16). Pooled weighted mean values for RA volumes and function are provided in Table 17 using the biplane area-length method (RA appendage excluded) or Simpson’s method (either RA appendage included or excluded) for men and women. Pooled weighted mean values for RA areas and diameters are provided in Table 18 for men and women.
Reference ranges for parameters characterizing RA function, including the reservoir, conduit and pump function, can be found in a separate publication by Maceira et al. [38].

Left and right ventricular dimensions and function in children

The presentation of normal values in children is different than in the adult population due to continuous changes in body weight and height as a function of age. Normal data in children are frequently presented in percentiles and/or z-scores (standard deviation score). Z-scores are given as:

\[ z\text{-value} = \frac{\text{measurement} - \text{mean of the population}}{\text{standard deviation of the mean of the population}} \]

Even though previous studies [39–41] have reported a linear correlation between ventricular volumes and BSA in children, there is increasing evidence that the assumption of a simple linear or exponential relationship between somatic growth and age may not be correct. Moreover the relationship between cardiac growth and body growth is still not clearly understood and may vary along age in the developing child [42, 43]. The construction of reference curves using the Lambda-Mu-Sigma (LMS) method is a different way of creating normalized growth percentile curves. In this approach after a power transformation skewness of

| Method                                      | Parameter                        | Men | Mean, SD, LL–UL | Women | Mean, SD, LL–UL |
|---------------------------------------------|----------------------------------|-----|-----------------|-------|-----------------|
| Biplane area-length method; LA appendage excluded | Max. LA volume (ml)\(^a\)  | 734 | 72, 20, 31–112 | 841   | 64, 18, 28–100  |
|                                             | Max. LA volume/BSA (ml/m\(^2\)) | 734 | 38, 11, 17–59  | 841   | 39, 11, 17–61  |
|                                             | Min. LA volume (ml)\(^b\)       | 171 | 25, 10, 6–44   | 146   | 22, 8, 7–38    |
|                                             | Min. LA volume/BSA (ml/m\(^2\)) | 171 | 14, 5, 3–24    | 146   | 13, 5, 4–23    |
|                                             | LA stroke volume (ml)\(^c\)      | 468 | 44, 12, 21–67  | 509   | 42, 10, 21–62  |
|                                             | LA stroke volume/BSA (ml/m\(^2\)) | 363 | 22, 6, 10–34  | 432   | 22, 6, 10–34  |
|                                             | LA ejection fraction (%)\(^d\)  | 534 | 62, 8, 46–77  | 578   | 63, 8, 48–78  |
| Simpson's method; LA appendage excluded     | Max. LA volume (ml)\(^e\)      | 66  | 70, 15, 40–99  | 69    | 66, 13, 39–93  |
|                                             | Max. LA volume/BSA (ml/m\(^2\)) | 66  | 41, 8, 24–57  | 69    | 44, 8, 28–60  |
|                                             | Min. LA volume (ml)\(^f\)       | 66  | 32, 9, 15–50  | 69    | 28, 7, 15–42  |
|                                             | Min. LA volume/BSA (ml/m\(^2\)) | 66  | 19, 5, 9–28   | 69    | 19, 4, 11–27  |
|                                             | LA ejection fraction (%)\(^g\)  | 66  | 54, 8, 38–70  | 69    | 57, 6, 45–69  |
| Simpson's method; LA appendage included     | Max. LA volume (ml)\(^h\)      | 256 | 78, 18, 42–115| 298   | 66, 14, 37–94  |
|                                             | Max. LA volume/BSA (ml/m\(^2\)) | 256 | 40, 8, 25–56  | 298   | 39, 7, 25–53  |
|                                             | Min. LA volume (ml)\(^i\)       | 196 | 32, 9, 14–50  | 238   | 24, 7, 10–38  |
|                                             | Min. LA volume/BSA (ml/m\(^2\)) | 196 | 17, 4, 9–25   | 238   | 15, 4, 7–23   |
|                                             | LA stroke volume (ml)\(^j\)     | 196 | 47, 13, 21–73 | 238   | 39, 10, 19–59 |
|                                             | LA stroke volume/BSA (ml/m\(^2\)) | 196 | 24, 6, 12–36  | 238   | 24, 5, 14–34  |
|                                             | LA ejection fraction (%)\(^k\)  | 196 | 59, 8, 43–75  | 238   | 61, 7, 47–75  |

\(n\) number of study subjects included in the weighted mean values, \(bSSFP\) balanced steady-state free precession, \(\text{Mean}_p\) pooled weighted mean, \(SD_p\) pooled standard deviation, \(LL\) lower limit, \(UL\) upper limit, \(Max.\) maximal, \(Min.\) minimal, \(LA\) left atrial, \(BSA\) body surface area

\(a\) Pooled weighted values from references [11, 16, 32–34]
\(b\) Pooled weighted values from references [22, 32, 33]
\(c\) Pooled weighted values from references [32, 33]
\(d\) Pooled weighted values from references [16, 32]
\(e\) Values from reference [16]
\(f\) Pooled weighted values from references [16, 22, 32, 33]
\(g\) Values from reference [33]
\(h\) Pooled weighted values from references [14, 31]
\(i\) Values from reference [14]
\(j\) Calculated as \(\text{Mean}_p \pm 2*SD_p\)
the data can be transformed into normality and trends are summarized in a smooth curve (L); trends in the mean (M) and coefficient of variation (S) are similarly smoothed. LMS curves are easy to use in daily practice and can account for nonlinear relationships between body and cardiac size and age.

The LMS method is highly efficient to obtain normality in small datasets, for instance in the group of young children. Thus, even extreme values (small children) can be so converted into exact standard deviation scores [44].

### Demographic parameters

The largest cohort of normal data on ventricular size and function in paediatric patients using the bSSFP sequence refers to a population of 141 healthy children collected in three European reference centers. All subjects were Caucasian and included 68 boys and 73 girls. Age distribution, body size and heart rate were equal between genders. Only 12/141 children were younger than 6 years [45].

Boys had larger ventricles than girls [45]. LVEF was found to be slightly higher in boys (67% vs 65%; p 0.01), but not for the RV [45]. Gender differences are more marked in older children, indicating that gender is more important after puberty and in adulthood.

### Studies included in this review

Table 19 shows studies meeting inclusion criteria. The reference values for the LV and RV presented in the study by van der Ven [45] have been pooled from three previous studies [39–41], that have been reported separately in the previous version of our review [1]. Data are presented in percentile curves referred to age by using the LMS Method (Figs. 5, 6).

### CMR analysis methods

For calculation of reference values from reference [45], the original bSSFP images (short axis) have been re-analysed by manual segmentation by one operator, after consensus on the segmentation rules was established within the group. These followed the standards proposed by SCMR [46], except for the trabeculations of the RV, required for calculating the RV mass. In the RV major trabeculae were included in the myocardium.

| Parameter | Men | | | | Women | | | |
|---|---|---|---|---|---|---|---|---|
| Max. LA area 2Ch (cm²)⁴ | 60 | 21 | 5 | 12–30 | 60 | 19 | 5 | 10–28 |
| Max. LA area 2Ch/BSA (cm²/m²)⁵ | 60 | 11 | 2 | 6–16 | 60 | 11 | 2 | 6–16 |
| Max. LA area 3Ch (cm³)⁴ | 60 | 19 | 4 | 12–26 | 60 | 17 | 4 | 10–24 |
| Max. LA area 3Ch/BSA (cm²/m²)⁵ | 60 | 10 | 2 | 6–14 | 60 | 10 | 2 | 6–14 |
| Max. LA area 4Ch (cm³)⁶ | 233 | 23 | 5 | 13–32 | 173 | 21 | 4 | 13–29 |
| Max. LA area 4Ch/BSA (cm²/m²)⁵ | 233 | 12 | 2 | 7–16 | 195 | 12 | 2 | 8–15 |
| Max. LA longitudinal diameter 2Ch (cm)⁷ | 185 | 4.9 | 0.7 | 3.5–6.2 | 181 | 4.6 | 0.7 | 3.3–5.9 |
| Max. LA longitudinal diameter 2Ch/BSA (cm/m²)⁸ | 185 | 2.6 | 0.5 | 1.6–3.6 | 181 | 2.8 | 0.6 | 1.6–3.9 |
| Max. LA transverse diameter 2Ch (cm)⁹ | 126 | 4.4 | 0.6 | 3.2–5.6 | 129 | 4.3 | 0.5 | 3.3–5.2 |
| Max. LA transverse diameter 2Ch/BSA (cm/m²)⁸ | 126 | 2.4 | 0.3 | 1.7–3.0 | 129 | 2.7 | 0.3 | 2.2–3.2 |
| Max. LA longitudinal diameter 3Ch (cm)⁹ | 66 | 5.5 | 0.6 | 4.2–6.8 | 69 | 5.4 | 0.7 | 4.0–6.7 |
| Max. LA longitudinal diameter 3Ch/BSA (cm/m²)⁹ | 66 | 3.2 | 0.4 | 2.4–4.0 | 69 | 3.6 | 0.5 | 2.7–4.6 |
| Max. LA antero-posterior diameter 3Ch (cm)⁹ | 185 | 3.0 | 0.5 | 2.0–4.0 | 181 | 3.0 | 0.5 | 2.0–4.0 |
| Max. LA antero-posterior diameter 3Ch/BSA (cm/m²)⁹ | 185 | 1.6 | 0.3 | 1.0–2.2 | 181 | 1.8 | 0.4 | 1.1–2.5 |
| Max. LA longitudinal diameter 4Ch (cm)⁹ | 126 | 5.8 | 0.6 | 4.6–7.1 | 129 | 5.5 | 0.6 | 4.2–6.8 |
| Max. LA longitudinal diameter 4Ch/BSA (cm/m²)⁹ | 126 | 3.2 | 0.4 | 2.3–4.1 | 129 | 3.5 | 0.5 | 2.5–4.4 |
| Max. LA transverse diameter 4Ch (cm)⁹ | 185 | 4.3 | 0.5 | 3.3–5.3 | 181 | 4.1 | 0.5 | 3.1–5.1 |
| Max. LA transverse diameter 4Ch/BSA (cm/m²)⁹ | 185 | 2.2 | 0.3 | 1.6–2.9 | 181 | 2.5 | 0.4 | 1.8–3.2 |

### Table 15

| Parameter | Meanp | SDp | LL–ULf | Meanp | SDp | LL–ULf |
|---|---|---|---|---|---|---|
| Max. LA area 2Ch | 21 | 5 | 12–30 | 19 | 5 | 10–28 |
| Max. LA area 2Ch/BSA | 11 | 2 | 6–16 | 11 | 2 | 6–16 |
| Max. LA area 3Ch | 19 | 4 | 12–26 | 17 | 4 | 10–24 |
| Max. LA area 3Ch/BSA | 10 | 2 | 6–14 | 10 | 2 | 6–14 |
| Max. LA area 4Ch | 23 | 5 | 13–32 | 21 | 4 | 13–29 |
| Max. LA area 4Ch/BSA | 12 | 2 | 7–16 | 12 | 2 | 8–15 |
| Max. LA longitudinal diameter 2Ch | 4.9 | 0.7 | 3.5–6.2 | 4.6 | 0.7 | 3.3–5.9 |
| Max. LA longitudinal diameter 2Ch/BSA | 2.6 | 0.5 | 1.6–3.6 | 2.8 | 0.6 | 1.6–3.9 |
| Max. LA transverse diameter 2Ch | 4.4 | 0.6 | 3.2–5.6 | 4.3 | 0.5 | 3.3–5.2 |
| Max. LA transverse diameter 2Ch/BSA | 2.4 | 0.3 | 1.7–3.0 | 2.7 | 0.3 | 2.2–3.2 |
| Max. LA longitudinal diameter 3Ch | 5.5 | 0.6 | 4.2–6.8 | 5.4 | 0.7 | 4.0–6.7 |
| Max. LA longitudinal diameter 3Ch/BSA | 3.2 | 0.4 | 2.4–4.0 | 3.6 | 0.5 | 2.7–4.6 |
| Max. LA antero-posterior diameter 3Ch | 3.0 | 0.5 | 2.0–4.0 | 3.0 | 0.5 | 2.0–4.0 |
| Max. LA antero-posterior diameter 3Ch/BSA | 1.6 | 0.3 | 1.0–2.2 | 1.8 | 0.4 | 1.1–2.5 |
| Max. LA longitudinal diameter 4Ch | 5.8 | 0.6 | 4.6–7.1 | 5.5 | 0.6 | 4.2–6.8 |
| Max. LA longitudinal diameter 4Ch/BSA | 3.2 | 0.4 | 2.3–4.1 | 3.5 | 0.5 | 2.5–4.4 |
| Max. LA transverse diameter 4Ch | 4.3 | 0.5 | 3.3–5.3 | 4.1 | 0.5 | 3.1–5.1 |
| Max. LA transverse diameter 4Ch/BSA | 2.2 | 0.3 | 1.6–2.9 | 2.5 | 0.4 | 1.8–3.2 |

### Table notes:

- **n**: number of study subjects included in the weighted mean values.
- **bSSFP**: balanced steady-state free precession.
- **Meanp**: pooled weighted mean.
- **SDp**: pooled standard deviation.
- **LL**: lower limit.
- **UL**: upper limit.
- **Max**: maximal.
- **LA**: left atrial.
- **BSA**: body surface area.
- **2Ch**: 2 chamber view.
- **3Ch**: 3 chamber view.
- **4Ch**: 4 chamber view.

Values from references [31–33, 35, 44, 46].
if they were visualized as being connected to the RV wall in more than 2 adjacent slices. Trabecular islands not connected to the wall were included in the blood pool [45].

**Left and right atrial dimensions and function in children**

**CMR acquisition parameters**

LA and RA dimensions and function were evaluated using bSSFP technique in a single publication [47], (Table 19). Measurements were obtained on a stack of transverse cine bSSFP images with a slice thickness between 5 and 6 mm without interslice gap [47].

**CMR analysis methods**

In [47], the pulmonary veins, the superior and inferior vena cava and the coronary sinus were excluded from the LA and RA volume, respectively, while the atrial appendages were included in the volume of the respective

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**Table 16** References, normal right atrial volumes, function and dimensions in the adult

| First author, year | CMR technique | n, male:female | Age range (years) |
|--------------------|---------------|----------------|------------------|
| Maceira, 2013 [37] | 1.5 T, short axis, RV 2 chamber and 4 chamber bSSFP, 3D modeling and measurement of area and diameters, atrial appendage included for volume analysis | 60:60 | 20–80 |
| Le Ven, 2015 [14] | 1.5 T, short axis bSSFP, quantification of volume and function (Simpson's method), atrial appendage included | 196:238 | 25–73 |
| Le, 2016 [11] | 3.0 T, 4 chamber bSSFP, measurement of area | 91:89 | 20–69 |
| Aquaro, 2017 [18] | 1.5 T, 4 chamber bSSFP, measurement of area | 173:135 | 16–> 60 |
| Li, 2017 [33] | 3.0 T, Short axis, RV 2 chamber and 4 chamber bSSFP, measurement of diameter, volume and function (biplane area-length and Simpson's method), atrial appendage excluded | 66:69 | 23–83 |

**Fig. 4** Measurement of right atrial (RA) parameters according to [37]. Areas and diameters were measured in atrial diastole (maximal size of the left atrium) on the 2-chamber (top row) and 4-chamber (bottom row) views. In B), longitudinal diameter (L) is obtained from the posterior wall of the RA to the center of the tricuspid plane, and transverse diameter (T) is obtained perpendicular to the longitudinal diameter, at the mid level of the RA. C shows measurements of the area for both views including the RA appendage.
Table 17 Right atrial volumes and function in the adult for men and women

| Method                                                                | Parameter                          | Men |        |        |        |        | Women |        |        |        |        |
|-----------------------------------------------------------------------|------------------------------------|-----|--------|--------|--------|--------|-------|--------|--------|--------|--------|
| Biplane area-length method; RA appendage excluded                     | Max. RA volume (ml)               | 66  | 65     | 20     | 24–105 | 69     | 53    | 14     | 24–81  | 69     | 53     |
|                                                                       | Max. RA volume/BSA (ml/m²)         | 66  | 38     | 12     | 15–61  | 69     | 35    | 10     | 16–54  | 69     | 35     |
|                                                                       | Min. RA volume (ml)               | 66  | 32     | 12     | 9–55   | 69     | 23    | 7      | 9–37   | 69     | 23     |
|                                                                       | Min. RA volume/BSA (ml/m²)         | 66  | 19     | 7      | 5–32   | 69     | 15    | 5      | 6–24   | 69     | 15     |
|                                                                       | RA ejection fraction (%)          | 66  | 50     | 9      | 32–68  | 69     | 56    | 9      | 38–74  | 69     | 56     |
| Simpson's method; RA appendage excluded                              | Max. RA volume (ml)               | 66  | 89     | 22     | 46–132 | 69     | 77    | 16     | 45–108 | 69     | 77     |
|                                                                       | Max. RA volume/BSA (ml/m²)         | 66  | 52     | 12     | 28–76  | 69     | 51    | 10     | 31–71  | 69     | 51     |
|                                                                       | Min. RA volume (ml)               | 66  | 46     | 16     | 14–79  | 69     | 35    | 9      | 17–53  | 69     | 35     |
|                                                                       | Min. RA volume/BSA (ml/m²)         | 66  | 27     | 9      | 9–45   | 69     | 23    | 6      | 12–35  | 69     | 23     |
|                                                                       | RA ejection fraction (%)          | 66  | 49     | 10     | 29–69  | 69     | 54    | 9      | 36–72  | 69     | 54     |
| Simpson's method; RA appendage included                              | Max. RA volume (ml)               | 256 | 108    | 25     | 59–158 | 298    | 85    | 18     | 49–122 | 298    | 85     |
|                                                                       | Max. RA volume/BSA (ml/m²)         | 256 | 56     | 12     | 32–79  | 298    | 50    | 10     | 31–69  | 298    | 50     |
|                                                                       | Min. RA volume (ml)               | 196 | 50     | 17     | 16–84  | 238    | 33    | 11     | 11–55  | 238    | 33     |
|                                                                       | Min. RA volume/BSA (ml/m²)         | 196 | 26     | 8      | 10–42  | 238    | 20    | 6      | 8–32   | 238    | 20     |
|                                                                       | RA stroke volume (ml)             | 196 | 58     | 16     | 26–90  | 238    | 47    | 12     | 23–71  | 238    | 47     |
|                                                                       | RA stroke volume/BSA (ml/m²)       | 196 | 30     | 8      | 14–46  | 238    | 28    | 7      | 14–42  | 238    | 28     |
|                                                                       | RA ejection fraction (%)          | 196 | 54     | 10     | 34–74  | 238    | 59    | 9      | 41–77  | 238    | 59     |

n number of study subjects included in the weighted mean values, mean pooling weighted mean, SD pooling standard deviation, LL lower limit, UL upper limit, Max. maximal, Min. minimal, RA right atrial, BSA body surface area

a Values from reference [33]
b Pooled weighted values from references [14, 37]
c Values from reference [14]
d Calculated as mean pooling ± 2*SD pooling

Table 18 Right atrial diameter and area in the adult for men and women, bSSFP technique

| Parameter                          | Men |        |        |        |        |        | Women |        |        |        |
|------------------------------------|-----|--------|--------|--------|--------|--------|-------|--------|--------|--------|
| Max. RA area 2Ch (cm²)             | 60  | 23     | 4      | 15–31  | 60     | 21     | 4      | 13–29  | 60     | 21     |
| Max. RA area 2Ch/BSA (cm²/m²)      | 60  | 12     | 2      | 7–17   | 60     | 12     | 2      | 7–17   | 60     | 12     |
| Max. RA area 4Ch (cm²)             | 324 | 21     | 4      | 13–30  | 284    | 19     | 3      | 12–26  | 284    | 19     |
| Max. RA area 4Ch/BSA (cm²/m²)      | 324 | 11     | 2      | 7–15   | 284    | 12     | 2      | 8–15   | 284    | 12     |
| Max. RA longitudinal diameter 2Ch (cm) | 126 | 5.5    | 0.6    | 4.2–6.7 | 129   | 5.1    | 0.6    | 3.9–6.3 | 129   | 5.1    |
| Max. RA longitudinal diameter 2Ch/BSA (cm²/m²) | 126 | 3.0    | 0.4    | 2.3–3.7 | 129   | 3.2    | 0.4    | 2.3–4.1 | 129   | 3.2    |
| Max. RA transverse diameter 2Ch (cm) | 126 | 4.2    | 0.9    | 2.4–6.0 | 129   | 4.1    | 0.9    | 2.4–5.9 | 129   | 4.1    |
| Max. RA transverse diameter 2Ch/BSA (cm²/m²) | 126 | 2.3    | 0.5    | 1.3–3.3 | 129   | 2.6    | 0.6    | 1.5–3.7 | 129   | 2.6    |
| Max. RA longitudinal diameter 4Ch (cm) | 126 | 5.3    | 0.6    | 4.0–6.6 | 129   | 5.1    | 0.6    | 4.0–6.3 | 129   | 5.1    |
| Max. RA longitudinal diameter 4Ch/BSA (cm²/m²) | 126 | 2.9    | 0.4    | 2.2–3.7 | 129   | 3.2    | 0.4    | 2.4–4.0 | 129   | 3.2    |
| Max. RA transverse diameter 4Ch (cm) | 126 | 4.8    | 0.6    | 3.7–5.9 | 129   | 4.3    | 0.6    | 3.2–5.4 | 129   | 4.3    |
| Max. RA transverse diameter 4Ch/BSA (cm²/m²) | 126 | 2.6    | 0.3    | 2.1–3.2 | 129   | 2.7    | 0.3    | 2.0–3.4 | 129   | 2.7    |

n number of study subjects included in the weighted mean values, mean pooling weighted mean, SD pooling standard deviation, LL lower limit, UL upper limit, Max. maximal, RA right atrial, 2Ch 2 chamber view, 3Ch 3 chamber view, 4Ch 4 chamber view, BSA body surface area

a Values from reference [37]
b Pooled weighted values from references [11, 18, 37]
c Pooled weighted values from references [33, 37]
d Calculated as mean pooling ± 2*SD pooling
atrium. The maximal atrial volume was measured at ven-
tricular end-systole and the minimal atrial volume at ven-
tricular end-diastole.

**Demographic parameters**
LA and RA volumes show an increase with age with a
plateau after the age of 14 for girls only. Absolute and
indexed volumes have been shown to be significantly
greater for boys compared to girls (except for the indexed
maximal volumes for both atria) [47].

**Studies included in this review**
Sarikouch et al. evaluated atrial parameters of 115 healthy
children (Table 19) [47] using bSSFP imaging. Data is
presented as L, M, S values to enable calculation of the
standard deviation score and in percentiles (Tables 20,
21).

**Cardiac chamber size in the athlete**

**CMR analysis methods**
Methodologic considerations for CMR analysis are the
same as for the non-athletes heart as described in the
sections above. In both studies included in this review,
papillary muscles and trabeculations were included in the
ventricular volumes and excluded from LV and RV mass.

**Demographic parameters**
Following the Mitchell classification, sports can be char-
acterized as being high or low in dynamic (endurance,
isotonic) versus static (strength/resistance, isometric)
training and performance components [48]. Athletic
competition can therefore be primarily (a) endurance
(e.g. long distance running, swimming), (b) combined
(e.g. rowers, cyclists) or (c) strength (e.g. body building
and weight training). There are insufficient numbers of
study subjects available in the literature to establish nor-
mative values for the strength category of athletes [49].

Cardiac chamber sizes may vary depending on the
extent of exercise and training. One approach to classi-
fication is 9–18 h training per week (regular athletes)
vs>18 h training per week (elite athletes) [50]. Adaptive
changes to exercise are greater with higher exercise/
training level [49].

Luijkx found a balanced increase of LV and RV cham-
ber volume in relationship in the athlete heart [51]; a
large meta-analysis of the literature had a similar con-
clusion [49]. RV and LV systolic function is commonly
characterized by ejection fraction, but this parameter is
known to show the most variation between observers.
Nevertheless, RVEF and LVEF are > 50% in reports of the
athlete’s heart by CMR [48].

The RV chamber volumes are greater in the athletes
heart than in normal individuals [51]. The athlete's
RV volumes may exceed CMR criteria for abnor-
mality in arrhythmogenic right ventricular cardiomyopa-
thy (ARVC). However, RVEF is in the normal range of non-
athletes even in the athlete heart (i.e. > 50%) whereas
RVEF is abnormally low (< 45%) in ARVC.

**Studies included in this review**
After elimination of redundant publications using the
same study population and publications with > 40 ath-
letes, there is one publication with data on the ath-
lete’s heart by Prakken et al. (Table 22) [50]. This study
was performed at 1.5 T and has sufficient descrip-
tion of CMR analysis technique to enable comparison
(Tables 23, 24). Papillary muscles and trabeculation
were included in ventricular volumes and excluded from LV and RV mass.

| First author, year | CMR technique | n, male:female | Age range (years) |
|--------------------|----------------|----------------|-----------------|
| van der Ven, 2019 [45] | 1.5 T, short axis bSSFP; dimensions of LV and RV; papillary mus-
cles included in LV mass; RV mass measured at end-systole; major trabeculae included in RV mass when connected to the ventricular wall, trabeculae not connected to the wall included in RV volume | 68:73 | < 1–18 |
| Sarikouch, 2011 [47] | 1.5 T, axial bSSFP; pulmonary veins, superior and inferior vena cava and coronary sinus excluded, atrial appendages included from/in left and right atrial volume, respectively | 56:59 | 4–20 |

n number of study subjects, bSSFP balanced steady-state free precession, LV left ventricular, RV right ventricular
Fig. 5 Reference curves for LV dimensions and function in children, reprinted with permission from reference [45]. Curves for boys are displayed in blue on the left, curves for girls are shown in pink on the right. Reference lines show the 3rd, 10th, 90th and 97th percentile. LV left ventricle, ED end diastolic, ES end systolic, SV stroke volume.
Fig. 6 Reference curves for RV dimensions and function in children, reprinted with permission from reference [45]. Curves for boys are displayed in blue on the left, curves for girls are shown in pink on the right. Reference lines show the 3rd, 10th, 90th and 97th percentile. LV left ventricle, ED end diastolic, ES end systolic, SV stroke volume.
Table 20 Normal left atrial and right atrial volume in boys; LMS parameters to calculate z-scores and percentiles relative to age according to reference [47]

| Agea | Left atrium | Percentiles (ml/m²) | Right atrium | Percentiles (ml/m²) |
|------|-------------|---------------------|--------------|---------------------|
|      | LMS-parameters |                      | LMS-parameters |                      |
|      | L  | M  | S  | P3 | P50 | P97 | L  | M  | S  | P3 | P50 | P97 |
| 6    | 1.378 | 36.715 | 0.263 | 14 | 37 | 55 | 1.806 | 33.342 | 0.191 | 20 | 39 | 68 |
| 7    | 1.378 | 38.610 | 0.246 | 17 | 39 | 56 | 1.806 | 48.385 | 0.203 | 22 | 43 | 71 |
| 8    | 1.378 | 40.291 | 0.229 | 20 | 40 | 57 | 1.806 | 51.247 | 0.205 | 24 | 47 | 73 |
| 9    | 1.378 | 41.762 | 0.212 | 22 | 42 | 58 | 1.806 | 51.742 | 0.205 | 26 | 49 | 74 |
| 10   | 1.378 | 43.375 | 0.197 | 25 | 43 | 59 | 1.806 | 52.579 | 0.204 | 28 | 52 | 75 |
| 11   | 1.378 | 45.120 | 0.183 | 27 | 45 | 61 | 1.806 | 54.891 | 0.200 | 30 | 54 | 76 |
| 12   | 1.378 | 46.671 | 0.171 | 29 | 47 | 62 | 1.806 | 56.348 | 0.197 | 32 | 57 | 77 |
| 13   | 1.378 | 47.784 | 0.161 | 31 | 48 | 62 | 1.806 | 57.830 | 0.193 | 33 | 59 | 78 |
| 14   | 1.378 | 48.331 | 0.152 | 33 | 48 | 62 | 1.806 | 59.473 | 0.188 | 34 | 61 | 79 |
| 15   | 1.378 | 48.581 | 0.142 | 34 | 49 | 62 | 1.806 | 61.042 | 0.181 | 35 | 63 | 80 |
| 16   | 1.378 | 49.112 | 0.131 | 36 | 49 | 61 | 1.806 | 63.114 | 0.171 | 37 | 65 | 81 |
| 17   | 1.378 | 50.353 | 0.120 | 38 | 50 | 62 | 1.806 | 64.322 | 0.161 | 38 | 67 | 82 |
| 18   | 1.378 | 52.583 | 0.111 | 40 | 53 | 64 | 1.806 | 66.227 | 0.145 | 40 | 69 | 84 |
| 19   | 1.378 | 55.860 | 0.103 | 44 | 56 | 67 | 1.806 | 72.157 | 0.110 | 43 | 71 | 85 |
| 20   | 1.378 | 59.928 | 0.097 | 48 | 60 | 71 | 1.806 | 77.498 | 0.064 | 45 | 72 | 86 |

LMS: L = Lambda (skewness of the distribution), M = Mu (median), S = Sigma (variance)

Standard deviation score (SDS) = [(X / M) - 1] / (L * S), where X is the measured atrial volume in ml/m² and L, M and S are the values interpolated for the child’s age; lower and upper limits correspond to a score of -2 and 2 and to the 3rd and 97th percentile, respectively.

* Age in years

Table 21 Normal left atrial and right atrial volume in girls; LMS parameters to calculate z-scores and percentiles relative to age according to reference [47]

| Agea | Left atrium | Percentiles (ml/m²) | Right atrium | Percentiles (ml/m²) |
|------|-------------|---------------------|--------------|---------------------|
|      | LMS-parameters |                      | LMS-parameters |                      |
|      | L  | M  | S  | P3 | P50 | P97 | L  | M  | S  | P3 | P50 | P97 |
| 4    | -1.100 | 37.566 | 0.248 | 22 | 34 | 44 | 0.889 | 47.196 | 0.328 | 18 | 47 | 79 |
| 5    | -0.956 | 38.333 | 0.242 | 23 | 36 | 46 | 0.774 | 47.386 | 0.318 | 20 | 47 | 80 |
| 6    | -0.717 | 39.568 | 0.234 | 25 | 39 | 50 | 0.587 | 47.733 | 0.302 | 23 | 48 | 80 |
| 7    | -0.478 | 40.739 | 0.225 | 26 | 41 | 53 | 0.421 | 48.181 | 0.284 | 25 | 48 | 80 |
| 8    | -0.239 | 41.934 | 0.217 | 28 | 43 | 55 | 0.266 | 48.837 | 0.265 | 28 | 49 | 80 |
| 9    | 0.000  | 43.072 | 0.208 | 28 | 44 | 56 | 0.106 | 49.868 | 0.244 | 30 | 50 | 80 |
| 10   | 0.239  | 43.953 | 0.199 | 28 | 44 | 56 | -0.033 | 51.098 | 0.221 | 33 | 51 | 80 |
| 11   | 0.478  | 44.548 | 0.191 | 29 | 44 | 57 | -0.071 | 52.283 | 0.197 | 35 | 52 | 78 |
| 12   | 0.717  | 45.080 | 0.182 | 29 | 45 | 58 | 0.029  | 53.388 | 0.175 | 38 | 53 | 76 |
| 13   | 0.956  | 45.636 | 0.173 | 30 | 45 | 59 | 0.262  | 54.329 | 0.157 | 39 | 54 | 73 |
| 14   | 1.195  | 46.118 | 0.165 | 30 | 46 | 60 | 0.595  | 55.205 | 0.147 | 40 | 55 | 72 |
| 15   | 1.434  | 46.070 | 0.156 | 30 | 47 | 60 | 0.991  | 55.815 | 0.145 | 40 | 56 | 72 |
| 16   | 1.673  | 45.343 | 0.148 | 30 | 46 | 59 | 1.149  | 56.153 | 0.148 | 38 | 56 | 72 |
| 17   | 1.912  | 44.258 | 0.139 | 29 | 44 | 57 | 1.852  | 56.470 | 0.155 | 36 | 56 | 72 |
| 18   | 2.151  | 43.116 | 0.130 | 28 | 42 | 55 | 2.276  | 57.000 | 0.164 | 31 | 57 | 73 |

LMS: L = Lambda (skewness of the distribution), M = Mu (median), S = Sigma (variance)

Standard deviation score (SDS) = [(X / M) - 1] / (L * S), where X is the measured atrial volume in ml/m² and L, M and S are the values interpolated for the child’s age; lower and upper limits correspond to a score of -2 and 2 and to the 3rd and 97th percentile, respectively.

* Age in years
Table 22  Reference, cardiac chamber size in the athlete

| First author, year | CMR technique | n, gender, sports intensity | Age range (years) |
|--------------------|---------------|-----------------------------|-------------------|
| Prakken, 2010 [50] | 1.5 T, short axis bSSFP, papillary muscles included in LV volume | 83, male, regular athletes (9–18 h/week) | 18–39 |
|                    |               | 46, male, elite athletes (> 18 h/week) | 18–39 |
|                    |               | 60, female, regular athletes (9–18 h/week) | 18–39 |
|                    |               | 66, female, elite athletes (> 18 h/week) | 18–39 |
|                    |               | 56, male, non-athletes | 18–39 |
|                    |               | 58, female, non-athletes | 18–39 |

n number of study subjects, bSSFP balanced steady-state free precession

Table 23  Left ventricular parameters for adult athletes (papillary muscles included in LV volume) according to reference [50]

| Parameter              | Non-athletes [mean ± SD (LL–UL)] | Regular athletesa [mean ± SD (LL–UL)] | Elite athletesb [mean ± SD (LL–UL)] |
|-----------------------|----------------------------------|---------------------------------------|-------------------------------------|
|                       | Men (n = 56)                     | Women (n = 58)                        | Men (n = 83)                        | Women (n = 60)                        | Men (n = 46)                     | Women (n = 33)                     |
| LVEDV (ml)            | 201 ± 33 (135–267)               | 156 ± 22 (112–200)                   | 250 ± 32 (186–314)                 | 194 ± 27 (140–248)                   | 261 ± 39 (183–339)               | 199 ± 31 (137–261)                |
| LVEDV/BSA (ml/m²)     | 101 ± 15 (71–131)                | 90 ± 11 (68–112)                     | 123 ± 13 (97–149)                  | 107 ± 14 (79–135)                   | 129 ± 17 (95–163)                | 107 ± 14 (79–135)                |
| LVESV (ml)            | 87 ± 19 (49–125)                 | 65 ± 13 (39–91)                      | 108 ± 20 (68–148)                  | 86 ± 15 (56–116)                    | 117 ± 24 (69–165)                | 85 ± 20 (45–125)                 |
| LVESV/BSA (ml/m²)     | 43 ± 10 (23–63)                  | 37 ± 7 (23–51)                       | 53 ± 9 (35–71)                     | 48 ± 8 (32–64)                      | 58 ± 11 (36–80)                  | 46 ± 11 (24–68)                  |
| LVM (g)               | 95 ± 20 (55–135)                 | 60 ± 11 (38–82)                      | 125 ± 22 (81–169)                  | 84 ± 17 (50–118)                    | 139 ± 28 (83–193)                | 92 ± 15 (62–122)                 |
| LVM/BSA (g/m²)        | 48 ± 9 (30–66)                   | 34 ± 6 (22–46)                       | 62 ± 11 (40–84)                    | 46 ± 9 (28–64)                      | 69 ± 13 (43–95)                  | 50 ± 8 (34–66)                   |
| LVEF (%)              | 57 ± 6 (45–69)                   | 58 ± 5 (48–68)                       | 57 ± 5 (47–67)                     | 55 ± 4 (47–63)                      | 55 ± 5 (45–65)                   | 58 ± 7 (44–72)                   |
| max. IVS (mm)         | 10 ± 1 (8–12)                    | 5 ± 1 (3–7)                          | 11 ± 1 (9–13)                      | 9 ± 1 (7–11)                        | 11 ± 1 (9–13)                    | 9 ± 1 (7–11)                     |

SD standard deviation, LL lower limit, UL upper limit, n number of study subjects, LV left ventricular, EDV end-diastolic volume, ESV end-systolic volume, EF ejection fraction, LVM left ventricular mass, max. IVS maximal thickness of the interventricular septum, BSA body surface area

a 9–18 h sports activity/week
b > 18 h sports activity/week
c Calculated as mean ± 2*SD

Table 24  Right ventricular parameters for adult athletes (papillary muscles included in right ventricular volume) according to reference [50]

| Parameter              | Non-athletes [mean ± SD (LL–UL)] | Regular athletesa [mean ± SD (LL–UL)] | Elite athletesb [mean ± SD (LL–UL)] |
|-----------------------|----------------------------------|---------------------------------------|-------------------------------------|
|                       | Men (n = 56)                     | Women (n = 58)                        | Men (n = 83)                        | Women (n = 60)                        | Men (n = 46)                     | Women (n = 33)                     |
| RVEDV (ml)            | 223 ± 40 (143–303)               | 166 ± 23 (120–212)                   | 277 ± 36 (205–349)                 | 209 ± 29 (151–267)                   | 291 ± 48 (195–387)               | 219 ± 35 (149–289)                |
| RVEDV/BSA (ml/m²)     | 111 ± 18 (75–147)                | 96 ± 12 (72–120)                     | 136 ± 16 (104–168)                 | 115 ± 15 (85–145)                   | 144 ± 20 (104–184)               | 118 ± 17 (84–152)                |
| RVESV (ml)            | 108 ± 24 (60–156)                | 75 ± 13 (49–101)                     | 135 ± 25 (85–185)                  | 102 ± 17 (68–136)                   | 148 ± 30 (88–208)                | 103 ± 24 (55–151)                |
| RVESV/BSA (ml/m²)     | 54 ± 12 (30–78)                  | 43 ± 7 (29–57)                       | 66 ± 12 (42–90)                    | 57 ± 9 (39–75)                      | 73 ± 13 (47–99)                  | 56 ± 13 (30–82)                  |
| RVM (g)               | 23 ± 5 (13–33)                   | 18 ± 4 (10–26)                       | 29 ± 6 (17–41)                     | 23 ± 4 (15–31)                      | 30 ± 6 (18–42)                   | 25 ± 5 (15–35)                   |
| RVM/BSA (g/m²)        | 12 ± 2 (8–16)                    | 10 ± 2 (6–14)                        | 14 ± 3 (8–20)                      | 13 ± 2 (9–17)                       | 15 ± 2 (11–19)                   | 14 ± 3 (8–20)                    |
| RVEF (%)              | 52 ± 5 (42–62)                   | 55 ± 5 (45–65)                       | 51 ± 4 (43–59)                     | 51 ± 4 (43–59)                      | 50 ± 4 (42–58)                   | 53 ± 7 (39–67)                   |

SD standard deviation, LL lower limit, UL upper limit, n number of study subjects, RV right ventricular, EDV end-diastolic volume, ESV end-systolic volume, EF ejection fraction, RVM right ventricular mass, BSA body surface area

a 9–18 h sports activity/week
b > 18 h sports activity/week
c Calculated as mean ± 2*SD
ranges. For the purposes of this review, that meta-analysis included multiple publications with overlapping/redundant study populations, small sample size (< 40 subjects in most studies) and did not take into account marked differences in analysis methods noted above. While useful to display overall trends in the literature for the athletes heart, the aforementioned meta-analysis was therefore not included in this study.

Normal thickness of the compact left ventricular myocardium in adults

CMR acquisition parameters
Normal values of the thickness of the compact LV myocardium have been shown to vary by type of pulse sequence (FGRE versus bSSFP) [53, 54]. For the purposes of this review, only bSSFP normal values are shown.

CMR analysis methods
In this review LV myocardial thickness refers to measurements of the thickness of the compact LV myocardium obtained at end-diastole (Fig. 7). Papillary muscles and trabeculations are excluded from measurement of the thickness of the compact LV myocardium.

Measures of LV myocardial thickness vary by the plane of acquisition (SAx versus long axis) [55]. Measurements obtained on long axis images at the basal and mid-cavity level have been shown to be significantly greater compared to measurements on corresponding SAx images, whereas measurements obtained at the apical level of long axis images are significantly lower compared to SAx images.

Demographic parameters
LV myocardial thickness is greater in men than women [14, 18, 25, 55, 56]. There are also small differences in LV myocardial thickness in relationship to ethnicity and body size, but these variations are not likely to have clinical significance [55]. Regarding age, one study of 120 healthy subjects age 20–80 years reported an increase in myocardial thickness with age—starting after the fourth decade [56]. In the study by Kawel el al. of 300 normal individuals without hypertension, smoking history or diabetes, there was no statistically significant difference in LV myocardial thickness with age [55].

Studies included in this review
There are five publications of a systematic analysis of LV myocardial thickness based on bSSFP imaging at 1.5 T with a sample size >40 healthy subjects per gender and a detailed description of the measurement technique (Table 25). Dawson et al. and Le Ven et al. published measurements for all 16 segments (apex excluded) obtained on short axis images (Table 26) [14, 56]. Kawel et al. published normal values of LV myocardial thickness for long and SAx imaging for 12 and 16 segments, respectively (Tables 26, 27) [55]. Yeon et al. and Aquaro et al. obtained measurements for only two myocardial segments on SAx images (Table 26) [18, 25].

Normal values of left ventricular trabeculation

CMR acquisition parameters
CMR methods used to assess LV trabeculation (Table 28) are based on the bSSFP technique to leverage on the blood-myocardial contrast it provides. The key methods are illustrated in Fig. 7.

CMR analysis methods
No uniformly accepted convention has been used for analyzing trabeculation. At least seven different measurement approaches have been described (Table 28). Principally these methods measure trabeculation in the LV either in terms of the trabeculated layer's thickness, mass, volume, or fractal complexity, with or without adjusting for the thickness, mass or volume of the adjacent compacted myocardium. Tables of normal values for trabeculation should specify the phase of the cardiac cycle in which measurements were taken together with imaging planes used. When reporting trabeculation mass, volume or fractal complexity, tables should specify whether papillary muscles were included or excluded in the trabecular assessment. Where

Table 25 References, normal thickness of the compact left ventricular myocardium in the adult

| First author, year | CMR technique | n, male:female | Age range (years) |
|-------------------|---------------|---------------|------------------|
| Dawson, 2011 [56] | 1.5 T, short axis bSSFP, 16 segments (apex excluded) | 60:60 | 20–80 |
| Kawel, 2012 [55]  | 1.5 T, short (16 segments, apex excluded) and long axis (12 segments) bSSFP | 131:169 | 54–91 |
| Le Ven, 2015 [14] | 1.5 T, short axis bSSFP, 16 segments (apex excluded) | 196:238 | 18–36 |
| Yeon, 2015 [25]   | 1.5 T, short axis bSSFP, 2 segments (basal inferolateral and anteroseptal) | 340:512 | (men: 61 ± 8; women: 62 ± 9) |
| Aquaro, 2017 [18] | 1.5 T, short axis bSSFP, 2 segments (basal anterior septum, basal inferolateral wall) | 173:135 | 15–80 |

n number of study subjects, bSSFP balanced steady-state free precession

* Age range not provided in original publication
semi-automated segmentation of trabecular contours is undertaken, the type of algorithm used may impact subsequent results so the methods must specify the algorithm in detail [57].

Table 29 provides normal adult values for thickness of the trabeculated LV myocardium, on a segment-by-segment basis. Table 30 provides normal values for mass and volume of trabeculation. Trabeculation mass ratio has additionally been reported [12, 58, 59] but measurement heterogeneity across studies, with respect to handling of the blood pool between trabeculations and inclusion/exclusion of papillary muscles, has led to differing definitions and no consensus normal values.

Tables 31 and 32 provide normal values for LV trabeculation measured as a fractal dimension. Four fractal parameters for quantifying LV trabeculation [59] include global LV, maximal basal, maximal mid and maximal apical fractal dimension. To derive the global LV fractal dimension, the fractal dimensions from each slice in the LV stack (Fig. 7d) were averaged; to derive local fractal characteristics, the maximal fractal dimension in the basal, mid and apical thirds of the left ventricle were recorded [59].

Normal values by this approach for global LV and maximal apical fractal dimension are presented in Table 31. Methodological developments for fractal analysis of the left ventricle are ongoing [60].

**Demographic parameters**

In the largest published reference cohort (n = 323) [61], there was no relationship between maximal non-compacted (NC)/compacted (C) wall thickness ratio and age, gender, race/ethnicity, height or weight.

For segment-by-segment (whole-heart) NC/C ratio [56], there was also no significant difference between genders, but age-related differences were present: the thickness of the trabeculated myocardium generally increased until the 3rd decade and subsequently decreased. This trend was significant in the anterior (1, 7, 13) and apical inferior segments, but not in the remainder of segments [56].

Using the fractal dimension, ethnicity was shown to influence LV trabeculation parameters, with greater endocardial complexity (i.e. higher fractal dimension) demonstrated in healthy blacks as opposed to healthy whites, and greater complexity demonstrated in Whites, African American and Hispanics compared to Chinese Americans [62].

**Studies included in this review**

For the purpose of this review, only cohorts of 40 or more normal subjects using bSSFP CMR technique have been included. Data from population-based studies where exclusions for comorbidities was undertaken have also been included [61, 62]. The majority of reported normal values were derived at 1.5 T although a few 3 T studies have also been undertaken (see Table 28). Inclusion criteria for reported tables included a full description of the subject cohort (including the analysis methods used), age and gender of subjects. One study evaluated elite male athletes which was not deemed to be representative of the average population and was therefore not included in this review [63].

The caliper-based linear measurement of thickness of trabeculation [61] has progressively evolved into more complex metrics: the maximal NC/C thickness ratio has been measured by at least four groups [58, 59, 61, 64] but reported normal values were too discordant for calculation of weighted means in this review (thus not shown in Table 29). The inter-study discordance of maximal NC/C parameters may stem from the subjective selection by readers of the visually most trabeculated segment/s for analysis (Fig. 7b). The largest of these studies, which also included reproducibility assessment, reported median values for normal adult maximal NC/C thickness of 2.2 [5th and 95th percentile: 1.0, 4.6] [61]. Other studies opted for a more systematic segment-by-segment analysis of thickness of trabeculation but still methodologies differed: Dawson et al. [56]. measured the maximal thickness of trabeculated myocardium per segment (Fig. 7a), whereas Tizon [65] measured the average of 20–30
Table 26  Normal left ventricular myocardial thickness (in mm) in the adult measured on short axis images for men and women

| Level   | Segment                      | Men | Women |
|---------|------------------------------|-----|-------|
|         | n   | Mean_p | SD_p | LL–UL | n  | Mean_p | SD_p | LL–UL |
| Basal   | 1^a | 387   | 7.8  | 1.3   | 5–10| 467  | 6.4  | 1.1   | 4–9 |
|         | 2^b | 900   | 9.0  | 1.4   | 6–12| 1114 | 7.6  | 1.2   | 5–10|
|         | 3^a | 387   | 8.8  | 1.2   | 6–11| 467  | 7.3  | 1.0   | 5–9 |
|         | 4^a | 387   | 7.9  | 1.2   | 6–10| 467  | 6.4  | 1.0   | 4–8 |
|         | 5^b | 900   | 7.7  | 1.2   | 5–10| 1114 | 6.3  | 1.1   | 4–9 |
|         | 6^c | 387   | 7.5  | 1.2   | 5–10| 467  | 6.1  | 1.0   | 4–8 |
| Mid-cavity | 7^d | 387   | 6.7  | 1.2   | 4–9 | 467  | 5.6  | 1.0   | 4–8 |
|         | 8^e | 387   | 7.4  | 1.3   | 5–10| 467  | 6.1  | 1.0   | 4–8 |
|         | 9^f | 387   | 7.9  | 1.2   | 6–10| 467  | 6.6  | 1.0   | 5–9 |
|         | 10^g| 387   | 7.0  | 1.2   | 5–9 | 467  | 5.8  | 1.0   | 4–8 |
|         | 11^h| 387   | 6.5  | 1.4   | 4–9 | 467  | 5.3  | 1.0   | 3–7 |
|         | 12^i| 387   | 6.6  | 1.2   | 4–9 | 467  | 5.5  | 1.1   | 4–8 |
| Apical  | 13^j| 387   | 6.5  | 1.2   | 4–9 | 467  | 5.9  | 1.3   | 3–9 |
|         | 14^k| 387   | 6.8  | 1.3   | 4–9 | 467  | 5.8  | 1.1   | 4–8 |
|         | 15^l| 387   | 6.1  | 1.1   | 4–8 | 467  | 5.2  | 1.0   | 3–7 |
|         | 16^m| 387   | 6.2  | 1.1   | 4–8 | 467  | 5.6  | 1.0   | 4–8 |

Segments: 1: basal anterior, 2: basal anteroseptal, 3: basal inferoseptal, 4: basal inferior, 5: basal inferolateral, 6: basal anterolateral, 7: mid anterior, 8: mid anteroseptal, 9: mid inferoseptal, 10: mid inferior, 11: mid inferolateral, 12: mid anterolateral, 13: apical anterior, 14: apical septal, 15: apical inferior, 16: apical lateral

n number of study subjects included in the weighted mean values, mean_p pooled weighted mean, SD_p pooled standard deviation, LL lower limits, UL upper limits

* Pooled weighted values from references [14, 55, 56]

* Pooled weighted values from references [14, 18, 25, 55, 56]

* Calculated as mean_p ± 2*SD_p.

Table 27  Normal left ventricular myocardial thickness (in mm) in the adult measured on long axis images for men and women according to reference [55]

| Level   | Region    | Men (n = 131) | Women (n = 169) |
|---------|-----------|---------------|-----------------|
|         | Mean   | SD     | LL–UL | Mean   | SD     | LL–UL |
| Basal   | Anterior | 8.2    | 1.3   | 6–11   | 7      | 1.1   | 5–9   |
|         | Inferior | 8.2    | 1.3   | 6–10   | 6.7    | 1.1   | 5–9   |
|         | Septal   | 9.1    | 1.3   | 7–12   | 7.3    | 1.1   | 5–10  |
|         | Lateral  | 7.6    | 1.3   | 5–10   | 6      | 1.1   | 4–8   |
|         | Mean     | 8.3    | 1.0   | 6–10   | 6.8    | 0.9   | 5–9   |
| Mid-cavity | Anterior | 6      | 1.3   | 3–9    | 4.9    | 1.1   | 3–7   |
|         | Inferior | 7.7    | 1.3   | 5–10   | 6.5    | 1.1   | 4–9   |
|         | Septal   | 8.3    | 1.3   | 6–11   | 6.8    | 1.1   | 5–9   |
|         | Lateral  | 6.6    | 1.3   | 4–9    | 5.3    | 1.1   | 3–8   |
|         | Mean     | 7.2    | 1.0   | 5–9    | 6      | 1     | 4–8   |
| Apical  | Anterior | 5.1    | 1.3   | 3–8    | 4.2    | 1.1   | 2–6   |
|         | Inferior | 5.8    | 1.3   | 3–8    | 5      | 1.1   | 3–7   |
|         | Septal   | 5.8    | 1.3   | 3–8    | 5      | 1.1   | 3–7   |
|         | Lateral  | 5.5    | 1.3   | 3–8    | 4.6    | 1.1   | 2–7   |
|         | Mean     | 5.6    | 1.0   | 4–8    | 4.7    | 0.9   | 3–7   |

n number of study subjects, SD standard deviation, LL lower limits, UL upper limits

* Calculated as mean ± 2*SD
measurements of the thickness of trabeculation per segment, with consequently different results.

### Cardiac valves and quantification of flow

#### CMR acquisition parameters

Prospectively and retrospectively electrocardiogram (ECG)-gated phase contrast (PC) CMR sequences are widely available. Prospectively-gated sequences use arrhythmia rejection and may be performed in a breath hold. Retrospectively gated techniques are mainly performed during free-breathing, often with higher spatial and temporal resolution compared to the breath hold techniques [67]. Four-dimensional flow-sensitive (4D Flow) PC CMR techniques have shown promising initial results, but 2D PC flow techniques remains the most commonly used approach in daily clinical practice [68]. In addition to PC-CMR, valve planimetry—using

| First author, year | CMR technique | n, male:female | Age range (years) |
|-------------------|---------------|----------------|------------------|
| Dawson, 2011 [56] | 1.5 T, short axis bSSFP, maximal thickness per segment at diastole and systole | 60:60 | 20–80 |
| **NC/C thickness ratio** (thickness of trabeculated [non-compacted] LV myocardium/ thickness of compact LV myocardium) | | | |
| Dawson, 2011 [56] | 1.5 T, short axis bSSFP, NC/C thickness ratio per segment measured manually at the “peak of the most prominent trabeculae in each segment” at diastole and systole | 60:60 | 20–80 |
| Kawel, 2012 [61] | 1.5 T, long axis bSSFP at diastole, maximal NC/C thickness ratio of 12 segments | 192:175 | 54–91 |
| Captur, 2013 [59] | 1.5 T, long axis bSSFP at diastole, maximal NC/C thickness ratio of 16 segments | 40 (total)* | 18–85 |
| Tizón-Marcos, 2014 [65] | 1.5 T, long- and short axis bSSFP, mean NC/C thickness ratio per segment measured semi-automatically by the centerline method (average of 20–30 chords/segment) at diastole and systole | 45:55 | 18–35 |
| Amzulescu, 2015 [58] | 1.5 T and 3 T, long axis bSSFP at diastole, maximal NC/C thickness ratio of 16 segments | 22:26 | (60 ± 10)** |
| André, 2015 [64] | 1.5 T, long axis bSSFP at diastole, maximal NC/C thickness ratio of 16 segments | 58:59 | 20–>50 |
| **Trabeculation mass** (mass of the trabeculated [non-compacted] LV myocardium) | | | |
| Bentatou, 2018 [12] | 1.5 T, short axis bSSFP at diastole, papillary muscles and blood between trabeculae excluded | 70:70 | 20–69 |
| **Trabeculation volume** (volume of the trabeculated [non-compacted] LV myocardium) | | | |
| André, 2015 [64] | 1.5 T, short axis bSSFP, blood between trabeculae included, papillary muscles excluded | 58:59 | 20–>50 |
| **NC/C mass ratio** (mass of trabeculated [non-compacted] LV myocardium/ mass of compact LV myocardium) | | | |
| Amzulescu, 2015 [58] | 1.5 T and 3 T, short axis bSSFP at diastole, mass of trabeculated myocardium includes trabeculae and blood between trabeculae, papillary muscles excluded from trabeculated and compact mass | 22:26 | (60 ± 10)** |
| Bentatou, 2018 [12] | 1.5 T, short axis bSSFP at diastole, blood between trabeculae excluded from mass of trabeculated myocardium, papillary muscles included in mass of compact myocardium | 70:70 | 20–69 |
| **NC/TM (mass of trabeculated [non-compacted] LV myocardium/ total LV myocardial mass [trabeculated + compact LV myocardial mass])** | | | |
| Captur, 2013 [59] | 1.5 T, short axis bSSFP at diastole, mass of trabeculated myocardium includes trabeculae and blood between trabeculae, papillary muscles included in mass of compact myocardium | 40 (total)* | 18–85 |
| **Fractal dimension** (fractal complexity of LV trabeculated [non-compacted] myocardium) | | | |
| Captur, 2013 [59] | 1.5 T, short axis bSSFP at diastole, papillary muscles included in the endocardial complexity | 51:54 (75 white, 30 black) | 18–85 |
| Captur 2015 [62] | 1.5 T, short axis bSSFP at diastole, papillary muscles included in the endocardial complexity | 279:325 | 46–91 |
| Cai, 2017 [66] | 3 T, short axis bSSFP at diastole, papillary muscles included in the endocardial complexity | 91:89 | 20–69 |

**n** number of study subjects, **LV** left ventricular, **bSSFP** balanced steady-state free precession

* Male:female ratio not provided in original publication

** Age range not provided in original publication
ECG-gated bSSFP CMR—can also be used to estimate stenosis or insufficiencies with good correlation to echocardiographic measurements [69]. Measurements of flow are most precise when (a) the imaging plane is positioned perpendicular to the vessel of interest and (b) the velocity encoded gradient echo (Venc) is encoded in a through plane direction [70]. The slice thickness should be ≤ 7 mm to minimize partial volume effects. Compared to aortic or pulmonary artery flow evaluation, quantification of mitral or tricuspid valves is more challenging using PC-CMR due to through plane motion during the cardiac cycle [71].

The flow encoding velocity (V_{enc}) should be chosen close to the maximum expected flow velocity of the examined vessel for precise measurements. Setting the V_{enc} below the peak velocity results in aliasing. For the normal aorta and main pulmonary artery, maximum velocities usually do not exceed 150 and 90 cm/s, respectively.

 Adequate temporal resolution is necessary to avoid temporal flow averaging, especially for the evaluation of short, fast, and turbulent jets within a vessel (e.g. aortic stenosis). For clinical routine, 25–30 ms temporal resolution is sufficient. The minimum required spatial resolution is less than one third of the vessel diameter to avoid partial volume effects with the adjacent vessel wall and surrounding stationary tissues for small arteries [70].

**CMR analysis methods**

For data analysis, dedicated flow software should be used. Most of the currently available flow software tools offer semi-automatic vessel contouring, which needs to be carefully checked by the examiner.

The modified Bernoulli equation (\Delta P = 4 \times V_{max}^2) is commonly used for calculation of pressure gradients using PC-CMR across the pulmonary or aortic valve [72, 73].

Velocity measurements of valvular stenosis with high jet velocities may be inaccurate due to (A) partial volume effects in case of a small jet width and (B) limited temporal resolution compared to the high velocity of the jet. Measurements are further affected by signal loss due to the high velocity that may lead to phase shift errors and dephasing. Misalignment of the slice relative to the direction of the jet may also lead to an underestimation of the peak velocity [74].

Mitral valve flow velocities and deceleration times can be quantified for assessment of LV diastolic function, in a manner analogous to that used with transthoracic echocardiography (TTE). 2D PC derived trans-mitral flow velocities and deceleration times are strongly correlated with transmitral flow velocities measured by TTE [75].

### Table 29

Normal thickness of the trabeculated (non-compacted) left ventricular myocardium on short axis at end-diastole (in mm) in the adult according to [56]

| Level   | Segment | Mean (median) | SD (IQR) |
|---------|---------|---------------|----------|
| Basal   | 1       | 3.0           | 0.46     |
|         | 2       | 0             |          |
|         | 3       | 0             |          |
|         | 4       | 0             |          |
|         | 5       | 0             | 0.39     |
|         | 6       | 0             | 0.41     |
| Mid-cavity | 7     | 5.6           | 2.8      |
|         | 8       | 0             |          |
|         | 9       | 0             |          |
|         | 10      | 0             | 0.21     |
|         | 11      | 4.2           | 2.5      |
|         | 12      | 4.4           | 2.7      |
| Apical  | 13      | 5.6           | 2.7      |
|         | 14      | 0             |          |
|         | 15      | 0             | 0.45     |
|         | 16      | 7.1           | 2.4      |

According to the original publication (n = 120), data are presented as mean ± SD for normally distributed variables and as median (first, third interquartile ranges) for nonparametric variables; Segments: 1 = basal anterior, 2 = basal anteroseptal, 3 = basal inferoseptal, 4 = basal inferior, 5 = basal inferolateral, 6 = basal anterolateral, 7 = mid anterior, 8 = mid anteroseptal, 9 = mid inferoseptal, 10 = mid inferior, 11 = mid inferolateral, 12 = mid anterolateral, 13 = apical anterior, 14 = apical septal, 15 = apical inferior, 16 = apical lateral.

### Table 30

Normal values for mass and volume of trabeculated (non-compacted) left ventricular myocardium in the adult measured on short axis images

| Parameter | Technique | Men |
|-----------|-----------|-----|
|           |           | n   | Mean | SD |
| Trabeculation mass (mass of the trabeculated [non-compacted] LV myocardium) per BSA (g/m²) from ref [12] | Papillary muscles and blood between trabeculae excluded | 70 | 5.4 | 2.3 |
| Trabeculation volume (volume of the trabeculated [non-compacted] LV myocardium) per BSA (ml/m²) from ref [64] | Blood between trabeculae included, papillary muscles excluded | 58 | 43.1 | 8.7 |

| Women |
|-------|
| n     | Mean | SD |
| 70 | 4.0 | 2.3 |
| 59 | 36.1 | 5.2 |

n number of study subjects, SD standard deviation, BSA body surface area
Table 31 Normal values for the fractal dimension (FD) (unitless) of left ventricular trabeculation in the adult for different ethnicities

| Parameter               | Ethnicity          | n  | Mean  | SD   |
|-------------------------|--------------------|----|-------|------|
| Global FD from ref [59] | Black              | 30 | 1.246 | 0.005|
| Maximal apical FD<sup>a</sup> from ref [59] | Black              | 30 | 1.235 | 0.03 |
| Global FD from ref [59] | White              | 75 | 1.228 | 0.002|
| Maximal apical FD<sup>a</sup> from ref [59] | White              | 75 | 1.253 | 0.025|
| Global FD from ref [66] | Singaporean Chinese | 180 | 1.205 | 0.031|
| Maximal apical FD<sup>a</sup> from ref [66] | Singaporean Chinese | 180 | 0.278 | 0.045|

<sup>n</sup> number of study subjects, <sup>SD</sup> standard deviation
<sup>a</sup> Measured for the apical third of the left ventricle
<sup>b</sup> Measured for the apical half of the left ventricle

with TTE derived parameters, but with a systematic underestimation [75].

Demographic parameters
To our knowledge, no comprehensive studies have been performed to investigate the association between age, gender and ethnicity and valvular flow or valve planimetry in normal healthy subjects based on PC-CMR. Two recent studies using 4D Flow CMR investigated the relationship of aortic flow velocity with age and gender, respectively [76, 77]. Callaghan et al. [76] compared measurements of mean peak systolic velocity obtained in the ascending aorta between 3 age groups and found a significant decrease with age. Garcia et al. [77] showed the mean aortic valve peak velocity was higher with greater age. In the study by Garcia et al. the differences in peak systolic velocity with gender were small and likely not clinically relevant [77].

Studies included in this review
There is good agreement between PC-CMR, bSSFP CMR planimetry, and echocardiography measurements. American Heart Association (AHA) criteria for grading valve stenosis or insufficiency is suggested [78, 79] (Table 33).

To our knowledge, there is no publication from a large study of normal reference values of trans-valvular flow and valve planimetry based on PC-CMR measurements.

Mitrail valve flow parameters for determination of diastolic LV function are shown in Table 34.

Garcia, et al. [77] and Callaghan, et al. [76] have reported normal thoracic aorta flow parameters using 4D Flow CMR. Amongst other parameters, Garcia obtained measurements of peak systolic velocity where the transvalvular velocity reaches its maximum during peak systole (vena contracta region) (Fig. 8a) while Callaghan acquired measurement 6 cm proximal from the most cranial point of the aortic arch centerline in the ascending aorta (Fig. 8b). Normal values of peak aortic velocity are given in Tables 35 and 36.

Normal aortic dimensions in the adult
CMR acquisition parameters
Three-dimensional contrast enhanced CMR angiography (CMRA) has gained broad acceptance and is widely used for the assessment and follow-up of thoracic aortic diameters in the clinical setting. The multi-planar reformation of CMRA images leads to an accurate measurement perpendicular to the lumen of the vessel. However, motion caused by pulsation leads to substantial blurring of the vessel contour at the level of the aortic root, hampering accurate diameter measurements [81]. The need of a contrast injection is another limitation for the use of this technique, particularly in patients who need multiple follow up examinations and in population based study settings [82]. Alternatively non-contrast techniques such as an ECG- and respiratory-gated gadolinium-enhanced CMRA or 3D bSSFP sequence can be applied, enabling accurate measurements of aortic diameters including the aortic root [82]. However, due to the long acquisition times or lack of sequence availability, these methods may not be widely applied [81]. The magnitude image of PC CMR has also been used to measure diameters of the aorta [83]. Black blood techniques are used for a more detailed assessment of the aortic wall [84].

In 2D acquisitions, the imaging plane needs to be acquired correctly at the time of the scan; thus, any alterations in the

Table 32 Normal values for the fractal dimension (FD) (unitless) of left ventricular trabeculation in the adult stratified by sex and body mass index (BMI) according to reference [62]

| Parameter | BMI ≥ 30 kg/m² (mean ± SD) | BMI ≥ 25 to < 30 kg/m² (mean ± SD) | BMI < 25 kg/m² (mean ± SD) |
|-----------|-----------------------------|-----------------------------------|-----------------------------|
|           | All (n = 163) | Men (n = 71) | Women (n = 92) | All (n = 206) | Men (n = 108) | Women (n = 98) | All (n = 235) | Men (n = 100) | Women (n = 135) |
| Max. apical FD<sup>a</sup> | 1.203 ± 0.06 | 1.212 ± 0.07 | 1.196 ± 0.06 | 1.194 ± 0.06 | 1.197 ± 0.05 | 1.190 ± 0.07 | 1.169 ± 0.07 | 1.177 ± 0.06 | 1.162 ± 0.05 |

<sup>n</sup> number of study subjects, <sup>SD</sup> standard deviation, <sup>Max. maximal</sup>
<sup>a</sup> Measured for the apical half of the left ventricle
imaging plane due to breath-holding or patient motion will result in variability of measurements. Through plane motion during the cardiac cycle can be minimized with ECG gating.

Potthast and colleagues compared the diameter of the ascending aorta obtained by different CMR sequences to ECG-triggered computed tomography angiography (CTA) as the standard of reference. They reported that ECG-gated navigator triggered 3D bSSFP sequence showed the best agreement with CTA.

**CMR analysis methods**

Beside the sequence type, imaging plane and cardiac phase (systole versus diastole), it is important to identify the anatomic locations of diameter measurements of the thoracic aorta (Fig. 9).

The sagittal oblique view of the LV outflow tract was used for measuring diameter at the level of the aortic annulus, the aortic sinus, and the sinotubular junction (Fig. 10) [11, 85, 86]. Axial cross sectional images at predefined anatomic levels were used for measuring the ascending and descending aorta as well as cusps commissure and cusp-cusp diameters at the level of the aortic sinus [85] (Fig. 11).

Luminal or outer to outer diameter of the aorta may be measured. The current SCMR guidelines on image post-processing recommend measurement of the outer contour in dilation while measurements of the inner

| **Table 33** Stages of valvular heart disease in the adult. adapted from echocardiography according to references [78, 79] |
|---|---|---|
| Valve disease | Parameter | Stage |
| | | Progressive | Severe |
| Aortic stenosis | Maximum velocity (m/s) | Mild: 2.0–2.9 | Severe: ≥ 4 |
| | | Moderate: 3.0–3.9 | Very severe: ≥ 5 |
| | Orifice area (cm²) | ≤ 1.0 | Low-flow/low-gradient: < 4 m/s (at rest) |
| | Orifice area /BSA (cm²/m²) | ≤ 0.6 |
| Aortic regurgitation | Regurgitant volume (ml/beat) | Mild: < 30 | ≥ 60 |
| | | Moderate: 30–59 |
| | Regurgitant fraction (%) | Mild: < 30 | ≥ 50 |
| | | Moderate: 30–49 |
| | Effective regurgitant orifice (cm²) | Mild: < 0.10 | ≥ 0.30 |
| | | Moderate: 0.10–0.29 |
| Mitral stenosis | Transmitral flow velocity (m/s) | Increased |
| | Orifice area (cm²) | > 1.5 | Severe: ≤ 1.5 |
| | | Very severe: ≤ 1.0 |
| Primary mitral regurgitation | Regurgitant volume (ml/beat) | < 60 | ≥ 60 |
| | | ≥ 60 |
| | Regurgitant fraction (%) | < 50 | ≥ 50 |
| | Effective regurgitant orifice (cm²) | < 0.40 | ≥ 0.40 |
| Secondary mitral regurgitation | Regurgitant volume (ml/beat) | < 60 | ≥ 60 |
| | | ≥ 60 |
| | Regurgitant fraction (%) | < 50 | ≥ 50 |
| | Effective regurgitant orifice (cm²) | < 0.40 | ≥ 0.40 |
| Pulmonic stenosis | Peak velocity (m/s) | > 4 |
| Tricuspid stenosis | Orifice area (cm²) | < 1.0 |

**BSA** body surface area

| **Table 34** Mitral valve flow for determination of diastolic left ventricular function according to reference [80] |
|---|---|---|---|---|
| Parameter | Normal | Type 1 (Impaired relaxation) | Type 2 (Pseudonormal) | Type 3 (Restrictive, partially reversible) | Type 3 (Restrictive, fixed) |
| MDT (ms) | 150–220 | Increased | Normal | Decreased | Decreased |
| E/A ratio | 1–2 | < 1 | 1–2 | > 2 | > 2 |

**MDT** mitral deceleration time, **E/A ratio** ratio of the mitral early (E) and atrial (A) components of the mitral inflow velocity profile
contour should be obtained in the setting of stenosis [9]. In the tables below, the method is specified.

Demographic parameters
In the MESA, a large population based study, the diameter of the ascending aorta has been shown to be larger in men compared to women even after adjustment for BSA [83]. In a publication by Le et al., however, the gender difference in diameters did not persist after normalization to BSA [11].

Several studies have shown an increase in aortic diameter with age [11, 83, 85, 86]. The association of age with aortic diameter was more marked in the ascending aorta compared to the descending thoracic and abdominal aorta, respectively [87, 88]. Further, age-related changes of the geometry of the thoracic aorta have been described. Age-related changes include increasing length of the ascending aorta and decreasing curvature of the aortic arch [89, 90].

In the MESA study, there were small differences in normal aortic diameter for Chinese and African American participants compared to Caucasians. These differences were small however relative to measurement error and reproducibility and therefore may not be clinically relevant [83].

Studies included in this review
Studies with normal values of aortic diameters based on measurements obtained in studies with 40 or more healthy subjects per gender have been included in this review (Table 37). There are five major publications regarding CMR-based measurements of the thoracic aorta in adults [11, 83–86]. There is substantial difference between the studies with respect to CMR sequences (cine bSSFP, PC CMRA and 3D-T1-black blood volume isotropic turbo spin echo acquisition), acquisition/measurement plane (cross sectional versus LV outflow tract view), measurement technique (luminal versus total diameter and area, respectively) and measurement sites of the aorta. Therefore, results of most studies are presented separately (Tables 38, 39, 40, 41). Details of image

### Table 35 Normal mean peak systolic velocity of the ascending aorta by 4D-flow for different age groups according to reference [76]

| Parameter | 18–33 years | 34–60 years | > 60 years |
|-----------|-------------|-------------|-----------|
| n         | Mean        | SD          | LL–UL     | n         | Mean        | SD          | LL–UL     | n         | Mean        | SD          | LL–UL     |
| Velocity (cm/s) | 64 66 15 | 36–96 | 64 51 13 | 25–77 | 67 35 12 | 11–59 |

* Calculated as mean ± 2*SD

### Table 36 Normal mean aortic valve peak velocity by 4D-flow CMR for men and women according to reference [77]

| Parameter | Men | Women |
|-----------|-----|-------|
| n         | Mean  | SD    | LL–UL  | n         | Mean  | SD    | LL–UL  |
| Velocity (m/s) | 57 1.3 0.3 | 0.8–1.8 | 41 1.2 0.2 | 0.8–1.6 |

* Calculated as mean ± 2*SD

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**Fig. 8** Images of a 4D flow sequence illustrating sites of measurement of peak systolic velocity. According to reference [77] measurements were obtained where the transvalvular velocity reaches its maximum during peak systole (vena contracta region) (a). In reference [76] peak systolic velocity was obtained in the ascending aorta 6 cm proximal from the most cranial point of the aortic arch centerline (b).
Weighted means were calculated based on the values of the diameter of the aortic root obtained on the 3D bSSFP sequence in LVOT view published by Burman, Davis and Le (Table 42) [11, 85, 86].

**Normal aortic dimensions in children**

**CMR acquisition parameters**

There is currently no consensus regarding the optimal CMR sequence to measure aortic diameters and areas in children. In three major publications documenting aortic dimensions in children (Table 43), measurements were obtained with three-dimensional contrast enhanced CMRA [91], gradient echo images [92] and phase contrast cine images [93].

**CMR analysis methods**

To minimize errors in measurement of aorta size, multiplanar reformation should be used to make double-oblique measurements perpendicular to the centerline of the course of the vessel. Kaiser et al. demonstrated that aortic diameter measurements vary slightly based on plane orientation, with a mean difference between measurements on cross-sectional and longitudinal images of 0.16 mm and a coefficient of variability of 2.1% [91].

Aorta measurements should also be made in a consistent manner with respect to the wall of the aorta—outer wall to outer wall, leading edge to leading edge, or luminal diameter. Kutty et al. indicated that in their study measurements were made from outer wall to outer wall.
Kawel-Boehm et al. J Cardiovasc Magn Reson (2020) 22:87

Table 37 References, normal aortic diameters, area and wall thickness in adults

| First author, year | CMR technique | n, male:female | Age range (years) |
|--------------------|---------------|----------------|------------------|
| Burman, 2008 [85]  | 1.5 T, cine bSSFP, luminal diameter at systole and diastole, average of 3 cusp-commissure and 3 cusp-cusp diameters, respectively on cross-sectional images of the aortic sinus and diameter of the aortic sinus on the sagittal LVOT plane | 60:60 | 20–80 |
| Davis, 2014 [86]   | 1.5 T, cine bSSFP, maximal luminal diameter at diastole, diameters calculated based on measurements of the area at 3 levels (ascending aorta, proximal and distal descending aorta) of the aorta on cross-sectional images and diameters at 3 levels (annulus, sinus, sinotubular junction) of the aortic root measured on the sagittal LVOT plane | 208:239 | 19–70 |
| Turkbey, 2014 [83] | 1.5 T, luminal diameter of the ascending aorta measured on the magnitude image of a phase contrast sequence | 770:842 | 45–84 |
| Eikendal, 2016 [84] | 3 T, fat suppressed 3D-T1-black blood VISTA acquired sagittal of the descending aorta, luminal and total vessel diameter and area, calculated average diameter, luminal and total vessel area, vessel wall area and thickness of the proximal to distal descending aorta after manual tracing of the luminal and outer aortic wall on axial reformatted images | 59:65 | 25–35 |
| Le, 2016 [11]      | 3 T, cine bSSFP, luminal diameter of the aortic annulus, sinus and sinotubular junction at diastole measured on the sagittal LVOT plane | 91:89 | 20–69 |

Table 38 Absolute and indexed (to BSA) normal values of aortic sinus luminal diameters and area for men and women at systole and diastole according to [85]

| Parameter                                      | Men (n = 60) [mean ± SD (LL–UL)] | Women (n = 60) [mean ± SD (LL–UL)] |
|------------------------------------------------|----------------------------------|-------------------------------------|
|                                                | Systolic                         | Diastolic                           | Systolic                           | Diastolic                           |
| Aortic sinus diameter (cusp-commissure) (mm)   | 34 ± 3 (27–40)                   | 32 ± 4 (25–39)                      | 30 ± 3 (25–35)                     | 26 ± 3 (23–34)                      |
| Aortic sinus diameter (cusp-commissure)/BSA (mm/m²) | 17 ± 2 (14–20)                  | 16 ± 2 (13–20)                     | 18 ± 2 (14–21)                    | 17 ± 2 (13–20)                     |
| Aortic sinus diameter (cusp-cusp) (mm)        | 36 ± 4 (28–44)                   | 35 ± 4 (27–43)                     | 32 ± 3 (26–38)                    | 31 ± 3 (24–37)                     |
| Aortic sinus diameter (cusp-cusp)/BSA (mm/m²) | 18 ± 2 (14–22)                  | 18 ± 2 (14–22)                    | 19 ± 2 (15–23)                    | 18 ± 2 (14–22)                     |
| Aortic sinus area (cm²)                       | 9.2 ± 2.1 (5.0–13.4)            | 8.4 ± 2.0 (4.4–12.4)              | 7.1 ± 1.4 (4.3–9.9)              | 6.5 ± 1.3 (3.9–9.1)              |
| Aortic sinus area/BSA (cm²/m²)                | 4.6 ± 1.0 (2.6–6.6)             | 4.2 ± 0.9 (2.4–6.0)               | 4.2 ± 0.8 (2.6–5.8)             | 3.8 ± 0.8 (2.2–5.4)             |

Values obtained as the average of 3 cusp-commissure and 3 cusp-cusp diameters, respectively measured on cross-sectional bSSFP images of the aortic sinus (Fig. 11)

* Calculated as mean ± 2*SD

Table 39 Normal values of the thoracic aortic luminal diameters for men and women measured at diastole on bSSFP images according to [86]

| Level                            | Men (n = 208) [mean ± SD (LL–UL)] | Women (n = 239) [mean ± SD (LL–UL)] |
|----------------------------------|-----------------------------------|--------------------------------------|
| Ascending aorta diameter (mm)    | 27 ± 4 (19–34)                    | 26 ± 4 (18–33)                      |
| Proximal descending aorta diameter (mm) | 21 ± 3 (15–26)                   | 19 ± 2 (15–23)                     |
| Distal descending aorta diameter (mm) | 18 ± 3 (13–23)                   | 16 ± 2 (12–20)                     |

Measurements obtained on cross-sectional bSSFP images of the aorta

bSSFP balanced steady-state free precession, n number of study subjects, SD standard deviation, LL lower limit, UL upper limit

* Calculated as mean ± 2*SD

[93]. Kaiser et al. and Voges et al. did not provide details on how measurements were made in this regard [91, 92].

Studies included in this review

Reference ranges for parameters measured in children are frequently presented in z-scores and reference curves using the LMS method as described under the LV/RV parameter section in children above.

There are three publications of systematic evaluation of aortic dimensions (diameter and/or area) in children

Demographic parameters

Aortic diameters vary by BSA [91, 93] but do not show sex differences in children [92, 93]. Aortic area has not been shown to be dependent upon sex differences either [92].
that vary by CMR-technique, measurement technique and data presentation (Table 43).

In this review we present (a) LMS parameters to calculate z-scores for aortic cross-section area based on reference [92] (Tables 44, 45) (b) regression equations of normal aortic diameters measured at 9 different sites based on [91] (Table 46) and (c) normal areas of the ascending aorta from [93] (Table 47).

Due to the differences in acquisition sequences, measurement techniques, and presentation of results, weighted mean values are not presented.

**Normal aortic distensibility and pulse wave velocity (PWV) in adults**

**CMR acquisition parameters**

Pulse wave velocity (PWV) calculations using a velocity-encoded CMR with phase contrast sequences allow accurate assessment of aortic systolic flow wave and the blood flow velocity. The sequence should be acquired at the level of the bifurcation of the pulmonary trunk, perpendicular to both, the ascending and descending aorta. The distance between two aortic locations (aortic length) can be estimated from axial and coronal cine breath hold bSSFP sequences covering the whole aortic arch [94]. Alternatively, sagittal oblique views of the aortic arch can be acquired e.g. using a black blood spin echo sequence [88].

Another parameter of aortic stiffness is aortic distensibility. The cross sectional aortic area at different phases of the cardiac cycle is measured using ECG-gated bSSFP cine imaging to assess aortic distensibility by CMR. Modulus images of cine phase contrast CMR can be used as well [95].

**CMR analysis methods**

PWV is the most validated method to quantify arterial stiffness using CMR. PWV is calculated by measuring the pulse transit time of the flow curves (Δt) and the distance (D) between the ascending and descending aortic locations of the phase contrast acquisition [88]: Aortic PWV = D/Δt (Fig. 12).

PWV increases with stiffening of arteries since the stiffened artery conducts the pulse wave faster compared to more distensible arteries.

Aortic distensibility is calculated with the following formula after measuring the minimum and maximum aortic cross sectional area [96]:

\[
\text{Aortic distensibility} = \frac{(\text{minimal area} - \text{maximal area})}{(\text{minimal area} \times \Delta P \times 1000)}
\]

where ΔP is the pulse pressure in mmHg.

**Demographic parameters**

Greater ascending aorta diameter and changes in aortic arch geometry with greater age was associated with increased regional stiffness of the aorta, especially of the ascending portion. The relationship of

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**Table 40** Absolute and BSA indexed normal values of ascending aortic luminal diameter for men and women of different age categories measured on phase contrast images according to [83]

| Age (years) | Men (n = 770) | Women (n = 842) |
|-------------|--------------|-----------------|
|             | Median (5th–95th percentile) | Median (5th–95th percentile) |
| Absolute values (mm) | | |
| 45–54 | 32 (27–37) | 29 (25–34) |
| 55–64 | 33 (28–41) | 30 (26–36) |
| 65–74 | 34 (29–41) | 31 (26–36) |
| 75–84 | 35 (29–41) | 31 (27–37) |
| Values indexed to BSA (mm/m²) | | |
| 45–54 | 16 (13–20) | 17 (14–21) |
| 55–64 | 17 (14–21) | 18 (15–22) |
| 65–74 | 18 (14–22) | 18 (15–22) |
| 75–84 | 19 (15–23) | 20 (15–28) |

*n number of study subjects, BSA body surface area

**Table 41** Normal values of descending thoracic aortic diameter, area and wall thickness for young men and women (25–35 years) according to [84]

| Parameter | Men (n = 59) | Women (n = 65) |
|-----------|--------------|----------------|
|            | Median (10th–90th percentile) | Median (10th–90th percentile) |
| Luminal diameter descending aorta (mm) | 19 (17–21) | 17 (16–19) |
| Total diameter descending aorta (mm) | 22 (20–24) | 20 (19–22) |
| Luminal area descending aorta (cm²) | 2.9 (2.2–3.5) | 2.3 (2.0–2.8) |
| Total area descending aorta (cm²) | 3.9 (3.1–4.6) | 3.3 (2.8–3.9) |
| Wall area descending aorta (cm²) | 1.0 (0.8–1.2) | 1.0 (0.8–1.1) |
| Wall thickness descending aorta (mm) | 1.5 (1.4–1.8) | 1.5 (1.4–1.9) |

Measurements obtained on axial reformatted images of a fat suppressed 3-dimensional T1-black blood VISTA (volume isotropic turbo spin echo acquisition) sequence. Calculated average vessel diameter and area as well as wall thickness and wall area of the descending aorta.

*n number of study subjects
age with measures of aortic stiffness is non-linear and the decrease of aortic distensibility occurs particularly before the fifth decade of life [88]. Males have stiffer aortas compared to females [97].

Studies included in this review
Two studies with a total sample size of more than 40 subjects reported reference ranges for PWV and/or distensibility in healthy subjects (Table 48): Kim et al. present reference ranges for PWV and distensibility for a cohort of 124 healthy Asian subjects [98]. Since both parameters have been shown to be highly age dependent, reference ranges are given per age decile according to the original publication [98]. However, sample size per decile was small (between 21 and 28 subjects) and standard deviations are relatively large (Tables 49, 50). In the study by Eikendal et al. reference values for PWV in young (25–35 years) healthy subjects are given (Table 51) [84].

With respect to PWV, in this review we present reference ranges for the distance between the ascending and the proximal descending thoracic aorta. This range is frequently measured since measurements at both locations can be obtained simultaneously on a single 2D acquisition at the level of the bifurcation of the pulmonary artery. PWV for other distances (ascending to distal descending aorta and total PWV) can be found in the original publications [84, 98]. In addition to the ascending and proximal descending thoracic aorta, distensibility for the distal descending and the total aorta is presented in the original publication by Kim et al. [98].

Normal aortic distensibility and pulse wave velocity (PWV) in children
CMR acquisition parameters
In the only publication of aortic distensibility and PWV by CMR in children, distensibility was obtained on gradient echo cine images and pulse wave velocity was measured on phase-contrast cine CMR [92].

Table 42 Normal diameters of the aortic root for men and women measured on sagittal left ventricular outflow tract bSSFP

| Parameter                                        | Men                      | Women                     |
|--------------------------------------------------|--------------------------|---------------------------|
|                                                  | n | Meanp | SDp | LL–ULE | n | Meanp | SDp | LL–ULE |
| Aortic annulus diameter (mm)a                    | 299 | 23     | 5   | 14–33   | 328 | 20     | 3   | 14–27   |
| Aortic annulus diameter/BSA (mm/m²)b             | 91  | 12     | 1   | 10–14   | 89  | 12     | 1   | 10–14   |
| Aortic sinus diameter (mm)c                      | 359 | 32     | 6   | 19–45   | 388 | 28     | 5   | 17–38   |
| Aortic sinus diameter/BSA (ml/m²)d               | 151 | 17     | 2   | 13–21   | 149 | 17     | 2   | 13–21   |
| Sinotubular junction diameter (mm)a              | 299 | 25     | 6   | 12–38   | 328 | 21     | 5   | 12–31   |
| Sinotubular junction diameter/BSA (ml/m²)d       | 91  | 13     | 2   | 10–17   | 89  | 14     | 2   | 10–17   |

Measurements obtained as shown in Fig. 10.

n number of study subjects included in the weighted mean values, bSSFP balanced steady-state free precession, meanp pooled weighted mean, SDp pooled standard deviation, LL lower limit, UL upper limit, BSA body surface area

a Pooled weighted values from references [11, 86]
b Values from reference [11]
c Pooled weighted values from references [11, 85, 86]
d Pooled weighted values from references [11, 85]
e Calculated as meanp ± 2*SDp

Table 43 References, normal aortic dimensions in children

| First author, year | CMR technique                                                                 | n, male:female | Age range (years) |
|--------------------|--------------------------------------------------------------------------------|----------------|------------------|
| Kaiser, 2008 [91]  | 1.5 T; contrast enhanced CMRA; shortest diameter measured on cross-sectional reformatted images at 9 locations | 30:23          | 2–20             |
| Kutty, 2012 [93]   | 1.5 T; magnitude image of a through-plane free-breathing phase contrast sequence; cross-sectional area calculated based on measurement of the maximal external aortic diameter perpendicular to the vessel and perpendicular to the maximal diameter in systole 1 to 2 cm distal to the sinotubular junction | 55:50          | 4–20             |
| Voges, 2012 [92]   | 3 T; cross sectional cine gradient echo images acquired at 4 positions perpendicular to the aortic axis, measurements obtained at maximal distension of the aorta | 30:41          | 2–28             |

n number of study subject
Distensibility was calculated as \( \frac{A_{\text{max}} - A_{\text{min}}}{A_{\text{min}}} \times \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}}} \), where \( A_{\text{max}} \) and \( A_{\text{min}} \) represent the maximal and minimal cross-sectional area of the aorta, and \( P_{\text{max}} \) and \( P_{\text{min}} \) represent the systolic and diastolic blood pressure measured with a sphygmomanometer cuff around the right arm.

PWV was calculated as \( \Delta x / \Delta t \), where \( \Delta x \) is defined as the length of the centerline between the sites of flow measurement in the ascending and descending aorta and \( \Delta t \) represents the time delay between the flow curve obtained in the descending aorta relative to the flow curve obtained in the ascending aorta (Fig. 12).

Demographic parameters
Aortic distensibility and PWV did not vary by gender. Aortic distensibility decreases with age and correlates with height, body weight and BSA. PWV has been shown to increase with age [92].

### Table 44: LMS parameters to calculate z-scores for aortic cross-sectional area relative to age for boys according to reference [92]

| Age  | Ascending aorta | Aortic arch | Aortic isthmus | Descending aorta<sup>a</sup> |
|------|-----------------|-------------|---------------|-----------------------------|
|      | L               | M           | S             | L                           | M     | S     |
| < 1  | 0.3091          | 91.5360     | 0.1207        | 0.8668                      | 80.1737 | 0.1898 |
| 1    | 0.3091          | 120.6960    | 0.1274        | 0.8668                      | 101.7001 | 0.1897 |
| 2    | 0.3091          | 149.8560    | 0.1341        | 0.8668                      | 123.2265 | 0.1895 |
| 3    | 0.3091          | 179.0160    | 0.1408        | 0.8668                      | 144.7529 | 0.1894 |
| 4    | 0.3091          | 208.1812    | 0.1475        | 0.8668                      | 166.2671 | 0.1893 |
| 5    | 0.3091          | 238.3791    | 0.1542        | 0.8668                      | 187.7555 | 0.1891 |
| 6    | 0.3091          | 272.8715    | 0.1604        | 0.8668                      | 208.8732 | 0.1890 |
| 7    | 0.3091          | 311.2493    | 0.1660        | 0.8668                      | 229.2411 | 0.1888 |
| 8    | 0.3091          | 346.8686    | 0.1707        | 0.8668                      | 248.8676 | 0.1887 |
| 9    | 0.3091          | 380.0230    | 0.1748        | 0.8668                      | 268.0557 | 0.1886 |
| 10   | 0.3091          | 413.8181    | 0.1782        | 0.8668                      | 287.2956 | 0.1884 |
| 11   | 0.3091          | 446.7220    | 0.1812        | 0.8668                      | 306.7317 | 0.1883 |
| 12   | 0.3091          | 476.5703    | 0.1841        | 0.8668                      | 326.2205 | 0.1881 |
| 13   | 0.3091          | 501.7973    | 0.1870        | 0.8668                      | 345.4511 | 0.1880 |
| 14   | 0.3091          | 524.0769    | 0.1902        | 0.8668                      | 364.2701 | 0.1879 |
| 15   | 0.3091          | 546.3695    | 0.1937        | 0.8668                      | 382.7610 | 0.1877 |
| 16   | 0.3091          | 569.8955    | 0.1972        | 0.8668                      | 400.9805 | 0.1876 |
| 17   | 0.3091          | 594.7536    | 0.2003        | 0.8668                      | 418.9724 | 0.1875 |
| 18   | 0.3091          | 620.9611    | 0.2025        | 0.8668                      | 436.7805 | 0.1873 |
| 19   | 0.3091          | 647.1204    | 0.2034        | 0.8668                      | 454.4848 | 0.1872 |
| 20   | 0.3091          | 670.2706    | 0.2030        | 0.8668                      | 472.0177 | 0.1871 |
| 21   | 0.3091          | 690.0681    | 0.2014        | 0.8668                      | 489.5219 | 0.1869 |
| 22   | 0.3091          | 706.8583    | 0.1990        | 0.8668                      | 506.9924 | 0.1868 |
| 23   | 0.3091          | 720.9831    | 0.1960        | 0.8668                      | 524.4603 | 0.1866 |
| 24   | 0.3091          | 732.2902    | 0.1926        | 0.8668                      | 541.9124 | 0.1865 |
| 25   | 0.3091          | 740.4053    | 0.1889        | 0.8668                      | 559.3076 | 0.1864 |
| 26   | 0.3091          | 747.1815    | 0.1849        | 0.8668                      | 576.7470 | 0.1862 |
| 27   | 0.3091          | 754.8518    | 0.1805        | 0.8668                      | 594.3196 | 0.1861 |
| 28   | 0.3091          | 763.4054    | 0.1758        | 0.8668                      | 611.9683 | 0.1860 |
| 29   | 0.3091          | 772.1960    | 0.1711        | 0.8668                      | 629.6783 | 0.1858 |
| 30   | 0.3091          | 780.9891    | 0.1663        | 0.8668                      | 647.3706 | 0.1857 |

Aortic area measured at maximum distension of the aorta on cross sectional cine gradient echo images acquired perpendicular to the aortic axis (n = 30)

LMS, L = Lambda (skewness of the distribution), M = Mu (median), S = Sigma (variance)

z-score = \( \frac{(X/M) - 1}{L*S} \), where X is the measured aortic area in mm\(^2\) and L, M and S are the values interpolated for the child's age; lower and upper limits correspond to a z-score of -2 and 2

<sup>a</sup> Age in years
<sup>b</sup> Measured above the diaphragm
Studies included in this review

There is a single publication only of a systematic evaluation of normal aortic distensibility and PWV in children (Table 52). In this review we present LMS parameters to calculate z-scores for distensibility of the ascending aorta and PWV based on reference [92] (Tables 53, 54). In the original publication LMS parameters for distensibility at 3 other levels of the thoracic aorta (aortic arch, aortic isthmus and distal descending aorta) are presented in addition [92].

Normal dimensions and distension of the pulmonary arteries in adults

CMR acquisition parameters

In the study by Burman et al. listed in this review [99] dimensions of the pulmonary arteries were measured on bSSFP images (Table 55). Burman et al. acquired cross sectional images of the main and the right and left pulmonary artery based on an oblique sagittal image of the RV outflow tract and pulmonary trunk, respectively (for the main pulmonary artery) and an axial image acquired

Table 45 LMS parameters to calculate z-scores for aortic cross-sectional area relative to age for girls according to reference [92]

| Age | Ascending aorta | Aortic arch | Aortic isthmus | Descending aorta |
|-----|----------------|-------------|---------------|-----------------|
|     | L  | M  | S   | L  | M  | S   | L  | M  | S   | L  | M  | S   |
| <1  | -0.7876 | 121.1903 | 0.2152 | 2.1750 | 73.6299 | 0.2114 | 1.0330 | 60.0696 | 0.1621 | 0.9371 | 41.0795 | 0.1398 |
| 1   | -0.7876 | 145.9923 | 0.2140 | 2.1750 | 92.7307 | 0.2089 | 1.0330 | 72.6142 | 0.1617 | 0.9371 | 52.4930 | 0.1398 |
| 2   | -0.7876 | 170.7944 | 0.2127 | 2.1750 | 111.8315 | 0.2064 | 1.0330 | 85.1587 | 0.1613 | 0.9371 | 63.9065 | 0.1398 |
| 3   | -0.7876 | 195.5999 | 0.2114 | 2.1750 | 130.9296 | 0.2039 | 1.0330 | 97.7032 | 0.1609 | 0.9371 | 75.3185 | 0.1398 |
| 4   | -0.7876 | 220.4539 | 0.2102 | 2.1750 | 149.9904 | 0.2013 | 1.0330 | 110.2465 | 0.1605 | 0.9371 | 86.7100 | 0.1398 |
| 5   | -0.7876 | 245.2481 | 0.2089 | 2.1750 | 168.9588 | 0.1988 | 1.0330 | 122.7870 | 0.1601 | 0.9371 | 98.0510 | 0.1398 |
| 6   | -0.7876 | 270.5738 | 0.2076 | 2.1750 | 187.8089 | 0.1963 | 1.0330 | 135.3263 | 0.1597 | 0.9371 | 109.3784 | 0.1398 |
| 7   | -0.7876 | 295.9027 | 0.2064 | 2.1750 | 206.5696 | 0.1938 | 1.0330 | 147.8724 | 0.1593 | 0.9371 | 120.8531 | 0.1398 |

Aortic area measured at maximum distension of the aorta on cross sectional cine gradient echo images acquired perpendicular to the aortic axis (n = 41)

LMS, L = Lambda (skewness of the distribution), M = Mu (median), S = Sigma (variance)

z-score = (X/M) - 1 / (L*S), where X is the measured aortic area in mm² and L, M and S are the values interpolated for the child’s age; lower and upper limits correspond to a z-score of -2 and 2

a Age in years
b Measured above the diaphragm
at the level of the bifurcation of the main pulmonary artery (for the left and right pulmonary artery) (Fig. 13). With three-dimensional acquisition, reconstruction of the imaging plane can be performed after image acquisition using multiplanar reformation.

Other sequences could also be used to obtain dimensions of the pulmonary arteries such as a three-dimensional contrast enhanced CMRA with contrast timing optimized to enhance the pulmonary arteries. Non-contrast techniques include respiratory and ECG-gated 3D bSSFP sequence and cine phase contrast imaging. However, similar to the aorta, measurements of the pulmonary artery are expected to vary by the sequence type and might not be comparable [82]. In contrast to static sequences, acquisition of dynamic sequences, e.g. cine bSSFP, enable measurements at systole and diastole and calculation of distension.

### CMR analysis methods

Luminal areas and diameters of the pulmonary arteries were measured on cross sectional images of the respective vessel at minimal diastolic and minimal systolic expansion. Since the cross section of the vessel is usually not perfectly circular, data presented in Table 56 shows the mean diameter of two diameters that were acquired per vessel and phase calculated from the greatest diameter and the lesser diameter orthogonal to the greater diameter. Percent systolic distension was calculated as [(maximum area – minimum area) * 100/minimum area].

### Demographic parameters

Area and mean diameters of the pulmonary arteries are greater in men compared to women and greater in

### Table 46 Normal aortic diameters in children measured on a contrast enhanced 3D-CMRA according to reference [91]

| Site                                      | Predicted diameter (mm) | SD of residuals (mm) |
|-------------------------------------------|-------------------------|----------------------|
| Aortic sinus                              | 0.57 + 19.37*BSA^{0.5}  | 2.38                 |
| Sinotubular junction                      | −0.03 + 16.91*BSA^{0.5} | 1.92                 |
| Ascending aorta                           | −1.33 + 18.6*BSA^{0.5}  | 1.99                 |
| Proximal to the origin of the brachiocephalic artery | −3.38 + 20.07*BSA^{0.5} | 1.69                 |
| First transverse segment                  | −3.52 + 18.66*BSA^{0.5} | 1.63                 |
| Second transverse segment                 | −2.63 + 16.5*BSA^{0.5}  | 1.31                 |
| Isthmic region                            | −3.37 + 16.52*BSA^{0.5} | 1.46                 |
| Descending aorta                          | −1.12 + 14.42*BSA^{0.5} | 1.64                 |
| Thoracoabdominal aorta at the level of the diaphragm | 1.27 + 9.89*BSA^{0.5} | 1.34                 |

Shortest diameter measured on cross-sectional reformatted images (n = 53).

Sites of measurement are shown in Fig. 9

z-score = (measured diameter – predicted diameter)/SD of residuals; lower and upper limits correspond to a z-score of -2 and 2

BSA body surface area, SD standard deviation

### Table 47 Normal aortic area on phase contrast cine images according to reference [93]

| Site                                      | Predicted area (cm²) |
|-------------------------------------------|----------------------|
| Ascending aorta                           | −0.0386 + 2.913*BSA  |

Cross sectional area calculated based on measurement of the maximal external aortic diameter perpendicular to the vessel and perpendicular to the maximal diameter in systole 1 to 2 cm distal to the sinotubular junction on the magnitude image of a phase contrast cine sequence (n = 105)

BSA body surface area

![Fig. 12](image-url)
systole compared to diastole. Some measurements of
the area and the mean diameter of the pulmonary arter-
ies slightly increase with BSA and age, while systolic dis-
tension decrease with age. For a detailed description of
the relationship of the area, mean diameters and systolic
distension of the pulmonary arteries with age and BSA
please see [99].

**Studies included in this review**

One publication of reference ranges of the area, diam-
eters and distension of the pulmonary arteries in adults
was found using a current CMR technique, sufficient
sample size (> 40 subjects per gender) and a clear descrip-
tion of image acquisition and measurements [99]. In
the original publication, reference ranges were presented
for age deciles for subjects between 20 and 79 years with 10
subjects per decile and gender. However, since the differ-
ences between age deciles were small and might not be
clinically relevant and for sample size considerations, in
the current review only values of the entire cohort sepa-
rated by gender are presented.

**Normal dimensions of the pulmonary arteries
in children**

**CMR acquisition parameters**

In analogy to dimensions of the pulmonary arteries
in adults, different sequences might be used to obtain
measurements. In the studies listed below, a contrast
enhanced three-dimensional CMRA and a cross sec-
tional through-plane free-breathing phase contrast
sequence were acquired to obtain the measurements
[93, 100].

**CMR analysis methods**

Knobel et al. obtained measurements of the pulmonary
arteries on reconstructed maximum intensity projection
(MIP) images (slice thickness is not mentioned) per-
pendicular to the respective vessel (Fig. 14) [100]. The

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**Table 48** References, normal aortic pulse wave velocity (PWV) and distensibility

| First author, year | CMR technique | n, male:female | Age range (years) |
|--------------------|---------------|----------------|------------------|
| Kim, 2013 [98]     | 1.5 T, phase contrast CMR to calculate PWV for 3 distances of the aorta; transit time calculated from the midpoint of the systolic up-slope on the flow versus time curve; cross sectional cine bSSFP at 4 levels of the aorta to calculate distensibility | 61:63 | 20–79 |
| Eikendal, 2016 [84] | 3 T, phase contrast CMR to calculate PWV for 2 distances of the aorta, time delay calculated from velocity–time curves | 57:61 | 25–35 |

*n number of study subjects, bSSFP balanced steady-state free precession, PWV pulse wave velocity*

**Table 49** Normal values of regional aortic distensibility for men and women according to [98]

| Level | Age (years) | Men (n = 61) Mean ± SD (10⁻³ mm/Hg) | Women (n = 63) Mean ± SD (10⁻³ mm/Hg) |
|-------|-------------|-------------------------------------|--------------------------------------|
| Ascending aorta | 20–29 | 5.6±1.5 | 7.9±3.4 |
| | 30–39 | 3.6±1.4 | 6.5±3.0 |
| | 40–49 | 3.5±1.5 | 5.3±1.2 |
| | 50–59 | 3.2±1.6 | 3.6±1.1 |
| | 60–69 | 2.1±1.3 | 2.7±1.0 |
| Proximal descending aorta | 20–29 | 4.2±0.9 | 6.0±1.4 |
| | 30–39 | 3.8±1.3 | 5.5±1.9 |
| | 40–49 | 3.3±0.6 | 4.2±1.2 |
| | 50–59 | 2.9±1.1 | 3.7±1.3 |
| | 60–69 | 2.3±0.9 | 3.1±0.9 |

*n number of study subjects

*a Measurements obtained at the level of the bifurcation of the pulmonary artery

**Table 50** Normal values for aortic pulse wave velocity according to [98]

| Age (years) | n | Median (5th–95th percentile) (m/s) |
|-------------|---|-----------------------------------|
| 20–29       | 26 | 3.7 (3.4–4.0) |
| 30–39       | 28 | 3.8 (3.5–6.0) |
| 40–49       | 24 | 4.3 (3.7–5.0) |
| 50–59       | 25 | 5.6 (5.4–7.2) |
| 60–69       | 21 | 9.0 (7.4–12.4) |

Regional pulse wave velocity from the ascending to the upper descending thoracic aorta

*n number of study subjects

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**Table 51** Normal values for aortic pulse wave velocity in young men and women (25–35 years) according to [84]

| Men (n = 57) | Women (n = 61) |
|-------------|----------------|
| Median (10th–90th percentile) (m/s) | Median (10th–90th percentile) (m/s) |
| 4.6 (3.9–5.6) | 4.5 (3.6–6.0) |

Regional pulse wave velocity from the ascending to the upper descending thoracic aorta

*n number of study subjects
Table 52  References, normal distensibility and pulse wave velocity (PWV) in children

| First author, year | CMR technique | n, male:female | Age range (years) |
|--------------------|---------------|---------------|-------------------|
| Voges, 2012 [92]  | 3 T; cross sectional cine GRE at 4 levels of the thoracic aorta to calculate distensibility; phase contrast CMR to calculate PWV for the distance between the sinotubular junction and the proximal descending aorta, transit time calculated from the midpoint of the systolic up-slope on the flow versus time curve | 30:41 | 2–28 |

n number of study subjects, GRE gradient echo, PWV pulse wave velocity

Table 53  LMS parameters to calculate z-scores for distensibility of the ascending aorta relative to age in children according to reference [92]

| Age (years) | Male (n = 30) | | Female (n = 41) | |
|-------------|---------------|-----------------|-----------------|-----------------|
|             | L             | M               | S               | L               | M               | S               |
| < 1         | −0.1879       | 12.3602         | 0.3680          | −0.0721         | 12.7303         | 0.2388          |
| 1           | −0.1879       | 11.9220         | 0.3680          | −0.0721         | 12.5028         | 0.2403          |
| 2           | −0.1879       | 11.4838         | 0.3680          | −0.0721         | 12.2753         | 0.2411          |
| 3           | −0.1879       | 11.0456         | 0.3680          | −0.0721         | 11.8176         | 0.2419          |
| 4           | −0.1879       | 10.6075         | 0.3680          | −0.0721         | 11.5817         | 0.2427          |
| 5           | −0.1879       | 10.1700         | 0.3680          | −0.0721         | 11.3421         | 0.2435          |
| 6           | −0.1879       | 9.7343          | 0.3680          | −0.0721         | 11.1121         | 0.2443          |
| 7           | −0.1879       | 9.2990          | 0.3680          | −0.0721         | 10.9051         | 0.2451          |
| 8           | −0.1879       | 8.8602          | 0.3680          | −0.0721         | 10.7290         | 0.2459          |
| 9           | −0.1879       | 8.4151          | 0.3680          | −0.0721         | 10.5679         | 0.2467          |
| 10          | −0.1879       | 7.9776          | 0.3680          | −0.0721         | 10.3851         | 0.2474          |
| 11          | −0.1879       | 7.5683          | 0.3680          | −0.0721         | 10.1582         | 0.2482          |
| 12          | −0.1879       | 7.2051          | 0.3680          | −0.0721         | 9.8884          | 0.2490          |
| 13          | −0.1879       | 6.9030          | 0.3680          | −0.0721         | 9.5911          | 0.2498          |
| 14          | −0.1879       | 6.6697          | 0.3680          | −0.0721         | 9.2905          | 0.2506          |
| 15          | −0.1879       | 6.5089          | 0.3680          | −0.0721         | 9.0033          | 0.2514          |
| 16          | −0.1879       | 6.4138          | 0.3680          | −0.0721         | 8.7345          | 0.2522          |
| 17          | −0.1879       | 6.3729          | 0.3680          | −0.0721         | 8.4850          | 0.2529          |
| 18          | −0.1879       | 6.3745          | 0.3680          | −0.0721         | 8.2574          | 0.2537          |
| 19          | −0.1879       | 6.4062          | 0.3680          | −0.0721         | 8.0546          | 0.2545          |
| 20          | −0.1879       | 6.4551          | 0.3680          | −0.0721         | 7.8749          | 0.2553          |
| 21          | −0.1879       | 6.5111          | 0.3680          | −0.0721         | 7.7106          | 0.2561          |
| 22          | −0.1879       | 6.5646          | 0.3680          | −0.0721         | 7.5479          | 0.2569          |
| 23          | −0.1879       | 6.6062          | 0.3680          | −0.0721         | 7.3842          | 0.2577          |
| 24          | −0.1879       | 6.6277          | 0.3680          | −0.0721         | 7.2113          | 0.2584          |
| 25          | −0.1879       | 6.6242          | 0.3680          | −0.0721         | 7.0343          | 0.2592          |
| 26          | −0.1879       | 6.5975          | 0.3680          | −0.0721         | 6.8647          | 0.2600          |
| 27          | −0.1879       | 6.5577          | 0.3680          | −0.0721         | 6.6951          | 0.2608          |
| 28          | −0.1879       | 6.5116          | 0.3680          | −0.0721         | 6.5250          | 0.2616          |
| 29          | −0.1879       | 6.4643          | 0.3680          | −0.0721         | 6.3550          | 0.2624          |
| 30          | −0.1879       | 6.4170          | 0.3680          | −0.0721         | 6.1937          | 0.2629          |

Distensibility was calculated based on measurements of the aortic area at systole and diastole on cross sectional cine gradient echo images obtained perpendicular to the axis of the ascending thoracic aorta.

LMS, L = Lambda (skewness of the distribution), M = Mu (median), S = Sigma (variance).

z-score = [(X/M)^0.5 – 1] / (L*S), where X is the measured aortic distensibility in 10^-3 mm Hg^-1 and L, M and S are the values interpolated for the child's age; lower and upper limits correspond to a z-score of -2 and 2.

n number of study subjects.
The diameter of the main pulmonary artery was obtained on an axial and a reformatted sagittal oblique view, the diameters of the proximal and distal right and left pulmonary artery were measured on an axial and reformatted right and left anterior oblique (coronal oblique) views.

### Table 54

| Age (years) | Male (n = 30) | Female (n = 41) |
|------------|---------------|-----------------|
|            | L  | M     | S    | L   | M     | S    |
| < 1        | 1.4844 | 3.4147 | 0.2122 | -1.5196 | 2.7808 | 0.1468 |
| 1          | 1.4844 | 3.4387 | 0.2122 | -1.5196 | 2.8144 | 0.1469 |
| 2          | 1.4844 | 3.4587 | 0.2122 | -1.5196 | 2.8481 | 0.1469 |
| 3          | 1.4844 | 3.4808 | 0.2122 | -1.5196 | 2.8817 | 0.1469 |
| 4          | 1.4844 | 3.5028 | 0.2122 | -1.5196 | 2.9154 | 0.1470 |
| 5          | 1.4844 | 3.5248 | 0.2122 | -1.5196 | 2.9490 | 0.1470 |
| 6          | 1.4844 | 3.5469 | 0.2122 | -1.5196 | 2.9827 | 0.1470 |
| 7          | 1.4844 | 3.5689 | 0.2122 | -1.5196 | 3.0163 | 0.1470 |
| 8          | 1.4844 | 3.5909 | 0.2122 | -1.5196 | 3.0499 | 0.1471 |
| 9          | 1.4844 | 3.6129 | 0.2122 | -1.5196 | 3.0836 | 0.1471 |
| 10         | 1.4844 | 3.6350 | 0.2122 | -1.5196 | 3.1172 | 0.1471 |
| 11         | 1.4844 | 3.6570 | 0.2122 | -1.5196 | 3.1509 | 0.1471 |
| 12         | 1.4844 | 3.6790 | 0.2122 | -1.5196 | 3.1845 | 0.1472 |
| 13         | 1.4844 | 3.7011 | 0.2122 | -1.5196 | 3.2182 | 0.1472 |
| 14         | 1.4844 | 3.7231 | 0.2122 | -1.5196 | 3.2518 | 0.1472 |
| 15         | 1.4844 | 3.7451 | 0.2122 | -1.5196 | 3.2855 | 0.1473 |
| 16         | 1.4844 | 3.7672 | 0.2122 | -1.5196 | 3.3192 | 0.1473 |
| 17         | 1.4844 | 3.7892 | 0.2122 | -1.5196 | 3.3528 | 0.1473 |
| 18         | 1.4844 | 3.8112 | 0.2122 | -1.5196 | 3.3865 | 0.1473 |
| 19         | 1.4844 | 3.8333 | 0.2122 | -1.5196 | 3.4201 | 0.1474 |
| 20         | 1.4844 | 3.8553 | 0.2122 | -1.5196 | 3.4538 | 0.1474 |
| 21         | 1.4844 | 3.8773 | 0.2122 | -1.5196 | 3.4875 | 0.1474 |
| 22         | 1.4844 | 3.8994 | 0.2122 | -1.5196 | 3.5211 | 0.1475 |
| 23         | 1.4844 | 3.9214 | 0.2122 | -1.5196 | 3.5548 | 0.1475 |
| 24         | 1.4844 | 3.9434 | 0.2122 | -1.5196 | 3.5885 | 0.1475 |
| 25         | 1.4844 | 3.9655 | 0.2122 | -1.5196 | 3.6221 | 0.1476 |
| 26         | 1.4844 | 3.9875 | 0.2122 | -1.5196 | 3.6558 | 0.1476 |
| 27         | 1.4844 | 4.0096 | 0.2122 | -1.5196 | 3.6895 | 0.1476 |
| 28         | 1.4844 | 4.0316 | 0.2122 | -1.5196 | 3.7231 | 0.1476 |
| 29         | 1.4844 | 4.0536 | 0.2122 | -1.5196 | 3.7568 | 0.1477 |
| 30         | 1.4844 | 4.0757 | 0.2122 | -1.5196 | 3.7905 | 0.1477 |

Pulse wave velocity calculated by phase contrast CMR for the distance between the sinotubular junction and the proximal descending aorta. Transit time calculated from the midpoint of the systolic up-slope on the flow versus time curve (Fig. 12).

LMS, L = Lambda (skewness of the distribution), M = Mu (median), S = Sigma (variance)

z-score = \((X/M)^4 - 1) / (L * S)\), where X is the measured pulse wave velocity in m/s and L, M and S are the values interpolated for the child's age; lower and upper limits correspond to a z-score of -2 and 2.

n number of study subjects

### Table 55

| First author, year | CMR technique | n, male:female | Age range (years) |
|--------------------|---------------|----------------|------------------|
| Burman, 2016 [99]  | 1.5 T, cross sectional bSSFP, luminal area and mean diameters | 60:60 | 20–79 |

n number of study subjects, bSSFP balanced steady-state free precession
In the study by Kutty et al. the maximal external diameter of the main pulmonary artery ($d_1$) was measured on the cross sectional magnitude image of the PC sequence in systole and also the diameter ($d_2$) perpendicular to $d_1$ [93]. After derivation of the radii ($r_1$ and $r_2$), the area was calculated as $\pi r_1 r_2$.

**Demographic parameters**

In both studies a relationship between pulmonary artery diameter and BSA was described [93, 100]. Kutty et al. could not find a significant gender difference of the size of the main pulmonary artery.

**Studies included in this review**

Two studies were identified presenting normal values of the size of the pulmonary arteries in children [93, 100] (Table 57). Knobel et al. included 69 children ranging from 2 to 20 years with a previous history of malignancy that were assessed for potential port-a-cath related complications but normal cardiovascular anatomy and
no evidence of cardiovascular disease [100] (Table 58). In the study by Kutty et al. 105 normal healthy subjects between 4 and 20 years were included (data presented here; Table 59) and also subjects with repaired tetralogy of Fallot (not presented in this review) [93].

Due to the differences in sequence type, measurement technique and data presentation the normal values of the two studies are presented separately.

### Normal values of myocardial T1 relaxation time and the extracellular volume (ECV)

#### CMR acquisition parameters

The field of myocardial T1 mapping has matured significantly with several studies reporting T1 relaxation times for normal cohorts [101]. An Expert Consensus document on parametric mapping has been published providing recommendations for the practical clinical application of T1, T2, T2*, and ECV mapping [102]. Most of the published myocardial T1 values have been acquired using variants of the Modified Look-Locker Inversion Recovery (MOLLI) technique [103] including the shortened-MOLLI (ShMOLLI) [104] method. Saturation recovery based techniques such as saturation recovery single-shot acquisition (SASHA) are alternative techniques but have less clinical evidence to date [105]. Images are typically acquired in diastole to limit cardiac motion and respiratory motion correction.

Native T1 maps are acquired without a contrast agent. Post contrast T1 maps allow assessment of gadolinium contrast distribution, as these agents shorten the T1 relaxation time of water. T1 maps acquired 10–30 min following injection of an extra-cellular non-protein binding gadolinium contrast agent can be used to quantify the extracellular volume fraction (ECV) [102]. Post contrast T1 values have been performed following a bolus or primed infusion (Equilibrium-EQCMR) with good agreement of ECV values up to 40% [106]. While the hematocrit can be approximated from the T1 of the blood in the LV cavity (“synthetic T1”), assessment of hematocrit by blood sampling as close as possible in time to the CMR (less than 24 h) is preferred due to normal daily variation of hematocrit [102].

#### Factors affecting T1 relaxation time and ECV

There are a number of CMR acquisition factors that can affect the measurement of normal T1 and ECV values. Field strength has a significant effect on T1 values; with 3 T scans producing 28% higher native T1 and 14% higher post contrast T1 values when compared with 1.5 T [107]. Post contrast T1 is also affected by the dose and relaxivity of the contrast agent used, contrast clearance, and the time between injection and measurement [107–109]. There is also greater heterogeneity for a T1 native normal range at 3 T [107, 110, 111]. Further, it has been shown that T1 varies by cardiac phase (diastole versus systole) and region of measurement (septal versus non-septal) [107]. ECV values are relatively unaffected by field strength (3 T versus 1.5 T). Both native T1 and ECV values have been shown to be less reliable in the inferolateral wall likely secondary to off-resonance effects [107, 112].

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### Table 56: Normal dimensions and distension of the pulmonary arteries in adults according to [99]

| Vessel   | Parameter          | Men (n = 60) | Women (n = 60) |
|----------|--------------------|--------------|----------------|
|          | Mean (SD)          | LL–ULa       | Mean (SD)      | LL–ULa         |
| MPA      | Systolic diameter (mm) | 27.4 (2.6)  | 21–33          | 25.3 (2.6)     | 19–31          |
|          | Diastolic diameter (mm) | 22.9 (2.4)  | 19–27          | 21.2 (2.1)     | 17–25          |
|          | Systolic area (cm²) | 5.9 (1.1) | 3.7–8.1        | 5.0 (1.0)      | 3.0–7.0        |
|          | Diastolic area (cm²) | 4.2 (0.8)  | 2.6–5.8        | 3.6 (0.7)      | 2.2–5.0        |
|          | Distension (%)     | 42.7 (17.2) | 9–77          | 41.8 (15.7)    | 10–74          |
| RPA      | Systolic diameter (mm) | 20.2 (2.9)  | 14–26          | 17.8 (2.4)     | 14–22          |
|          | Diastolic diameter (mm) | 16.6 (2.8)  | 11–23          | 14.7 (2.2)     | 11–19          |
|          | Systolic area (cm²) | 3.3 (1.0) | 1.3–5.3        | 2.6 (0.7)      | 1.2–4.0        |
|          | Diastolic area (cm²) | 2.2 (0.8)  | 0.6–3.8        | 1.8 (0.6)      | 0.6–3.0        |
|          | Distension (%)     | 50.6 (16.9) | 17–85          | 48.2 (14.5)    | 18–78          |
| LPA      | Systolic diameter (mm) | 20.1 (2.4)  | 16–24          | 18.4 (2.1)     | 14–22          |
|          | Diastolic diameter (mm) | 17.3 (2.5)  | 11–23          | 15.9 (2.0)     | 12–20          |
|          | Systolic area (cm²) | 3.3 (0.8) | 1.7–4.9        | 2.8 (0.6)      | 1.6–4.0        |
|          | Diastolic area (cm²) | 2.4 (0.7)  | 1.0–3.8        | 2.1 (0.5)      | 1.1–3.1        |
|          | Distension (%)     | 35.6 (10.1) | 16–56          | 35.2 (10.3)    | 15–55          |

*a Calculated as mean ± 2*SD

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n number of study subjects, SD standard deviation, LL lower limit, UL upper limit, MPA main pulmonary artery, RPA right pulmonary artery, LPA left pulmonary artery

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[99] Kawel-Boehm et al. J Cardiovasc Magn Reson (2020) 22:87
A number of pulse sequence parameters can affect normal values. For MOLLI pulse sequences the number of inversions, number of images following each inversion, and number of recovery beats between inversion pulses, and the flip angle affect normal values [101]. Furthermore, the type of inversion pulses, which may be vendor specific can also affect T1 values.
The aforementioned factors contribute to the large heterogeneity of published reference ranges. Heterogeneity in published values are present even if the same manufacturer scanner was used at the same field strength with the same pulse sequence [101]. It is thus imperative to standardize local pulse sequences and sequence parameters, and to follow current consensus guidelines for establishing site specific reference ranges [102]. In contrast to other CMR parameters, the SCMR has indicated that literature normal values of T1 relaxation times should not serve as absolute reference values, but rather than site-specific reference ranges should be established [102].

### CMR analysis methods

T1 maps are based on pixel-wise quantification of longitudinal relaxation from the T1-weighted source images. The native T1 relaxation time, expressed in milliseconds (ms), is a composite measurement reflecting the signal from water within multiple compartments within the myocardium including myocytes, the blood pool, and the interstitial space [113]. Under assumptions of an equilibrium of gadolinium concentrations between the blood pool and interstitium, pre and post contrast blood and myocardial T1 values can be used to quantify the partition coefficient of gadolinium which when multiplied by (1-hematocrit) quantifies the fractional volume of the extracellular space. This ECV is expressed as a percentage [114].

Offline post-processing involves manually tracing endocardial and epicardial contours [109, 115] (Fig. 15) or placing a region of interest within the septal myocardium. Inclusion of blood pool or adjacent tissue should be carefully avoided. Motion correction is generally used to correct undesired breathing motion. However, motion correction can only correct for in-plane motion and not through-plane motion. All methods, therefore, are vulnerable to partial volume effects.

### Demographic parameters

In one large study, there was no relationship of age to myocardial or blood native T1 in male subjects aged 11–69 years [116]. In female subjects there was a trend of lower native T1 with increased age (e.g. approximately 20 ms lower for females less than 45 years vs. those greater than 45 years) [116]. Female subjects < 45 years of age had a consistently higher native T1 then males, but after this age there was no difference in native T1 by gender [116]. However, other studies have failed to demonstrate a significant trend in native T1 with age or gender [117]. For ECV measurement, ECV is reported to be higher in females than males, but data are conflicting regarding the relationship of ECV with age [110, 118].

### Table 58

| Site                                      | Predicted diameter (mm) | SD of residuals (mm) |
|-------------------------------------------|-------------------------|----------------------|
| Main pulmonary artery (axial)             | 4.85 + 13.43*BSA0.5     | 2.72                 |
| Main pulmonary artery (sagittal)          | 1.04 + 17.07* BS A0.5   | 2.01                 |
| Proximal right pulmonary artery (axial)   | 2.63 + 9.19* BS A0.5    | 1.65                 |
| Distal right pulmonary artery (axial)     | 3.9 + 6.25* BS A0.5     | 1.49                 |
| Proximal right pulmonary artery (RAO)     | -0.69 + 14.3* BS A0.5   | 1.76                 |
| Distal right pulmonary artery (RAO)       | -1.08 + 14.62* BS A0.5  | 1.6                  |
| Proximal left pulmonary artery (axial)    | 1.7 + 11.27* BS A0.5    | 1.37                 |
| Distal left pulmonary artery (axial)      | -0.1 + 11.89* BS A0.5   | 1.51                 |
| Proximal left pulmonary artery (LAO)      | -2.13 + 16.82* BS A0.5  | 1.88                 |
| Distal left pulmonary artery (LAO)        | -2.08 + 13.64* BS A0.5  | 1.5                  |


### Table 59

| Site                                      | Predicted area (cm²) |
|-------------------------------------------|----------------------|
| Ascending aorta                           | -0.2880 + 3.386*BSA  |

Cross sectional area calculated based on measurements of the maximal external aortic diameter perpendicular to the vessel and perpendicular to the maximal diameter obtained midway between the level of the pulmonary valve and the bifurcation of the branch pulmonary arteries.

BSA body surface area

- **Diameters measured perpendicular to the vessel (Fig. 14).**
- **Fitting model for regression: diameter = a + b*BSA0.5**
- **z-score = (measured diameter – predicted diameter)/SD of residuals; lower and upper limits correspond to a z-score of -2 and 2.**
- **BSA body surface area, SD standard deviation, RAO right anterior oblique view (paracoronal, parallel to right pulmonary artery; Fig. 14), LAO left anterior oblique view (paracoronal, parallel to left pulmonary artery; Fig. 14).**
The above relationships were formally assessed in a recent meta-analysis [101]. Overall, there was no significant association between native T1 and age or percent of male participants at either 1.5 T or 3 T. However, there was a significant effect of gender with studies including more females on average having higher reported ECV values [101].

Studies included in this review
SCMR guidelines indicate each site should establish their own site specific reference ranges for T1 mapping parameters. In the absence of such data however, the weighted mean values and reference ranges for native T1 time and ECV based on publications of at least 40 healthy subjects extracted from Table 60 are summarized in Table 61.

Normal values of myocardial T2 relaxation times
CMR acquisition parameters
T2 relaxation time is the exponential time constant for the relaxation of transverse magnetization. To determine myocardial T2 time, a relaxation curve is constructed based on a CMR multi-echo pulse sequence. The most-commonly used technique utilizes a T2-preparation module followed by either a single-shot bSSFP or GRE readout [150, 151]. This technique typically acquires 3 source images with effective echo times of 0, 30 and 60 ms. 3–4 heart-beats are allowed for T1 relaxation between acquisition of source images, and data is acquired during a single breath-hold of 9–12 heart-beats. Inadequate time for complete T1-relaxation between source images can cause a T1-based bias in the T2 maps. The bSSFP technique has higher signal-to-noise but is more susceptible to off-resonance artifacts than the GRE technique. Other techniques are based on turbo-spin echo (TSE) or GRadient And Spin Echo (GRASE) acquisition modes. TSE sequences consist of a 90° excitation followed by a train of 180° refocusing pulses, with each focusing pulse producing a spin-echo with a different echo time (TE). By creating images corresponding to each echo time in the train, T2 maps can be produced by fitting the T2-signal decay equation. TSE sequences are robust to off-resonance, but they can suffer from inaccuracies due to imperfect 180° pulses which result in stimulated-echo contamination. GRASE sequences consist of a 90° excitation followed by a train of 180° pulses which produce a spin echo, and 2–4 gradient echoes. This technique is more efficient than TSE but is subject to similar biases as the TSE technique, and additionally is more sensitive to off-resonance effects due to the presence of gradient echoes and longer spacing between 180° pulses. Of note, performing multiple TSE sequences with different effective-TEs are inaccurate for determining T2 and are not recommended.

Factors affecting T2 relaxation time
There are a number of factors which can affect the measurement of normal T2 values. Field strength has a small effect on T2 values, with 3 T scans typically having T2 values that are ~6 ms shorter than those obtained on 1.5 T scanners [152]. There are differences in measured T2 based on technical factors such as the type of pulse-sequence used and the vendor. The T2-preparation pulse may be sensitive to off-resonance and B1 inhomogeneity effects; these effects are more severe at 3 T. T2-preparation based on adiabatic radiofrequency (RF)-pulses have been shown to lessen these effects at 3 T. TSE and GRASE sequences are sensitive to specifics of the RF-pulses which are vendor and implementation dependent. Similar to T1 mapping, it is imperative to standardize local pulse sequence parameters. As for T1 mapping, site-specific reference ranges should be established.
CMR analysis methods

T2 is the relaxation time (in milliseconds) of the transverse magnetization. Similar to T1 assessment, to generate parametric maps of T2, the source images typically need to be aligned using non-rigid registration. Again, these techniques can correct for in-plane motion but not through-plane motion. Both off-line and on-line techniques have been used as for T1 mapping.

Demographic parameters

Published data on T2 values have sample sizes smaller than those of T1 methods. Thus, effects of demographic parameters in relationship to T2 times are not well established. One paper using GRASE demonstrated a slightly higher native T1 in females as compared to males (56.7 ms vs 54.6 ms; p = 0.008) at 1.5 T but no difference at 3 T. No significant differences

Table 60  References, native myocardial T1 relaxation time and extracellular volume fraction (ECV)

| First author, year | CMR technique | n, male:female | Age range or mean ± SD (years) |
|--------------------|---------------|----------------|-------------------------------|
| Fontana, 2012 [120] | 1.5 T, Siemens, ShMOLLI, ECV | 27:23 | 47 ± 17 |
| Kellman, 2012 [121] | 1.5 T, Siemens, MOLLI, native T1 and ECV | 30:32 | 47 ± 17 |
| Piechnik, 2013 [116] | 1.5 T, Siemens, ShMOLLI, native T1 | 169:173 | 11–69 |
| Sado, 2013 [122] | 1.5 T, Siemens, ShMOLLI, native T1 | 30:37 | 24–88 |
| Ferreira, 2014 [123] | 1.5 T, Siemens, ShMOLLI, native T1 | 37:13 | 41 ± 13 |
| Fontana, 2014 [124] | 1.5 T, Siemens, ShMOLLI, native T1 | 17:35 | 46 ± 15 |
| Liu, 2014 [125] | 3 T, Siemens, MOLLI, native T1 | 38:54 | 27–44 |
| Punthmann, 2014 [126] | 3 T, Philips, MOLLI, native T1 | 47 (total) | — |
| Reiter, 2014 [118] | 1.5 T, Siemens, MOLLI, native T1 | 20:20 | 20–35 |
| aus dem Siepen, 2015 [127] | 1.5 T, Philips, MOLLI, native T1 and ECV | 37:19 | 52 ± 9 |
| Banyapersad, 2015 [128] | 1.5 T, Siemens, ShMOLLI, native T1 and ECV | 25:29 | 46 ± 15 |
| Edwards, 2015 [129] | 1.5 T, Siemens, MOLLI, native T1 and ECV | 24:19 | 57 ± 10 |
| Fontana, 2015 [130] | 1.5 T, Siemens, ShMOLLI, native T1 and ECV | 21:26 | 24–69 |
| Treibel, 2015 [131] | 1.5 T, Siemens, ShMOLLI, native T1 and ECV | 26:24 | 28–69 |
| Goebel, 2015 [132] | 1.5 T, Siemens, MOLLI, native T1 | 31:23 | 18–63 |
| Gormeli, 2016 [133] | 3 T, Siemens, MOLLI, native T1 | 26:15 | 24 ± 4 |
| Inojar, 2016 [134] | 3 T, Philips, MOLLI, native T1 | 9:37 | 42 ± 15 |
| Ntusi, 2016 [135] | 1.5 T, Siemens, ShMOLLI, native T1 | 53:39 | 44 ± 10 |
| Rauhalammi, 2016 [136] | 1.5 T and 3 T, Siemens, MOLLI, native T1 | 43:41 | 45 ± 18 |
| Costello, 2017 [137] | 3 T, Siemens, ShMOLLI, native T1 and ECV | 29:28 | 48 ± 15 |
| Avitzur, 2018 [138] | 3 T, Siemens, ShMOLLI, native T1 | 83:57 | 54 ± 9 |
| Dermer, 2018 [139] | 1.5 T, Philips, MOLLI, native T1 and ECV | 30:20 | 39 ± 17 |
| Guo, 2018 [140] | 3 T, Philips, MOLLI, native T1 and ECV | 18:32 | 36 ± 16 |
| Ridouani, 2018 [141] | 1.5 T, Siemens, MOLLI, native T1 | 20:20 | 40 ± 12 |
| Rosmini, 2018 [142] | 1.5 T, Siemens, MOLLI and ShMOLLI, native T1 and ECV | 49:45 | 20–76 |
| Shang, 2018 [143] | 3 T, Siemens, MOLLI, ECV | 45 (total) | — |
| Yang, 2018 [144] | 3 T, Siemens, MOLLI, native T1 and ECV | 18:26 | 33 ± 16 |
| Grantz, 2019 [145] | 1.5 T and 3 T, Philips, MOLLI, native T1 | 26:32 | 42 ± 13 (male), 40 ± 14 (female) |
| Imran, 2019 [146] | 1.5 T, Philips, MOLLI, native T1 | 26:25 | 46 ± 14 |
| Lehmomen, 2019 [147] | 1.5 T, Siemens, ShMOLLI, native T1 | 46 (total) | 46 ± 9 |
| Vijapurapu, 2019 [148] | 1.5 T, Siemens, ShMOLLI, native T1 | 40:37 | 49 ± 14 |
| Wan, 2019 [149] | 3 T, Siemens, MOLLI, native T1 and ECV | 20:20 | 56 ± 9 |

n number of study subjects, MOLLI modified look locker inversion-recovery, ShMOLLI short MOLLI, T1 T1 relaxation time, ECV extracellular volume fraction

* Not provided in original publication
Another study showed no difference between male and female subjects when controlling for age, but did see a trend of lower T2 with increasing age [153]. Another study using T2-prepared bSSFP at 3 T demonstrated no significant differences in T2 by age or gender [154]. Studies included in this review

SCMR guidelines indicate each site should establish their own site specific reference ranges for T2 mapping parameters. In the absence of such data however, the weighted mean values and reference ranges for T2 on publications of at least 40 healthy subjects (combined males and females) are shown in Table 62.

Table 61  Native myocardial T1 relaxation time and extracellular volume fraction (ECV)

| Parameter                  | FS (T) | Vendor | Technique | n   | Mean<sub>p</sub> | SD<sub>p</sub> | LL–UL<sub>m</sub> |
|----------------------------|--------|--------|-----------|-----|-----------------|---------------|------------------|
| Native T1 time (ms)        | 1.5    | Siemens| MOLLI     | 417<sup>a</sup> | 972  | 43             | 885–1059       |
|                            | 1.5    | Siemens| ShMOLLI   | 971<sup>b</sup> | 960  | 29             | 903–1017       |
|                            | 1.5    | Philips | MOLLI     | 215<sup>c</sup> | 989  | 42             | 905–1073       |
|                            | 3      | Siemens| MOLLI     | 301<sup>d</sup> | 1196 | 47             | 1103–1290      |
|                            | 3      | Siemens| ShMOLLI   | 197<sup>e</sup> | 1130 | 55             | 1021–1240      |
|                            | 3      | Philips | MOLLI     | 201<sup>f</sup> | 1097 | 66             | 964–1230       |
| ECV (%)                    | 1.5    | Siemens| MOLLI     | 199<sup>g</sup> | 26   | 3              | 20–32          |
|                            | 1.5    | Siemens| ShMOLLI   | 295<sup>h</sup> | 27   | 3              | 21–33          |
|                            | 1.5    | Philips | MOLLI     | 56<sup>i</sup>  | 23   | 3              | 17–29          |
|                            | 3      | Siemens| MOLLI     | 129<sup>j</sup> | 26   | 3              | 20–32          |
|                            | 3      | Siemens| ShMOLLI   | 57<sup>k</sup>  | 25   | 2              | 20–29          |
|                            | 3      | Philips | MOLLI     | 100<sup<l</sup> | 26   | 5              | 16–36          |

ECV extracellular volume fraction, FS field strength, T Tesla, n number of study subjects included in the weighted mean values, mean<sub>p</sub> pooled weighted mean, SD<sub>p</sub> pooled standard deviation, LL lower limit, UL upper limit, MOLLI modified look locker inversion-recovery, ShMOLLI short MOLLI, Siemens Siemens Medical Solutions, Erlangen, Germany, Philips Philips Healthcare, Best, The Netherlands

<sup>a</sup> Pooled weighted values from references [118, 121, 129, 132, 136, 141, 142]
<sup>b</sup> Pooled weighted values from references [116, 122–124, 128, 130, 131, 135, 142, 147, 148]
<sup>c</sup> Pooled weighted values from references [127, 139, 145, 146]
<sup>d</sup> Pooled weighted values from references [125, 133, 136, 144, 149]
<sup>e</sup> Pooled weighted values from references [137, 138]
<sup>f</sup> Pooled weighted values from references [126, 134, 140, 145]
<sup>g</sup> Pooled weighted values from references [121, 129, 142]
<sup>h</sup> Pooled weighted values from references [124, 128, 130, 131, 142]
<sup>i</sup> Values from reference [127]
<sup>j</sup> Pooled weighted values from references [143, 144, 149]
<sup>k</sup> Values from reference [137]
<sup>l</sup> Pooled weighted values from references [139, 140]
<sup>m</sup> Calculated as mean<sub>p</sub> ± 2*SD<sub>p</sub>

in T2 were seen as a function of age [145]. Another study showed no difference between male and female subjects when controlling for age, but did see a trend of lower T2 with increasing age [153]. Another study using T2-prepared bSSFP at 3 T demonstrated no significant differences in T2 by age or gender [154].

Studies included in this review

SCMR guidelines indicate each site should establish their own site specific reference ranges for T2 mapping parameters. In the absence of such data however, the weighted mean values and reference ranges for T2 on publications of at least 40 healthy subjects (combined males and females) are shown in Table 62.

Normal values of myocardial T2* relaxation time

CMR acquisition parameters

Quantification of the T2* relaxation time plays an important role for estimation of myocardial iron overload [156]. T2* time is also altered in myocardial necrosis and hemorrhage [102]. For quantification of the myocardial T2* time, the gradient-echo T2* technique with multiple increasing echo times is preferred over the spin-echo T2 technique due to a greater sensitivity to iron deposition [157–159]. According to the current consensus statement by the SCMR, a dark-blood multi-echo gradient echo sequence with 8 equally spaced echoes between 2 and 18 ms should be used for T2*-mapping at 1.5 T [102]. Usually a single-breath hold technique is used. Normal values and a grading system for myocardial iron overload are available for 1.5 T [158].

CMR analysis methods

Gradient-echo T2* images are vulnerable to distortions of the local magnetic field e.g. by air-tissue interfaces. The myocardial septum is surrounded by blood on both sides, so susceptibility differences are less than in the lateral wall with improved image quality on T2* images. Therefore, T2* measurements are obtained by placing a region of interest on the interventricular septum of a midventricular short axis slice [102, 159] (Fig. 16).
T2* times are frequently reported as relaxation rate, representing the reciprocal of the time constant and calculated as $R_2^* = \frac{1000}{T_2^*}$. The units of $R_2^*$ is s$^{-1}$ [159]. Cardiac iron concentration can be calculated from T2* values by the following equation: $[Fe] = \frac{45}{(T2^*)^{1.22}}$, where $[Fe]$ is the cardiac iron concentration in milligrams per gram dry weight and T2* in milliseconds [160].

**Demographic parameters**

T2* of the myocardium is not related to age [161]. To our knowledge the relationship between other demographic parameters and T2* has not been assessed.

**Studies included in this review**

The mean T2* of the myocardium (interventricular septum) is approximately 36 ms [161] at 1.5 T using a multi-echo GRE sequence. T2* > 20 ms is considered within the range of normal.

Depending on the risk to develop heart failure as a consequence of myocardial iron overload, a grading system for disease severity has been published (Table 63) [102, 156, 162].

**Regional measurements and cardiac strain**

**CMR acquisition parameters**

A number of imaging methods have been developed to acquire cardiac strain information from cine CMR. These methods include tagged cine CMR, PC-CMR, velocity encoded CMR, displacement encoding with stimulated echoes (DENSE), and strain-encoding (SENC) [163, 164]. Tagged CMR is a widely validated reproducible tool for strain estimation. The method is used in clinical studies and is considered the reference standard for assessing regional function [165, 166]. Recently feature-tracking CMR (FT-CMR) has been increasingly reported due to compatibility with existing cine CMR images [167].

**CMR analysis methods**

Cardiac strain is a dimensionless measurement of the deformation that occurs in the myocardium. Cardiac strain can be reported as three normal strains (circumferential, radial, and longitudinal) and six shear strains—the angular change between two originally mutually orthogonal line elements, with the more clinically investigated shear strain and the circumferential-longitudinal shear strain (also known as torsion). They can also be computed as fiber and cross-fiber strains which require anatomical knowledge of fiber architecture, or
as principal strains along the principal stretching and shortening directions [168]. Here, we concentrate on the widely reported circumferential and longitudinal strains. Although frequently reported, radial strain is less reproducible because of the reduced resolution of imaging in the radial direction as opposed to the circumferential or longitudinal directions.

There are a number of different methods to quantify strain: registration methods, feature-based tracking methods, deformable models, Gabor Filter Banks, optic flow methods, harmonic phase analysis (HARP) [169], and local sine wave modeling (SinMod) [163]. Technical review papers for these methods can be found in the following literature [167, 170–172].

HARP is one of the most widely reported and validated methods for analyzing tagged CMR for cardiac strain, in part due to its large scale use in the MESA study [169, 173]. Strain patterns are reported according to the 16 or 17 segment AHA model. Consistent manual tracing of the endocardial and epicardial contours is necessary to reproducible strain results. With tagged CMR, midwall strain is preferred to epicardial and endocardial strain to maximize the amount of tagging data available for strain calculations [172, 174]. With HARP analysis such as that used in the MESA trial [169], careful selection of the first harmonic is necessary. Figure 17a shows an outline of tagged CMR analysis using HARP.

FT-CMR has shown diagnostic and prognostic utility across a variety of pathologies. Currently, FT-CMR software from TomTec (TomTec Imaging Systems, Unterschleissheim, Germany), QStrain (Medis Medical Imaging Systems, Leiden, The Netherlands) and CVI42 (Circle Cardiovascular Imaging Inc., Calgary, Canada) are widely used in clinical research for calculation of LV strains. Similar to tagged CMR from HARP, strains are reported in the 16 or 17 segment models.

Segmentation of the myocardium (either semi-automated or completely automated) at the start of the cardiac cycle is an essential first step across all software. The software records a characteristic pixel pattern (an area of pixels typically in the order of 10–15 mm²) in the reference frame; an area with an identical pixel pattern is recognized in the next frame from which displacement of the pixels is computed. This is repeated through the entire cycle to obtain displacement from which strain is computed. Figure 17b shows an outline of the concept underlying strain analysis by FT-CMR.
Demographic parameters

Using both tagged CMR and FT-CMR, several studies report greater age is associated with decrease in peak circumferential or longitudinal shortening [176–178]. In tagged CMR and a few FT-CMR reports, gender also affects normal values. Cardiac strain values for women are higher than those of men [66, 176, 179–181]. However, some FT-CMR reports showed no association of circumferential or longitudinal strains with age or gender [26, 177].

Studies included in this review

Several studies have presented cohorts for determining normal LV strain. For the purpose of this review, only cohorts of 40 or more normal subjects using SPAMM (spatial modulation of magnetization tagging) or FT-CMR have been included. Inclusion criteria include a full description of the subject cohort (including the analysis methods used), age and gender of subjects. Table 64 represents a summary of publications reporting normal values for strain that fit the criteria. We have only included reference values for global values of strain as the inter-reader and inter-study reproducibility of regional strain values vary widely between published reports.

With tagged CMR, normal midwall circumferential strain values are relatively comparable between studies [182, 183] (Table 65). With 2D FT-CMR, small differences between published results exist for reference values, probably due to inter-vendor differences [26, 66, 177, 179]. The reference ranges of normal circumferential strains from FT-CMR (Table 66) are comparable to those obtained from tagged CMR (Table 65). Strain values are traditionally reported as more negative values meaning greater contractility. For both global circumferential and global longitudinal strain, a strain value of approximately -14% is the limit of normal; values more positive than this are considered to be abnormal.

Given the inclusion criteria noted above, one publication [176] used 3D FT-CMR (Table 67). The mean values and reference ranges were lower compared to 2D FT-CMR and tagged-CMR.

Myocardial perfusion

Myocardial perfusion has been quantified with T1-weighted dynamic imaging during the first pass of a contrast bolus by semi-quantitative methods that derive dimensionless indices (e.g. the upslope of myocardial signal intensity changes during initial contrast enhancement). Alternatively, absolute estimates of MBF may be determined (in units of ml per g of tissue and per minute (ml/g/min)). To derive absolute measures of blood flow, the CMR signal intensity changes must be converted to be linearly proportional to contrast concentration. This assumption may not hold true at high contrast concentrations (e.g. in the blood pool). Instead, low-dose bolus injections of contrast agent (e.g. < ~ 0.04 mmol/kg of Gd-DTPA) with saturation correction [184] or special pulse sequences are used for CMR perfusion (e.g. “dual-sequence” [185], dual-bolus techniques [186, 187]) to provide linear measures of gadolinium concentration.

CMR acquisition parameters

Normal values for quantitative myocardial perfusion measures have been obtained by ECG-gated, T1-weighted dynamic imaging during the first pass of an injected contrast bolus using gradient-echo image

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Table 64  References, myocardial strain

| First author, year | CMR technique | n, male:female | Age range (years) |
|-------------------|---------------|---------------|------------------|
| Neizel, 2009 [182] | 1.5 T, 3 short axis images, tagged CMR (SPAMM), tagged resolution 7 mm; HARP method | 40:35 | 22–69 |
| Augustine, 2013 [177] | 1.5 T, short axis stack bSSFP, 2, 3, and 4 chamber bSSFP; feature tracking (TomTec software) | 54:62 (30 ± 8) | |
| Venkatesh, 2015 [183] | 1.5 T, 3 short axis images, tagged CMR (SPAMM), tagged resolution 7 mm, HARP method | 46:83 | 45–84 |
| Andre, 2015 [179] | 1.5 T, short axis stack, 2, 3, and 4 chamber bSSFP; feature tracking (TomTec software) | 75:75 | 21–71 |
| Cai, 2017 [66] | 3 T, short axis stack, 2, 3, and 4 chamber bSSFP; feature tracking (QStrain software) | 91:89 | 20–69 |
| Liu, 2018 [26] | 1.5 T, short axis stack bSSFP, 2, 3, and 4 chamber bSSFP; feature tracking (CVI42 software, 3D) | 50:50 | 20–70 |
| Peng, 2018 [176] | 1.5 T and 3 T; short axis stack, 2, 3, and 4 chamber bSSFP; feature tracking (QStrain software) | 75:75 | 18–82 |

n number of study subjects, SPAMM spatial modulation of magnetization, HARP harmonic phase, bSSFP balanced steady state free precession

a Mean ± SD (age-range not provided in original publication)

b HARP commercial, Diagnosoft, Palo Alto, CA, USA
c TomTec Imaging Systems, Unterschleissheim, Germany
d CMI42, Circle Cardiovascular Imaging Inc., Calgary, Canada
e QStrain, Medis Medical Imaging Systems, Leiden, The Netherlands
readouts without or with bSSFP. Echo-times are kept as short as possible for any of these image acquisition methods to minimize T2*-related signal loss. T1-weighting is generally maximized by using saturation-recovery magnetization preparations. Semi-quantitative parameters depend on contrast dosage and injection protocol, sequence technique and acquisition parameters. The normal ranges for semi-quantitative parameters should therefore only be used as reference when the same protocol settings are employed. MBF (in units of mL/min/g) should be independent of the specific perfusion imaging protocol settings. However, a specific technique may still introduce a bias to under or over-estimate MBF.

In clinical use, myocardial perfusion imaging is generally performed at rest and during vasodilator stress. Adenosine and regadenoson are currently the most frequently used pharmacological stress agents for myocardial perfusion imaging and have supplanted dipyridamole in this role. Adenosine and regadenoson have similar hemodynamic effects on coronary artery blood flow [188]. The choice of pharmacologic stress agent is mostly determined by considerations of patient comfort, safety and cost. Regadenoson is more expensive, but better tolerated than adenosine. A unique application of myocardial perfusion imaging is its use in combination with the cold-pressor test to assess coronary endothelial function [189, 190].

Table 65 Left ventricular global peak circumferential strain using tagging

| Parameter                  | n  | Meanp | SDp  | LL–ULa |
|---------------------------|----|-------|------|--------|
| Circumferential strain (%)| 204| −20.1 | 3.0  | −26.0 to −14.2 |

Pooled weighted values from references [182, 183]
n number of study subjects included in the weighted mean values, meanp, pooled weighted mean, SDp, pooled standard deviation, LL, lower limit, UL, upper limit
*a Calculated as meanp ± 2*SDp
### CMR analysis methods

All quantitative approaches for CMR myocardial perfusion are based on signal-intensity versus time curves that depict the contrast enhancement during the first pass and recirculation of an injected contrast bolus. The myocardial perfusion images are segmented along the endo- and epicardial borders, and the ventricular wall is divided into segments following a standardized segmentation model for cardiac perfusion studies (Fig. 18).

The most widely used semi-quantitative parameter has been the up-slope parameter for initial myocardial contrast enhancement. Because the upslope derives from signal-intensity curves with arbitrary units, the value of the upslope depends on the image acquisition settings and on the characteristics of the contrast bolus. For this reason, the myocardial up-slope parameter is generally normalized by the up-slope of the arterial blood pool of the LV to obtain a dimensionless perfusion index. This index is quantified during resting conditions and “stress” at maximal vasodilation (i.e. hyperemia) after infusion of a pharmacological agent (e.g. adenosine). The coronary flow reserve is the ratio of the “stress” index, divided by “rest” index. We refer below to this parameter as the “up-slope” perfusion reserve.

Absolute quantification of the myocardial perfusion reserve entails estimating MBF in ml/min/g. MBF quantification can be based on tracer-kinetic modeling, or by using a deconvolution technique that is based on Zierler’s central volume theorem [191]. In either case it is important to have an accurate depiction of the arterial input of contrast to a myocardial region of interest, which in practice is approximated by the arterial contrast enhancement observed in the LV cavity. The myocardial perfusion reserve is estimated as “stress” MBF, divided by “rest” MBF. Nevertheless, hyperemic MBF by itself is also a useful measure of the maximal vasodilator response and its normal range is also provided by some studies in the literature. Rest MBF increases in proportion to the cardiac workload, and the rate-pressure product (RPP) is used as measure of cardiac workload to provide an RPP-normalized MBF value (rest MBF/RPP), whose normal range is narrower in healthy persons than for the rest MBF without any adjustment for RPP.

### Demographic parameters

In the CMR study by Wang et al. [192], rest MBF was higher in women than in men; this agrees with previous studies in healthy subjects using positron emission tomography [193]. Men have a lower hyperemic MBF compared to women, with adjustment for coronary heart disease risk factors [192]. Although male sex carries a higher risk for coronary heart disease, few studies of myocardial perfusion in healthy subjects have considered gender-related differences in MBF. The coronary flow response to the cold-pressor test is also higher in women compared to men [194].

### Studies included in this review

There are two publications reporting reference values of absolute MBF at rest and under pharmacological stress with a sufficient sample size (>40 healthy subjects) (Table 68). The original study published by Wang et al. included subjects from the MESA population with comorbidities such as hypertension and diabetes [192]. However, for the purpose of this review, a re-analysis of [192] was performed for a subset of 99 healthy subjects of the cohort by one of the authors (MJH). Values are given for the entire cohort and for men and women separately. In the other study by Brown et al. reference ranges are presented for the entire cohort of 42 healthy subjects [195]. Although in both studies images were acquired by means of a T1 weighted saturation recovery prepared single-shot GRE sequences, normal reference ranges

### Table 66 Left ventricular global peak circumferential and longitudinal strain for men and women using 2D feature tracking

| Parameter                | Men | Women |
|--------------------------|-----|-------|
|                          | n   | Mean±SD | n   | Mean±SD |
| Circumferential strain (%) | 295 | −20.9 | 3.2 | −27.2 to −14.6 |
| Longitudinal strain (%) | 295 | −19.4 | 3.3 | −26.1 to −12.7 |

Pooled weighted values from references [66, 176, 177, 179]

* Calculated as mean±2SD

### Table 67 Left ventricular global peak circumferential and longitudinal strain using 3D feature tracking according to reference [26]

| Parameter                | n   | Mean| SD | LL–UL |
|--------------------------|-----|-----|----|-------|
| Circumferential strain (%) | 100 | −17.6 | 2.6 | −22.8 to −12.4 |
| Longitudinal strain (%) | 100 | −14.6 | 2.7 | −20.0 to −9.2 |

* Calculated as mean±2SD

### Table 68 Absolute quantification of myocardial perfusion reserve in healthy subjects

| Reference | Study design | Subjects | Gender | RPP | Normal range |
|-----------|-------------|----------|--------|-----|--------------|
| Wang et al. [192] | N/A | 99 | Women | N/A | N/A |
| Brown et al. [194] | N/A | 42 | N/A | N/A | N/A |
differ substantially. Therefore, in this review we abstained from calculation of weighted mean values and present reference ranges given in the two publications separately (Table 69).

There is a single study presenting reference ranges of myocardial perfusion in children [196] (Table 68). Although the sample size is small (n = 20) and children have cardiovascular pathologies (e.g. atrial and ventricular septal defects), data is presented here since a study of myocardial stress perfusion imaging in a larger subset of entirely healthy children seems not feasible (Table 68).

### Artificial Intelligence (AI)-based segmentation methods for analysis of cine MRI

Currently no AI-based normal values have been published in the literature. In recent years however, major improvements have been made in the development of automated CMR segmentation methods based on AI technology using so called Convolutional Neural Networks (CNN). Most published work report methods for automated LV and RV segmentation in Cine CMR [3, 197–203]. CNN based methods have also been presented for automated quantification of atrial dimensions [2, 204], myocardial scar tissue from LGE [205, 206], T1 mapping [207], aortic flow [208] and disease classification [209]. Given the potential importance of this topic to the field of CMR, this section summarizes relevant literature in this area and provides a summary of the publicly available CMR data sets relevant to AI segmentation of CMR data.

#### Table 68  References, normal absolute myocardial blood flow at rest and stress and perfusion reserve in adults and children

| First author, year | CMR technique | n, male:female | Age mean ± SD (years) |
|--------------------|--------------|----------------|----------------------|
| Wang, 2006 [192]   | 1.5 T, T1weighted saturation recovery single-shot GRE, at rest and under adenosine stress | 49:50 59 ± 11 |
| Madriago, 2015 [196] | 3 T, T1weighted saturation recovery single-shot GRE, at rest and under adenosine stress | 11.9 8 ± 5 |
| Brown, 2018 [195] | 3 T, T1weighted saturation recovery single-shot GRE, at rest and under adenosine stress | 19:23 23 (22–29) |

n number of study participants, GRE gradient echo

*a Analysis of a subset of healthy subjects (without hypertension, no use of antihypertensive or other medication for a cardiovascular condition, no diabetes, normal glucose tolerance, no smoking history and normal total cholesterol (< 240 mg/dl)) of the original cohort

*b Median (interquartile range)

#### Table 69  Reference ranges of normal absolute myocardial blood flow (MBF) at rest and during adenosine stress and perfusion reserve in adults and children

| References | n | MBF at rest (ml/min/g) | MBF during Adenosine stress (ml/min/g) | Perfusion reservea |
|------------|---|----------------------|--------------------------------------|-------------------|
|            |   | Mean ± SD (LL–UL)b   | Mean ± SD (LL–UL)b                   | Mean ± SD (LL–UL)b |
| Wang, 2006 [192] | 99 | All: 1.02 ± 0.24 (0.54–1.5) | All: 3.13 ± 0.80 (1.53–6.19) | All: 3.17 ± 0.87 (1.43–4.91) |
|            | 49 | Men: 0.96 ± 0.23 (0.5–1.96) | Men: 2.79 ± 0.72 (1.35–5.49) |                |
|            | 50 | Women: 1.08 ± 0.23 (0.62–2.32) | Women: 3.46 ± 0.73 (2.02–7.50) |                |
| Madriago, 2015 [196] | 20 | 0.94 ± 0.17 (0.6–1.28) | 2.34 ± 0.82 (0.7–3.98) | 2.63 ± 0.96 (0.71–4.55) |
| Brown, 2018 [195] | 42 | 0.65 ± 0.13 (0.39–0.91) | 2.71 ± 0.61 (1.49–3.93) | 4.24 ± 0.69 (2.86–5.62) |

n number of study participants, MBF myocardial blood flow

*a Ratio of MBF during stress divided by MBF at rest

*b Calculated as mean ± 2*SD

*c Data table was made available by senior author to calculate mean and SD
in which participants are invited to develop the best segmentation algorithm for a given type of data [211]. Table 70 lists the most relevant public CMR Cine CMR data sets that have been used for this purpose.

Validation of CNN based segmentation methods is based on comparing the results of automated segmentation with manual results from a trained observer. Commonly used geometrical validation metrics include the Dice overlap, Hausdorff distance and average distance between contours [198]. Additionally, derived quantitative parameters from either automated or manual contours can be compared. As manual analysis is subject to observer bias and variability it can only serve as surrogate gold standard. Some papers report the observer variability of manual analysis in order to assess how the limits of agreement of an automated method compare with the limits of agreement within or between manual observers.

CNN-based image segmentation methods are being introduced in commercially available image analysis software packages. The question arises whether results from such automated methods can be used interchangeably with results from manual image analysis. Although CNN’s are designed to replicate the image segmentation performed by an expert observer, it is conceivable that relevant differences may occur, especially in myocardial pathologies which were not well represented in the cohort that was used to train the CNN.

Table 70  Publicly available data sets that have been used for training and testing for automated segmentation algorithms of the left and right ventricle.

| Data set          | Conference/source          | n   | Segmented structure | Data description                                                                 |
|-------------------|---------------------------|-----|---------------------|-----------------------------------------------------------------------------------|
| MICCAI-2009 [213]| MICCAI 2009               | 45  | Left ventricle      | Single center, single vendor<br>5 sub-groups: healthy, hypertrophy, heart failure with infarction and heart failure without infarction<br>Data hosted on: https://www.cardiacatlas.org/studies/sunnybrook-cardiac-data/ |
| LVSC-2011 [214]  | STACOM-2011               | 200 | Left ventricle      | Multi center, multi-vendor<br>Myocardial infarction                                |
| RVSC-2012 [215]  | MICCAI 2012               | 48  | Right ventricle     | Single center<br>Randomly selected clinical cases                                |
| ACDC-2017 [198]  | MICCAI 2017               | 150 | Left ventricle      | Single center, 2 scanners, 1 vendor<br>5 sub-groups (Normal, post-myocardial infarction, dilated cardiomyopathy, hypertrophic cardiomyopathy, abnormal right ventricle) |
| KAGGLE-2015 [216]| KAGGLE 2015s annual data science bow | 1100 | Left ventricle      | Multi center, multi scanner<br>Mix of patient and volunteer scans<br>Only end-diastolic and end-systolic ground truth results provided. No gold standard segmentations available |
| Multiple sources  | Cardiac Atlas Project [217]| >6500 | Left ventricle | Multi center, multi-vendor<br>Asymptomatic subjects<br>Data acquired with gradient echo cine acquisition<br>Data hosted on: https://www.cardiacatlas.org/studies/mesa/ |

n number of subjects, MICCAI Medical Image Computing and Computer Assisted Intervention, LVSC Left Ventricle Segmentation Challenge, STACOM Statistical Atlases and Computational Modelling of the Heart, RVSC Right Ventricle Segmentation Challenge, ACDC Automatic Cardiac Diagnosis Challenge

Studies included in this review

Table 71 lists 11 studies presenting CNN based image segmentation methods for automated analysis of CMR imaging data. Studies are included based on having either used a well described public data set for training and testing, or a dataset of > 300 subjects selected according to a properly described inclusion protocol. Most published work have used publicly available datasets for training and testing of algorithms for LV [198–202, 204] or RV [198, 200, 202–204] segmentation in short-axis cine CMR. The use of public data sets for algorithm training and validation enables objective comparison of the performance of the methods. Due to the relatively small size of training sets used and the limitation in variation in patient pathology, scanner manufactures, field strength and scanning protocol, it is uncertain how these methods perform on routine clinical CMR data. However, the above studies do convincingly demonstrate the high potential of CNN based image segmentation.

There are several studies for which AI methods were developed and applied to larger cohorts of subjects. Bai et al. presented a CNN method that was trained on a large dataset of 4875 subject scans of the UK Biobank cohort [2]. This method provides automated segmentation and quantification of short-axis and long-axis cine CMR for all four heart chambers. It was shown that the method provides excellent segmentation results when applied to cases from the UK Biobank cohort. However,
for application in clinical patients, the method demonstrated sub-optimal performance. Retraining the network by including additional cases of a clinical cohort did result in better results in patient data.

In the study of Tao et al., multi-center, multi-vendor, multi-pathology data was used to train and test vendor specific CNNs and a mixed-vendor CNN [3]. The authors showed that the CNN trained using a mix of data from all centers, vendors and pathologies had the highest overall performance. This indicates that it is feasible to use the same optimally trained CNN across multiple centers, vendors and patient pathologies.
A retrospective clinical validation of a commercial image analysis software tool was presented by Backhaus et al. [212]. In a randomly selected cohort of 300 CMR examination LV and RV parameters were automatically derived using a commercial software tool (SuiteHEART; NeoSoft, Pewaukee, Wisconsin, USA) incorporating CNN based image segmentation. The agreement between manual and automated LV parameter assessment was good (Bias in LV-EF: −2.5%±5.9%), while for RV assessment the agreement was lower (Bias in RV EF: 5.8%±9.6%). As expected, the agreement between manual and automated analysis was lowest in cases of poor image quality and in patients with abnormal cardiac anatomy.

Bhuva et al. used another approach to assess the performance of CNN based image segmentation as compared to manual analysis [197]. In their study a CNN LV segmentation method was trained on 599 subjects and tested on scan-rescan data of 110 patients with multiple pathologies. It was shown that automated image segmentation yielded similar scan-rescan reproducibility as manual image analysis, which suggests that automated segmentation is a viable alternative to manual analysis in a clinical setting.

Conclusions

CMR enables quantification of various functional and morphological parameters of the cardiovascular system. Advantages of a quantitative evaluation are a better differentiation between pathology and normal conditions, grading of pathologies, monitoring changes under therapy, and evaluating prognosis and the possibility of comparing different groups of patients and normal subjects.

Hence, here we present an updated and expanded version of the “normal value CMR review”. This review has provided reference values and factors affecting these parameters on current CMR techniques and sequences. Due to continuing publications in the field and new techniques transferred from research tools into clinical practice existing reference ranges need to be updated and values for new techniques integrated.

Abbreviations

AA: Ascending aorta; ACDC: Automatic Cardiac Diagnosis Challenge; AHA: American Heart Association; AI: Artificial intelligence; ARVC: Arrhythmogenic right ventricular cardiomyopathy; AVPDE: Ativoventricular plane descent; BMI: Body mass index; BSA: Body surface area; bSSFP: Balanced steady state free precession; CE: Contrast enhanced; CI: Cardiac index; CLBR: Challenge leader board ranking; CO: Cardiac output; CMR: Cardiovascular magnetic resonance; CMRA: Cardiovascular magnetic resonance angiography; CNN: Convolutional neural network; DENSE: Displacement encoding with stimulated echoes; DCM: Dilated cardiomyopathy; DICE: Dice overlap metric; ECG: Electrocardiogram; ECV: Extracellular volume; EDV: End-diastolic volume; EF: Ejection fraction; ESV: End-systolic volume; FD: Fractal dimension; FT: Feature-tracking; FGRE: Fast gradient echo; GRASE: Gradient and spin echo; GRE: Gradient echo; HARP: Harmonic phase analysis; HD: Hausdorff distance; HCM: Hypertrophic cardiomyopathy; IVS: Interventricular septum; JI: Jaccard index; LA: Left atrial; LV: Left ventricle; LVEF: Left ventricular ejection fraction; LVM: Left ventricular mass; LVO: Left ventricular outflow tract; LVSC: Left Ventricle Segmentation Challenge; LMS: Lambda Mu Sigma; LPA: Left pulmonary artery; M: Myocardial blood flow; Mean,: Pooled weighted mean; MESA: Multi-Ethnic Study of Atherosclerosis; MICCAI: Medical Image Computing and Computer Assisted Intervention; MOLLI: Modified Look-Locker inversion recovery; MP: Main pulmonary artery; MRI: Magnetic resonance imaging; MRA: MR angiography; NC/C: Non-compact/compact (left ventricular myocardium); PFR: Peak filling rate; PC: Phase contrast; RA: Right atrium/right atrial; RF: Radiofrequency; RPA: Right pulmonary artery; RPP: Rate-pressure product; RV: Right ventricle; RV: Right ventricular; RVSC: Right Ventricle Segmentation Challenge; SASHA: Saturation Recovery Single-shot Acquisition; SENC: Strain-encoding; SD: Standard deviation; SDp: Pooled weighted standard deviation; SEMOLLI: Shortened modified Look-Locker inversion recovery; SimMod: Sine wave modeling; SPAMM: Spatial modulation of magnetization; STACOM: Statistical Atlases and Computational Modelling of the Heart; SV: Stroke volume; T: Tesla; T1: T1-relaxation time; T2: T2-relaxation time; TM: Total (left ventricular myocardial) mass; TSE: Turbo-spin echo; TTE: Transthoracic echocardiography; UL: Upper limit (of normal); Venc: Flow encoding velocity; VISTA: Volume isotropic turbo spin echo; yrs: Years.

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