Reference value of left and right atrial size and phasic function by SSFP CMR at 3.0 T in healthy Chinese adults

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The size and function of the left atrium (LA) and right atrium (RA) are related closely with the prognosis of cardiovascular diseases. However, their normal reference values, as measured by cardiac magnetic resonance (CMR), are not well established in Chinese populations. Healthy Chinese subjects (n = 135, 66 males, age 23–83 years) without cardiovascular risk factors were recruited. We imaged the LA and RA of all subjects using short axis and long axis slices by steady-state free precession (SSFP) sequences using a 3.0 T scanner. The size and functional parameters were measured. Age and gender differences in LA were further explored. The normal reference values of atrial dimensions, volumes, and empty fractions (EFs) were provided by short axis (SAX) and area-length methods. Volumes and EFs derived by the area-length method showed correlated well with those derived by the by SAX method, but significantly underestimated the volumes (all P < 0.001) and overestimated the LA EFs (all P < 0.001). Atrial dimensions and volumes were generally larger in males. Conduit EFs and total EFs showed gender differences. Most atrial parameters correlated with age. In general, our results showed that gender and age have considerable impact on LA and RA size and function.

The left atrium (LA) and right atrium (RA) are not only reservoirs, but also have active emptying functions that contribute 15–30% of ventricular filling¹,². LA impairment increases with age³,⁴ and in diseases such as hypertension⁵, heart failure⁶, atrial fibrillation⁷, hypertrophic cardiomyopathy⁸, and amyloidosis⁹. In addition, LA enlargement and LA functional changes are associated with cardiovascular mortality or worse prognosis in patients with atrial fibrillation⁴,¹⁰, non-ischemic dilated cardiomyopathy¹¹, hypertrophic cardiomyopathy¹², and in the general population with different cardiovascular risks¹³. Compared with the LA, the RA is less studied²,¹⁴, although RA function is related to the severity and prognosis of pulmonary hypertension and congenital heart disease¹⁵,¹⁶. Traditionally, two-dimensional (2D) echocardiography has been used to evaluate LA dimension and size, and the newer three-dimensional (3D) echocardiography has improved the accuracy of measurement of the atrial volume. Cardiovascular magnetic resonance imaging (CMR) has advantages in the evaluation of atrial size and phasic function compared with echocardiography and cardiac computed tomography (CT)¹⁷.¹⁸.¹⁹. CMR can provide accurate measurements of dimension, volume, and structure of the atria, with high temporal and spatial resolution. Cardiac CT also has high spatial resolution; however, radiation and nephrotoxic contrast limit its widespread use in repeated measurements. CMR is the gold standard to evaluate ventricular volumes and should also be the standard for atrial volume assessment. Accurate normal atrial reference values are crucial in clinical practice and research. Maceria et al. published normal atrial reference values derived from subjects of European descent²⁰,²¹. Similar data is not available for the Chinese population. Therefore, we aimed to provide the normal reference values for the Chinese population and study the impact of gender and age on atrial size and function.

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Materials and Methods

Subjects. Healthy volunteers (n = 135) were recruited into this prospective study. All subjects provided a detailed history, and received a physical examination, a 12-lead electrocardiography, blood pressure measurement, and blood tests (including complete blood count), liver and renal function tests, and transthoracic echocardiography screening. The exclusion criteria were as follows: any known cardiovascular disease, hypertension, cerebrovascular disease or nervous system disease, chronic lung disease, diabetes, cancer, autoimmune diseases, recent systemic infection (within a month), recent surgery or severe trauma (within a month), any recent medications, and a history of implantation of pacemaker or other metals that are a contraindication for CMR. Subjects with abnormal findings on the comprehensive examination were also excluded. This study was approved by the ethics committee of West China Hospital, and all methods were performed in accordance with the approved guidelines. All subjects gave written informed consent.

Cardiac Magnetic Resonance Imaging. Image acquisition was performed with a 3.0-T MRI scanner (Magnetom Tim Trio; Siemens Medical Solutions, Erlangen, Germany) using a 4-channel phased-array receiver coil combined with a spine coil. Images were acquired by steady-state free precession (SSFP) sequence during breath-holds with retrospective electrocardiogram (ECG) gating (TR, 3.4 ms; TE, 1.3 ms; flip angle, 50 degrees; FOV, 320–340 mm; matrix size, 256 × 144; and slice thickness 6 mm, with no gap). Temporal resolution was 42 ms and reconstruction in plane spatial resolution was 1.4 mm × 1.3 mm. Atrial images were acquired in consecutive short-axis views from the atria-ventricular ring to the base of the atria and in long-axis views (2-, 3-, and 4-chamber (ch)). Right ventricle (RV) 2-ch slice was performed to evaluate the RA.

Image Analysis. LA Measurement. All CMR images were measured using a dedicated CMR post-processing software (Qmass 7.6, Medis, The Netherlands). LA dimensions were measured at the end of the systolic phase of the left ventricle (before the opening of the mitral valve) on 2-ch, 3-ch, and 4-ch SSFP cine images (Fig. 1). The LA volume was measured by two methods. First, the bi-plane area-length method with manually drawn endocardial contours in 2-and 4-ch views with exclusion of left atrial appendage and pulmonary veins; and second, the short axis (SAX) method using Simpson's method on the short axis slices of the atria. To calculate the atrial stoke volume and empty fraction (EF), the atrial volume at three phases during the cardiac cycle was measured. LA maximal volume (LAV_max) was defined at the end systole before the opening of the mitral valve. LA minimal volume (LAV_min) was defined at the end of diastole, just before the closure of the mitral valve. The pre-atrial contraction volume (LAV_p-ac) was defined at the beginning of left atrial active contraction phase at the mid diastole of the ventricle. Parameters for atrial emptying volume and emptying function were calculated as follows:

Reservoir function: Total EF(%): 100 × (LAV_max − LAV_min)/LAV_max
Conduit function: Conduit EF(%): 100 × (LAV_max − LAV_p-ac)/LAV_max
Booster function: Booster pump EF(%): 100 × (LAV_p-ac − LAV_min)/LAV_p-ac

The indexed dimension and volume values were calculated by the corresponding values divided by body surface area (BSA). The BSA values were derived from the height and weight by the DuBois & DuBois formula (BS A = (W^{0.425} × H^{0.725}) × 0.007184).36

RA Measurement. The dimensions of the RA were measured on 4-ch SSFP images and RV 2-ch SSFP images (Fig. 2). The RA volume was measured by the area-length method and the SAX method, similar to the LA. Single plane area-length and bi-plane area length were both used to calculate the RA volume. Similar to the measurement of the LA, maximal RA volume (RAV_max), minimal RA volume (RAV_min), and pre-ative contraction RA
volume (RAVp,ac) were acquired at the same phases as the LA. RA phasic functions were defined the same as LA phasic function. RA total emptying fraction, RA passive emptying fraction, and RA active emptying fraction were calculated using the same formulas. Similarly, indexed dimension and volume values were also calculated for the RA.

**Inter-observer and Intra-observer Variability.** Subjects (20%, 24 cases) were selected randomly to test inter- and intra-observer variability. For inter-observer variability, two independent observers (WHL and KW), with more than 2 years experience and 500 cases of CMR image analysis, finished the post-processing for atrial dimensions and volumes blindly. For intra-observer variability, one observer (WHL) repeated the measurements for all parameters using the identical methods 8 weeks apart.

**Statistical Analyses.** Statistical analyses were performed using SPSS (version 17.0; SPSS Inc., Chicago, IL, USA) and MedCalc (MedCalc Software version 13.0; Ostend, Belgium). The Kolmogorov-Smirnov test was used to check the normal distribution of the continuous variables. Independent-sample T tests were used to compare the mean values between men and women. Continuous data are presented as the mean ± SD. Non-normally distributed data were converted into log (normally distributed data), and then expressed as the mean ± SD. The normal reference range was calculated as the mean ± 2 SD. Linear regression was used to analyse the relationships between cardiac parameters and age. The inter- and intra-observer variability was assessed using the Bland-Altman method. A P value of <0.05 was considered statistically significant.

**Data Availability.** The datasets is available from the corresponding author on reasonable request.
Upper limits calculated as mean ± 2 SD; Long., Longitudinal dimension; Trans., Transverse dimension; AP, Antero-posterior dimension; 2ch, 2-chamber view; 3ch, 3-chamber view; 4ch, 4-chamber view; Indexed dimensions are calculated by corresponding dimensions in mm divided by BSA in m².

Table 2. Total and gender specific left atrial dimensions (mean ± SD, and reference range) (n = 135). Lower/upper limits calculated as mean ± 2 SD; Long., Longitudinal dimension; Trans., Transverse dimension; AP, Antero-posterior dimension; 2ch, 2-chamber view; 3ch, 3-chamber view; 4ch, 4-chamber view; Indexed dimensions are calculated by corresponding dimensions in mm divided by BSA in m².

| Parameters                          | Total (n = 135) | Male (n = 66) | Female (n = 69) | P (Male vs. Female) |
|-------------------------------------|----------------|--------------|----------------|--------------------|
|                                     | Mean ± SD      | Lower/upper limits | Mean ± SD      | Lower/upper limits | Mean ± SD      | Lower/upper limits | Mean ± SD | Lower/upper limits | Mean ± SD | Lower/upper limits | Mean ± SD | Lower/upper limits | Mean ± SD | Lower/upper limits | Mean ± SD | Lower/upper limits | Mean ± SD |
| Long. − 2ch[mm]                    | 50.1 ± 6.3     | (37.6, 62.6)  | 51.2 ± 6.2     | (38.8, 63.7)     | 49.1 ± 6.1     | (36.8, 61.3)     | 0.046      |
| Trans. − 2ch[mm]                   | 42.1 ± 5.5     | (31.1, 53.2)  | 42.5 ± 6.5     | (29.5, 55.6)     | 41.8 ± 4.4     | (33.0, 50.5)     | 0.425      |
| Long. − 3ch [mm]                   | 54.4 ± 6.6     | (41.1, 67.6)  | 55.1 ± 6.4     | (42.3, 67.9)     | 53.7 ± 6.8     | (40.1, 67.3)     | 0.239      |
| AP − 3ch[mm]                       | 29.9 ± 5.5     | (18.9, 41.0)  | 28.7 ± 5.3     | (18.1, 39.3)     | 31.1 ± 5.5     | (20.1, 42.1)     | 0.011      |
| Long. − 4ch [mm]                   | 56.5 ± 6.0     | (44.6, 68.5)  | 57.9 ± 5.7     | (46.5, 69.3)     | 55.2 ± 6.0     | (43.3, 67.1)     | 0.008      |
| Trans. − 4ch [mm]                  | 41.0 ± 4.8     | (31.3, 50.7)  | 41.6 ± 4.9     | (31.8, 51.4)     | 40.4 ± 4.8     | (30.9, 49.9)     | 0.169      |
| Indexed Long. − 2ch [mm/m²]        | 31.5 ± 4.7     | (22.1, 41.0)  | 30.0 ± 4.2     | (21.5, 38.5)     | 33.0 ± 4.7     | (23.6, 42.4)     | <0.001     |
| Indexed Trans. − 2ch [mm/m²]       | 26.4 ± 3.7     | (18.9, 33.9)  | 24.8 ± 3.8     | (17.2, 32.4)     | 28.0 ± 2.9     | (22.1, 33.9)     | <0.001     |
| Indexed Long. − 3ch [mm/m²]        | 34.2 ± 4.8     | (24.5, 43.8)  | 32.2 ± 4.1     | (23.9, 40.4)     | 36.1 ± 4.7     | (26.7, 45.4)     | <0.001     |
| Indexed AP − 3ch [mm/m²]           | 18.8 ± 3.8     | (11.3, 26.3)  | 16.7 ± 2.8     | (11.0, 22.3)     | 20.8 ± 3.4     | (14.0, 27.7)     | <0.001     |
| Indexed Long. − 4ch [mm/m²]        | 35.5 ± 4.4     | (26.8, 44.2)  | 33.8 ± 3.9     | (26.0, 41.7)     | 37.0 ± 4.2     | (28.7, 45.4)     | <0.001     |
| Indexed Trans. − 4ch [mm/m²]       | 25.7 ± 3.5     | (18.8, 32.7)  | 24.2 ± 2.8     | (18.6, 29.9)     | 27.1 ± 3.5     | (20.2, 34.1)     | <0.001     |

Table 3. Short axis vs. bi-plane area-length left atrial volume parameters in the whole group (n = 135). Lower/upper limits calculated as mean ± 2 SD; LAV, left atrial volume; LAVp, left atrial volume prior to atrial contraction; LAVmin, minimal left atrial volume; Indexed volumes are calculated by corresponding volume in ml divided by BSA in m²; Conduit EF, Conduit left atrial emptying fraction: 100% × (LAVmax − LAVp)/LAVmax; Booster pump EF, Booster pump left atrial emptying fraction: 100% × (LAVp − LAVp<sub>ac</sub>)/LAVp.<sup>ac</sup>; Total EF, total left atrial emptying fraction: 100% × (LAVmax − LAVmin)/LAVmax.

Table 4. Table showing the correlation between parameters measured by the SAX method and the bi-plane method. The correlation coefficients are shown, along with the P-values for the significance of the correlation.

Results

Subject Demographic Data. The demographic data of the 135 healthy volunteers are shown in the Table 1. The average age in this group was 49.9 ± 17.1 years, and 49% were males.

Normal Reference Values for LA. LA Dimensions. The normal LA dimensions and indexed values are shown in Table 2. Most dimensions showed no gender differences. The anterior-posterior dimension on the 3-ch view was greater in females than in males (31.1 ± 5.5 vs. 28.7 ± 5.3 mm, P = 0.011). The longitudinal diameter on 4-ch was shorter in females than in males (55.2 ± 6.0 vs. 57.9 ± 5.7 mm, P = 0.008). However, after indexing by BSA, the indexed LA diameters in females were slightly greater than those in males (All P < 0.001).

LA Volume and Phasic Function. The LA volume parameters are shown in Table 3. Correlations between parameters measured by the SAX method and the bi-plane method were moderate. Compared with the SAX method, the bi-plane method underestimated the LA volumes and overestimated the phasic function (all P < 0.001).
### Table 4. Gender specific short axis and bi-plane area-length reference values of LA volume and phasic function (n = 135). Lower/upper limits calculated as mean ± 2SD; LAVmax, maximal left atrial volume; LAVp-ac, left atrial volume prior to atrial contraction; LAVmin, minimal left atrial volume; Indexed volumes are calculated by corresponding volume in ml divided by BSA in m²; Conduit EF, Conduit left atrial emptying fraction; 100% × (LAVmax − LAVp-ac)/LAVmax; Booster pump EF, Booster pump left atrial emptying fraction: 100% × (LAVp-ac − LAVmin)/LAVp-ac; Total EF, total left atrial emptying fraction: 100% × (LAVmax − LAVmin)/LAVmax.

| Parameter                        | Total            | Male                          | Female                        | P (Male vs. Female) |
|----------------------------------|------------------|-------------------------------|-------------------------------|--------------------|
|                                 | Mean ± SD        | Lower/upper limits            | Mean ± SD                     | Lower/upper limits |
| LAVmax, in ml                   | 40.5 ± 8.3       | (23.9, 57.1)                 | 43.9 ± 8.2                    | (27.4, 60.4)       | 0.018 |
| Indexed LAVmax, in ml/m²        |                 |                               |                               |                    |
|                                 | 30.2 ± 7.7       | (14.8, 45.6)                 | 30.8 ± 7.5                    | (15.8, 45.7)       | 0.668 |
| Indexed LAVp-ac, in ml/m²       | 18.6 ± 4.8       | (9.0, 28.2)                  | 19 ± 4.2                      | (10.5, 27.4)       | 0.654 |
| Conduit EF, %                   | 26 ± 9           | (8, 44)                      | 30 ± 9                        | (13, 48)           | 0.004 |
| Booster pump EF, %              | 37 ± 10          | (17, 58)                     | 37 ± 10                       | (18, 57)           | 0.984 |
| Total EF, %                     | 54 ± 8           | (37, 70)                     | 57 ± 6                        | (44, 70)           | 0.028 |

### Table 5. Total and gender specific right atrial dimension parameters (mean ± SD, and reference range) (n = 135). Lower/upper limits calculated as mean ± 2SD; Long., Longitudinal dimension; Trans, Transverse dimension; AP, Antero-posterior dimension; 2ch, 2-chamber view; 3ch, 3-chamber view; 4ch, 4-chamber view; Indexed dimensions are calculated by corresponding dimensions in mm divided by BSA in m².

LA volumes in females were significantly lower than those in males, except for LAVmax (P = 0.119 for SAX method and 0.090 for bi-plane area-length method, all others P < 0.05, namely 0.009 for the LAVp-ac SAX method, 0.008 for the LAVmin SAX method, 0.004 for the LAVp-ac bi-plane area-length method, 0.020 for the LAVmin bi-plane area-length method) (Table 4). However, after indexing by BSA, most of the volume parameters were similar between genders (P = 0.668 for the indexed LAVp-ac SAX method, P = 0.654 for the indexed LAVmin SAX method, P = 0.096 for the indexed LAVmax bi-plane area-length method, P = 0.755 for the indexed LAVp-ac bi-plane area-length method, and P = 0.949 for the indexed LAVmax bi-plane area-length method), except for LAVmax by the SAX method (female vs. male: 43.9 ± 8.2 mL/m² vs. 40.5 ± 8.3 mL/m², P = 0.018). The LA conduit EF was greater in females than in males when measured by either the SAX method or the bi-plane method (P = 0.004 and 0.008, respectively), while there was no significant difference in booster pump EF and total LA EF (P = 0.984 for the booster pump EF by the SAX method, P = 0.372 for the booster pump EF by the bi-plane area-length method, P = 0.095 for the total EF by the bi-plane area-length method, and P = 0.654 for the total EF by the SAX method).

**Normal Reference for RA.** RA Dimensions. The linear RA dimensions measured on the 4-ch view and RV 2-ch view are shown in Table 5. The absolute RA dimensions were similar in males and females (P = 0.193 for
longitudinal diameter in 2-ch, P = 0.581 for longitudinal diameter in 4-ch, and P = 0.127 for transverse diameter in 2-ch, except P < 0.001 for the transverse dimension in 4-ch), while the indexed diameters were higher in females than in males (P < 0.001 for the indexed longitudinal diameter in 2ch and 4ch, P = 0.020 for the indexed transverse diameter in 4ch), except for the indexed transverse diameter in 2ch, where P = 0.087).

**RA Volume and Phasic Function.** The RA volume and phasic function data are shown in Table 6. Compared with the SAX method, the absolute volume and indexed volume measured by either single plane or bi-plane area-length methods were much lower (all P < 0.001). Correlations between the SAX and the area-length methods were moderate. The phasic functions of the RA were similar when assessed by the two methods (all P > 0.05), namely P = 0.278 for the conduit EF by the bi-plane area-length method vs. the SAX method, P = 0.209 for the total EF by the bi-plane area-length method vs. the SAX method, P = 0.064 for the conduit EF area-length in the 4ch method vs. the SAX method, P = 0.073 for the booster pump EF area-length in the 4ch method vs. the SAX method, P = 0.369 for the total EF area-length in the 4ch method vs. the SAX method, except P = 0.002 for the booster pump EF by the bi-plane area-length method vs. the SAX method). The absolute RA volume was larger in males than in females (All P < 0.001), and this difference persisted for a number of methods after indexing by BSA (P = 0.021 for indexed RAVp_ac by the SAX method, P = 0.001 for indexed RAVp_ac by the bi-plane area-length method, P = 0.005 for indexed RAVmin by the SAX method, P = 0.001 for indexed RAVmin by the bi-plane area-length method, P = 0.011 for indexed RAVmax area-length in the 4ch method, except for 0.070 for indexed RAVp_ac area-length in the 4ch method), except for the RV maximal volume index (P = 0.678 for indexed RAVmax by the SAX method, P = 0.181 for indexed RAVmax by the bi-plane area-length method, and P = 0.142 for indexed RAVmax by the SAX method) (Table 7). RA conduit EF and RA total EF were higher in females than in males by either method (for conduit EF, P = 0.003 by the SAX method, P < 0.001 by the bi-plane area-length method, and P < 0.001 by the area-length method in the 4-ch view; for total EF, P < 0.001 by the SAX method, P = 0.001 by the bi-plane area-length method, and P = 0.010 by the area-length method in the 4-ch view). The RA booster pump EF showed no gender difference (P = 0.092 by SAX, P = 0.152 by bi-plane area-length, and P = 0.660 by the area-length method in the 4-ch view).

**Age Related Changes in LA and RA parameters.** Correlations between age and parameters of LA or RA are shown in Table 8. Age was mildly to moderately correlated with the size of the LA and RA (R from 0.074 to 0.559). Age also correlated positively with LA volume (R = 0.329, 0.518, 0.259 for LAVmax, LAVp_ac, and LAVmin respectively, P < 0.001, <0.001, and <0.003, respectively), while it correlated only mildly with RA maximal volume (R = −0.220, 0.061, −0.092, and P = 0.111, 0.479, and 0.288, respectively). There was a negative correlation between age and atrial conduit EF, and a positive correlation between age and atrial booster pump EFs for both atria (All P < 0.001); however total EFs were not correlated with age (P = 0.568 for LA and P = 0.376 for RA).

| Parameter | Short axis method Mean ± SD | Lower/upper limits | Bi-plane area-length method Mean ± SD | Lower/upper limits | Area-length method (4-chamber) Mean ± SD | P (sax vs. bi-plane) | Pearson's Correlation P | Mean ± SD | Lower/upper limits | P (sax vs. 4ch) | Difference (Mean ± SE) Pearson's Correlation P | Mean ± SD | Lower/upper limits | P (sax vs. 4ch) | Difference (Mean ± SE) Pearson's Correlation P |
|-----------|-----------------------------|--------------------|--------------------------------------|--------------------|---------------------------------------------|-------------------|--------------------------|-------------------|--------------------|-------------------|-----------------------------------------------|-------------------|--------------------|-------------------|-----------------------------------------------|
| RAVmax, in ml | 82.7 ± 19.8 (43.2, 122.3) | 58.3 ± 18.5 (21.4, 95.2) | <0.001 24.1 ± 1 | 0.825 <0.001 | 59.6 ± 18.3 (22.9, 96.2) | <0.001 23.4 ± 1.3 | 0.699 <0.001 |
| RAVp_ac, in ml | 61.5 ± 16.8 (27.8, 95.2) | 43.8 ± 14.9 (14.7, 73.6) | <0.001 17.4 ± 0.9 | 0.786 <0.001 | 45.6 ± 16.2 (13.2, 78) | <0.001 16 ± 1.1 | 0.704 <0.001 |
| RAVmin, in ml | 40.3 ± 14.3 (11.6, 69) | 27.5 ± 10.5 (6.4, 48.6) | <0.001 12.5 ± 0.8 | 0.737 <0.001 | 28.9 ± 12.7 (3.5, 54.3) | <0.001 11.4 ± 1 | 0.636 <0.001 |
| Indexed RAVmax, in ml/m2 | 51.6 ± 11.0 (29.6, 73.6) | 36.3 ± 10.6 (15.2, 57.4) | <0.001 15.1 ± 0.6 | 0.797 <0.001 | 37 ± 10.3 (16.3, 57.6) | <0.001 14.7 ± 0.8 | 0.631 <0.001 |
| Indexed RAVp_ac, in ml/m2 | 38.2 ± 9.0 (20.2, 56.2) | 27.2 ± 8.4 (10.5, 43.9) | <0.001 10.8 ± 0.5 | 0.740 <0.001 | 28.2 ± 9.2 (9.9, 46.5) | <0.001 10 ± 0.7 | 0.631 <0.001 |
| Indexed RAVmin, in ml/m2 | 24.9 ± 7.7 (9.5, 40.4) | 17.0 ± 5.9 (5.2, 28.9) | <0.001 7.7 ± 0.5 | 0.691 <0.001 | 17.9 ± 7.3 (3.3, 32.5) | <0.001 7 ± 0.6 | 0.567 <0.001 |
| Conduit EF, % | 25 ± 10 (4.4, 66) | 25 ± 10 (4.4, 66) | 0.278 ± 0 | 0.539 <0.001 | 24 ± 10 (3.4, 44) | 0.064 ± 0 | 0.557 <0.001 |
| Booster pump EF, % | 35 ± 11 (13, 56) | 38 ± 8 (21, 55) | 0.002 ± 0 | 0.295 0.001 | 37 ± 11 (15, 59) | 0.073 ± 0 | 0.299 0.001 |
| Total EF, % | 52 ± 10 (32, 71) | 53 ± 9 (35, 72) | 0.209 ± 0 | 0.373 <0.001 | 52 ± 11 (30, 74) | 0.761 ± 0 | 0.369 <0.001 |

**Table 6.** Right atrial volume and phasic function parameters measured by the short axis or area-length method (n = 135). Lower/upper limits calculated as mean ± 2 SD; RAVmax, maximal right atrial volume; RAVp_ac, right atrial volume prior to atrial contraction; RAVmin, minimal right atrial volume; Indexed volumes are calculated by corresponding volume in ml divided by BSA in m²; Conduit EF, Conduit right atrial emptying fraction: 100% × (RAVmax − RAVp_ac)/RAVmax; Booster pump EF, Booster pump right atrial emptying fraction: 100% × (RAVp_ac − RAVmin)/RAVp_ac; Total EF, total right atrial emptying fraction: 100% × (RAVmax − RAVmin)/RAVmax.
Inter- and Intra-observer Variability. Inter-and intra-observer variability are shown in Tables 9, 10, and 11. Inter- and intra-observer variabilities in atrial dimensional parameters were moderate. Compared with the SAX method, variability was lower by the area-length method in RA 4-ch view, while it was greater by the bi-plane area-length method compared with other measuring methods.

Discussion

The present study provides comprehensive reference values for the atrial size and function assessed by the short axis or area–length method (n = 135). Lower-upper limits calculated as mean ± 2 SD; RAV max, maximal right atrial volume; RAV p, ac, right atrial volume before atrial contraction; RAV min, minimal right atrial volume; Indexed volumes are calculated by the corresponding volume in mL divided by BSA in m²; Conduit EF, Conduit right atrial emptying fraction: 100% × (RAV max − RAV p, ac)/RAV max; Booster pump EF, Booster pump right atrial emptying fraction: 100% × (RAV p, ac − RAV min)/RAV p, ac; Total EF, total right atrial emptying fraction: 100% × (RAV max − RAV min)/RAV max.

Table 7. Gender specific reference values of the RA volume and phasic function assessed by the short axis or area–length method (n = 135). Lower-upper limits calculated as mean ± 2 SD; RAV max, maximal right atrial volume; RAV p, ac, right atrial volume before atrial contraction; RAV min, minimal right atrial volume; Indexed volumes are calculated by the corresponding volume in mL divided by BSA in m²; Conduit EF, Conduit right atrial emptying fraction: 100% × (RAV max − RAV p, ac)/RAV max; Booster pump EF, Booster pump right atrial emptying fraction: 100% × (RAV p, ac − RAV min)/RAV p, ac; Total EF, total right atrial emptying fraction: 100% × (RAV max − RAV min)/RAV max.

Inter- and intra-observer variability are shown in Tables 9, 10, and 11. Inter- and intra-observer variabilities in atrial dimensional parameters were moderate. Compared with the SAX method, variability was lower by the area-length method in RA 4-ch view, while it was greater by the bi-plane area-length method compared with other measuring methods.

Discussion

The present study provides comprehensive reference values for the atrial size and function assessed by SSFP sequence in a population of healthy Chinese volunteers with a wide age range. In addition to providing normal reference standard values, we also found that the left or right atrial volume measured by area-length method was considerably lower than that produced by the SAX volume method, and gender and age have a considerable impact on atrial phasic function, especially on the conduit emptying function and booster pump function.

CMR is an accurate quantitative tool for ventricular and atrial volume and function, based on multi-slice 2D volume acquisition. The SSFP sequence has high signal-to-noise ratio, good myocardium-to-blood pool contrast, and is used routinely in a clinical setting. SSFP at 3.0T further improved the signal-to-noise contrast and could potentially have high spatial resolution to delineate thin-walled chambers. In recent years, new techniques, such as GRE shimming or short TR, have been introduced to increase the robustness of SSFP at 3.0T and could potentially have high spatial resolution to delineate thin-walled chambers. In recent years, new techniques, such as GRE shimming or short TR, have been introduced to increase the robustness of SSFP at 3.0T and could potentially have high spatial resolution to delineate thin-walled chambers. In recent years, new techniques, such as GRE shimming or short TR, have been introduced to increase the robustness of SSFP at 3.0T and could potentially have high spatial resolution to delineate thin-walled chambers.

Reference LA dimensions and volume have been studied in normal populations before. However, data derived from earlier sequences, such as TSE or GRE, are not truly comparable to SSFP sequences. Also, data acquired by SSFP sequence with prospectivI ECG gating not fully covering diastole are not comparable to retrospective ECG gating, which is the current routine in clinical practice. Therefore, very limited LA data could be comparable to our present study. We found the LA dimensions to be similar to those reported by Maceira, et al., e.g., the upper limit provided by the LA antero–posterior dimension in the Chinese population was 41 mm, comparable to the 42 mm for those of European descent. The LA absolute maximal volume in our study was lower than that reported for people of European descent, but was accounted for by the BSA. However, the LA maximal volume in our study was lower than that in the Singaporean Chinese population, even after adjusting by BSA (LA maximal volume index: 50 ± 10 mL/m² vs. 38.2 ± 10.1 mL/m²). The reason for this difference is unknown, as the sequence parameters, analysis methods used, and ethnicities of the study population are similar. Left atrial phasic function is a very interesting topic in cardiovascular disease. However, few previous studies showed normal references in healthy populations. The total LA EF in our study was similar to the data presented in the study by Marceira et al.
In addition, our study demonstrated gender specific LA phasic function systemically, which was not fully explored in previous studies. Few previous studies investigated RA size and volume. Accurate RA volume is difficult to estimate by 1D or 2D measurements. RA size, as measured by volume, was greater in males than in females, despite similar single dimension measurements in our study. Dimensions derived from the 4-ch view or RV 2-ch view were generally lower than those in previous data and the indexed dimensions were slightly higher than the indexed dimensions in people of European descent. In our study, absolute RA maximum volumes measured on short axis slices were lower than those measured in people of European descent; however, the indexed values were similar (51.6 ± 11.0 mL/m²; versus Sievers’s 52.8 ± 16.3 mL/m², and Maceira’s 54 ± 10.3 mL/m²). This was the first study to demonstrate the phasic function of RA in a normal population. A recent study showed that the RA

| Parameter | Correlation coefficient | P  |
|-----------|-------------------------|----|
| LA Long. – 2ch [mm] | 0.337 | <0.001 |
| LA Trans. – 2ch [mm] | −0.145 | 0.096 |
| LA Long. – 3ch [mm] | 0.559 | <0.001 |
| LA AP – 3ch [mm] | 0.207 | 0.016 |
| LA Long. – 4ch [mm] | 0.303 | <0.001 |
| LA Trans. – 4ch [mm] | 0.075 | 0.385 |

Table 8. Correlation between age and atrial parameters (all volume parameters were measured by the short axis method) (n = 135). Long., Longitudinal dimension; Trans, Transverse dimension; AP, Antero-posterior dimension; 2ch, 2-chamber view; 3ch, 3-chamber view; 4ch, 4-chamber view; LAV_max, maximal left atrial volume; LAV_p-ac, left atrial volume before atrial contraction; LAV_max, minimal left atrial volume; LA Conduit EF, Conduit left atrial emptying fraction; LA Booster EF, Booster left atrial emptying fraction; LA Total EF, total left atrial emptying fraction. RAV_max, maximal right atrial volume; RAV_p-ac, right atrial volume before atrial contraction; RAV_min, minimal right atrial volume; RA Conduit EF, Conduit right atrial emptying fraction; RA Booster EF, Booster right atrial emptying fraction; RA Total EF, total right atrial emptying fraction.

| Parameter | Intra-observer consistency (limits of agreement) | CoV  | Inter-observer Bias (limits of agreement) | CoV  |
|-----------|-----------------------------------------------|------|------------------------------------------|------|
| LA Long. – 2ch [mm] | 0.69 (0.41, 0.85) | 7.11 | 0.66 (0.36, 0.84) | 8.74 |
| LA Trans. – 2ch [mm] | 0.67 (0.40, 0.87) | 8.64 | 0.62 (0.34, 0.82) | 11.16 |
| LA Long. – 3ch [mm] | 0.91 (0.80, 0.96) | 3.63 | 0.81 (0.6, 0.91) | 5.81 |
| LA AP – 3ch [mm] | 0.69 (0.41, 0.85) | 8.78 | 0.59 (0.26, 0.80) | 10.60 |
| LA Long. – 4ch [mm] | 0.83 (0.64, 0.92) | 3.82 | 0.63 (0.32, 0.82) | 5.62 |
| LA Trans. – 4ch [mm] | 0.84 (0.67, 0.93) | 5.64 | 0.71 (0.44, 0.86) | 7.56 |
| RA Long. – 2ch [mm] | 0.76 (0.67, 0.86) | 10.59 | 0.66 (0.47, 0.79) | 9.52 |
| RA Trans. – 2ch [mm] | 0.91 (0.80, 0.96) | 18.97 | 0.86 (0.71, 0.94) | 8.74 |
| RA Long. – 4ch [mm] | 0.78 (0.56, 0.90) | 5.12 | 0.59 (0.26, 0.80) | 7.98 |
| RA Trans. – 4ch [mm] | 0.87 (0.72, 0.94) | 5.52 | 0.77 (0.53, 0.89) | 7.59 |

Table 9. Inter- and intra-variability of the atrial dimensions (n = 135). CoV, coefficient of variation. LA, left atrium; RA, right atrium; Long., Longitudinal dimension; Trans, Transverse dimension; AP, Antero-posterior dimension; 2ch, 2-chamber view; 3ch, 3-chamber view; 4ch, 4-chamber view.

(60 ± 8% vs. 59 ± 8%) In addition, our study demonstrated gender specific LA phasic function systemically, which was not fully explored in previous studies.

Few previous studies investigated RA size and volume. Accurate RA volume is difficult to estimate by 1D or 2D measurements. RA size, as measured by volume, was greater in males than in females, despite similar single dimension measurements in our study. Dimensions derived from the 4-ch view or RV 2-ch view were generally lower than those in previous data and the indexed dimensions were slightly higher than the indexed dimensions in people of European descent. In our study, absolute RA maximum volumes measured on short axis slices were lower than those measured in people of European descent; however, the indexed values were similar (51.6 ± 11.0 mL/m²; versus Sievers’s 52.8 ± 16.3 mL/m², and Maceira’s 54 ± 10.3 mL/m²). This was the first study to demonstrate the phasic function of RA in a normal population. A recent study showed that the RA
emptying fraction was an independent and robust indicator for mortality in patients with pulmonary hypertension. This study suggested the potential importance of RA phasic function evaluation in future studies.

While SAX method is considered the gold standard for measuring atrial volume without geometric assumption, the area-length method is a simple alternative. Previous comparisons of these two methods based on small normal populations showed good correlation with the LA volume. Our study validated the area-length method further in a Chinese population and demonstrated that the area-length method gives a reasonable estimation of LA volume, although the absolute volume is lower than the true volume, as measured by the SAX method. Left atrial conduit function estimated by the SAX method was significantly higher than that estimated by the area-length method. Therefore, the LA volume and function derived by the area-length method should be interpreted cautiously, especially when these parameters are the main indications for the CMR examination in patients with cardiac remodelling. In contrast to the LA, area-length methods for estimating the RA volume have not been studied in depth. In our study, neither the area-length of the 4-ch nor the bi-plane area-length from 4-ch could estimate the RA volume accurately. The RA volume was underestimated remarkably by the area-length method. Therefore, the LA volume and function derived by the area-length method should be interpreted cautiously, especially when these parameters are the main indications for the CMR examination in patients with cardiac remodelling.

In summary, in the present study, we investigated the reference values of the left and right atrial dimension, volume, and phasic function using the state of art SSFP sequence at 3.0T MRI in a healthy Chinese population. The SAX method provided more accurate values for the atrial volume and showed better reproducibility than the area-length method. However, the area-length method is preferred.

| Parameter | Short axis method | Bi-plane area-length method | Area-length method (4-chamber) |
|-----------|------------------|-----------------------------|-------------------------------|
|           | Intra-observer consistency (limits of agreement) | CoV | Intra-observer Bias (limits of agreement) | CoV | Intra-observer consistency (limits of agreement) | CoV | Inter-observer Bias (limits of agreement) | CoV |
| LAV_{max}, in ml | 0.97 (0.93, 0.99) | 3.40 | 0.89 (0.76, 0.95) | 5.89 | 0.77 (0.53, 0.89) | 8.84 | 0.77 (0.54, 0.89) | 8.79 |
| LAV_{p-ac}, in ml | 0.92 (0.83, 0.97) | 6.49 | 0.86 (0.7, 0.94) | 9.33 | 0.87 (0.72, 0.94) | 8.41 | 0.88 (0.75, 0.95) | 8.43 |
| LAV_{min}, in ml | 0.94 (0.87, 0.97) | 6.18 | 0.89 (0.77, 0.95) | 8.65 | 0.93 (0.84, 0.97) | 8.68 | 0.85 (0.67, 0.93) | 11.71 |

Table 10. Inter- and intra-variability in left atrial volumes (n = 135). LAV_{max}, maximal left atrial volume; LAV_{p-ac}, left atrial volume before atrial contraction; LAV_{min}, minimal left atrial volume.

| Parameter | short axis method | Bi-plane area-length method | Area-length method (4-chamber) |
|-----------|------------------|-----------------------------|-------------------------------|
|           | Intra-observer consistency (limits of agreement) | CoV | Intra-observer Bias (limits of agreement) | CoV | Intra-observer consistency (limits of agreement) | CoV | Inter-observer Bias (limits of agreement) | CoV |
| RAV_{max}, in ml | 0.94 (0.87, 0.96) | 6.94 | 0.93 (0.84, 0.97) | 7.50 | 0.90 (0.78, 0.96) | 8.33 | 0.88 (0.75, 0.95) | 8.88 |
| RAV_{p-ac}, in ml | 0.78 (0.56, 0.90) | 15.72 | 0.77 (0.53, 0.9) | 17.42 | 0.85 (0.66, 0.93) | 14.68 | 0.86 (0.69, 0.94) | 14.18 |
| RAV_{min}, in ml | 0.86 (0.69, 0.94) | 15.18 | 0.84 (0.67, 0.93) | 16.44 | 0.82 (0.61, 0.93) | 20.43 | 0.76 (0.49, 0.9) | 22.76 |

Table 11. Inter- and intra-variability in right atrial volumes (n = 135). RAV_{max}, maximal right atrial volume; RAV_{p-ac}, right atrial volume before atrial contraction; RAV_{min}, minimal right atrial volume.
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**Author Contributions**

W.H.L. and H.L. designed the study, analysed the images and the data, and drafted the manuscript cooperatively. Y.C.H. reviewed the data and contributed to the critical revision of the manuscript. K.W. recruited the volunteers, and analysed and interpreted the data. W.C. and J.Y.S. acquired the scans for all the patients in the study, was involved in the acquisition of data and gave valuable advice on the content. Y.L. recruited the volunteers, and analysed and interpreted the data. Y.-C.C. was involved in the critical revision of the manuscript. Y.C.C. conceived the study design, analysed the images, interpreted the data, and drafted the manuscript. All authors read and approved the final manuscript.

**Additional Information**

**Competing Interests:** The authors declare that they have no competing interests.

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