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Comparison of right atrial volume measurements using single-plane area-length and stack-of-short-axis methods: A 3.0 T cardiac magnetic resonance study

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Abstract

Purpose The stack-of-short-axis volumes (SAX) summation and single-plane area-length (AL) methods are established approaches for right atrial (RA) volume quantification in cardiovascular magnetic resonance (CMR) imaging. However, data regarding the reliability and agreement between these methods are limited. Furthermore, there is no validation on whether to include the right atrial appendage (RAA) in the analysis. This study aims to evaluate the reliability of the single-plane AL and SAX methods for measuring RA volumes and to assess the agreement between these two approaches.

Methods CMR (3.0T, Siemens) data from 40 healthy volunteers were analyzed to quantify RA volumes, both including and excluding RAA volume, using the SAX and single-plane (4-chamber view) AL methods.

Results The mean age of 40 participants was 33.6 ± 6.1 years (50% male). RA volumes measured by the SAX method were significantly larger than those obtained by the single-plane AL method (maximum RA volume including RAA: 84.9 ± 22.9 vs. 63.7 ± 16.0 ml, p-value < 0.001; minimum RA volume including RAA: 45.3 ± 15.9 vs. 34.7 ± 12.2 ml, p-value < 0.001). RA ejection fraction (RAEF) was the only parameter that showed no statistical difference between the two methods. Bland-Altman plots demonstrated poor agreement between the techniques, with substantial biases and wide limits of agreement. Both methods exhibited excellent reproducibility when the RAA volume was included (ICC = 0.89–0.96). However, reproducibility was reduced when the RAA volume was excluded, particularly in terms of inter-observer agreement (ICC = 0.73–0.96).

Conclusions The single-plane AL method underestimates RA volumes compared to the SAX method, and the poor agreement between the two techniques suggests they should not be used interchangeably. RA volume

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measurements should be interpreted using method-specific reference values. Additionally, including the RAA in RA volume quantification—regardless of the method—may improve measurement reproducibility.

Keywords Cardiac magnetic resonance, Right atrium volume, Single-plane area-length, Stack-of-short-axis

Background

Right atrial (RA) volume and right atrial ejection fraction (RAEF) are important predictors of various diseases, including pulmonary hypertension, heart failure, and atrial arrhythmias [1–5]. Accurate measurement of RA volume is therefore useful in evaluating patients with cardiopulmonary diseases. Cardiovascular magnetic resonance imaging (CMR) is considered the gold standard for cardiac chamber quantification, including RA volume. The two CMR techniques for RA volume quantification are the stack-of-short-axis volumes (SAX) summation and the single-plane area-length (AL) methods. The SAX method is regarded as the reference standard since it directly measures absolute RA volume, but it is time-consuming and requires whole-heart imaging [6, 7]. In contrast, the single-plane AL method, which only requires RA area and length measured from a 4-chamber (4CH) view and relies on geometric assumptions to estimate RA volume, is less complicated [8, 9].

Although the single-plane AL method is frequently employed in routine clinical practice, data on its agreement and reliability compared to the SAX method are limited and sometimes conflicting [10, 11]. Moreover, there is no consensus on whether to include or exclude the right atrial appendage (RAA) volume in RA measurements. This study aims to assess the agreement between the single-plane area-length (AL) and stack-of-short-axis (SAX) methods for right atrial volume measurement, with a particular emphasis on the impact of including or excluding the right atrial appendage (RAA) in resolving discrepancies and improving measurement reliability.

Methodology

Forty healthy volunteers (20 for each gender) were prospectively recruited to undergo a CMR scan with 3.0T Magnetom Vida (Siemens Healthineers, Erlangen, Germany), at King Chulalongkorn Memorial Hospital. The inclusion criteria were: (i) age 18 years or older, (ii) BMI range from 18.5 to 29.9 kg/m^2, (iii) no known underlying disease and cardiovascular risk factors, and (iv) normal blood tests in the previous year. The exclusion criteria were: (i) pregnancy, (ii) claustrophobia, (iii) metallic implantation, and (iv) structural abnormality on the CMR findings. Baseline demographics, including age, gender, body mass index (BMI), body surface area (BSA), and CMR parameters, were collected. The study protocol was approved by the institutional ethics committee (IRB No. 0498/67, COA No. 1187/2024). All volunteers were informed and provided consent prior to recruitment.

CMR protocol

All CMR images were acquired using a scanner equipped with an 18-channel cardiac phased array receiver. The non-contrast CMR protocol included localizer sequences and bright-blood axial images covering the thoracic inlet to the upper abdomen. All cine images were acquired using a standard retrospective ECG-gated, end-expiratory breath-hold technique. In contrast to conventional segmented cine sequences, our protocol employed compressed sensing (CS) acceleration to enable faster acquisition with preserved image quality (short-axis views: TR = 3.1 ms, TE = 1.26 ms, flip angle = 35 degrees, field of view = 320 × 242.7 mm, matrix size = 166 × 240, voxel size = 1.6 × 1.6 × 8.0 mm^3, acceleration factor = 8.4 and long-axis views: TR = 3.1 ms, TE = 1.37 ms, flip angle = 56 degrees, field of view = 320 × 242.5 mm, matrix size = 181 × 256, voxel size = 1.3 × 1.3 × 6.0 mm^3, acceleration factor = 9.5). The resulting temporal resolution was approximately 31 ms for both views. The read-out for cine images was True Fast Imaging with Steady-State Free Precession (TRUFI). The long-axis cine images included 2-chamber (2CH), 3-chamber (3CH), and 4-chamber (4CH) views. The short-axis cine images covered from the atrial roof to the ventricular apex (8-mm slice thickness without a gap between slices). The short-axis plane was aligned parallel to the atrioventricular groove and perpendicular to the interatrial and interventricular septum. The short-axis image scan time was approximately 44 s, while the long-axis image acquisition took around 2 s. Image reconstruction was completed in less than 15 s.

Post-processing CMR analysis

The post-processing software, Syngo.via (Siemens Healthineers, Erlangen, Germany), was used to analyze all CMR images. The endocardial borders of the right ventricle (RV), left ventricular (LV), and LV epicardium were manually traced in the whole-heart short-axis cine images during LV end-diastolic and LV end-systolic phases to quantify their volumes and ejection fractions [12, 13]. Papillary muscles and trabeculation were included in the ventricular chamber volume.

For RA volume quantification using the SAX method, the endocardial borders of the RA were manually traced from the whole-heart short-axis cine images during the LV end-diastolic and LV end-systolic phases to evaluate the minimum and maximum RA volume, respectively (Fig. 1A-D). Fig. S1 demonstrates how the RA border was contoured in each SAX slice. For the single-plane

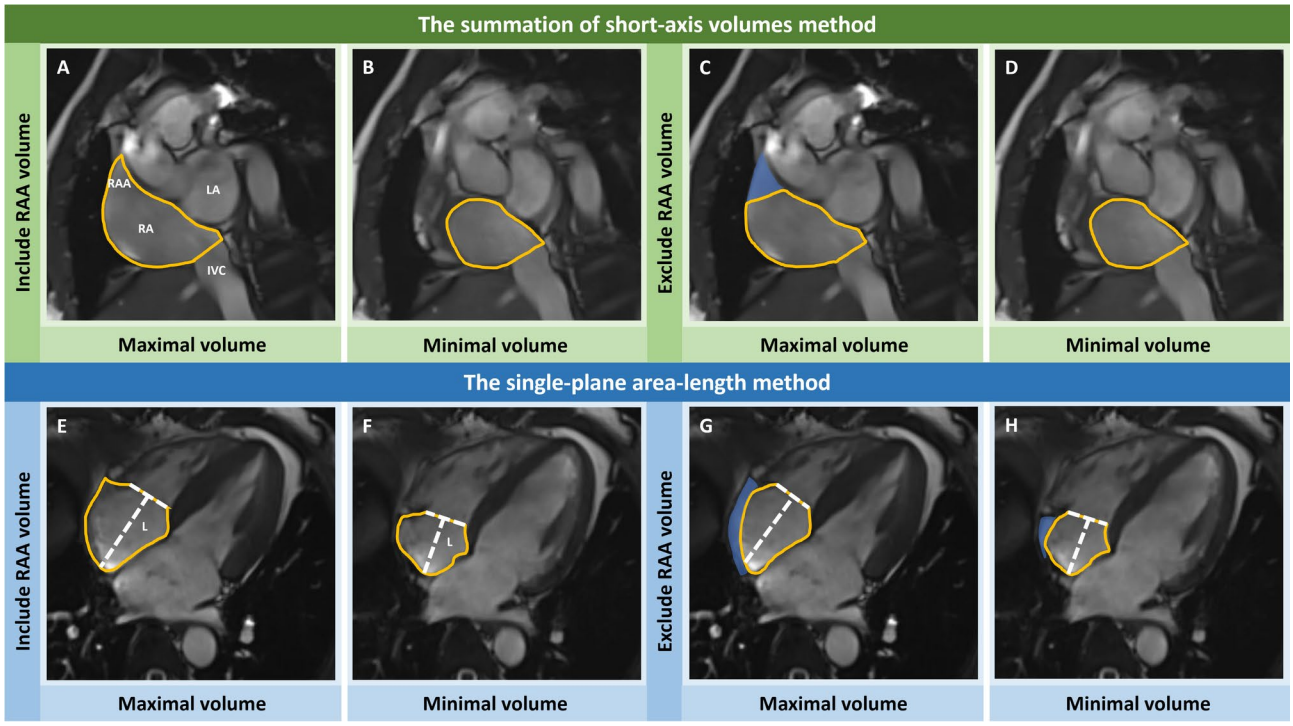

Fig. 1 Illustration of right atrial volume measurement methods. Upper row: RA volume measurement with the summation of stacking short-axis volumes method, including (**A** and **B**) and excluding (**C** and **D**) RAA. Lower row: RA volume measurement with the single-plane area-length method, including (**E** and **F**) and excluding (**G** and **H**) RAA. RA longitudinal diameter (L) was drawn at the midpoint of the tricuspid annulus to the RA roof (white dot line). The blue shady area represented excluded RAA. L, length; RA, right atrium; RAA, right atrial appendage; IVC, inferior vena cava

AL method, the RA longitudinal diameter (RA length, L) was measured from the midpoint of the line between the lateral and septal insertion of the tricuspid valve to the RA roof in the 4CH view. The RA endocardial border was delineated to obtain the maximum and minimum RA area (RA area, A) during LV end-systolic and end-diastolic phases, respectively (Fig. 1E-H). RA volume was calculated using the formula " $\frac{8 \times A^2}{3\pi L}$ ", where A is the RA area and L is the RA length from the 4CH view [8, 14, 15]. The superior vena cava (SVC) and inferior vena cava (IVC) were excluded from the RA volume by placing a straight line at their ostium. Two sets of volumetric measurements were performed, one including and one excluding the RAA volume, by placing a straight line at the RAA ostium (Figure 1).

Two cardiac imaging specialists, N.N. (3 years of experience) and N.T. (7 years of experience), independently measured the RA volumes to assess inter-rater reproducibility. Measurements using the AL and SAX methods were performed at least one week apart. Inter-observer variation was tested between the two assessors, and intra-observer variation was evaluated by having the first assessor re-measure the RA volumes after a one-month interval.

Statistical analysis

Continuous variables were presented as means with standard deviations (SD). Data distribution was assessed using the Shapiro-Wilk test. Comparison and agreement between the two measurement methods were assessed using paired t-tests and Bland-Altman plots, respectively. Independent t-test was used to compare data between female and male participants. Inter-observer and intra-observer variations were assessed using the intraclass correlation coefficient (ICC) with a two-way random-effects model, correlation coefficients (Pearson's r), and coefficients of variation (CoV). ICC values > 0.80 indicated excellent agreement, while values between 0.61 and 0.80 indicated substantial agreement. A two-sided $p < 0.05$ was considered statistically significant. All statistical analyses were performed using SPSS 25.0 (IBM Corporation, Armonk, New York).

Results

Of 40 healthy participants, the mean age was 33.6 ± 6.1 years and 50% were male. The mean BMI and BSA were 22.7 ± 3.2 kg/m^2 and 1.7 ± 0.2 m^2, respectively. The mean left ventricular ejection fraction (LVEF) was 55.8 ± 3.2%, and the mean right ventricular ejection fraction (RVEF) was 57.5 ± 5.9%. Full details of the conventional LV and RV parameters are provided in Table 1.

Table 1 Baseline characteristics and CMR parameters (*N* = 40)

	Total (*N* = 40)	Female (*n* = 20)	Male (*n* = 20)
Age (year)	33.6 ± 6.1	33.5 ± 6.6	33.8 ± 5.8
Body weight, kg	63.20 ± 10.57	56.30 ± 8.65	70.10 ± 7.38
Height, cm	166.80 ± 7.92	161.30 ± 5.50	172.30 ± 5.90
Body mass index (kg/m^2)	22.7 ± 3.2	21.6 ± 3.2	23.7 ± 2.9
Body surface area (m^2)	1.7 ± 0.2	1.6 ± 0.1	1.8 ± 0.1
LV parameters			
LVEDV (ml)	138 ± 27.4	120 ± 20.5	156 ± 20.3
Indexed LVEDV (ml/m^2)	81 ± 12.0	75 ± 10.0	86 ± 11.5
LVESV (ml)	61 ± 13.1	53 ± 10.8	69 ± 9.9
Indexed LVESV (ml/m^2)	36 ± 5.7	33 ± 5.2	38 ± 5.3
LVSV (ml)	77 ± 15.7	67 ± 11.1	87 ± 12.5
Indexed LVSV (ml/m^2)	45 ± 7.3	42 ± 6.1	48 ± 7.3
LVCO (l/min)	5.1 ± 0.9	4.7 ± 0.8	5.5 ± 0.8
LVCi (l/min/m^2)	3.0 ± 0.5	3.0 ± 0.5	3.0 ± 0.5
LVEF (%)	55.8 ± 3.2	55.8 ± 3.4	55.7 ± 3.0
Indexed LVM (g/m^2)	46 ± 8.7	41 ± 4.3	52 ± 8.1
RV parameters			
RVEDV, ml	132.4 ± 30.8	108.8 ± 16.8	156.0 ± 22.3
Indexed RVEDV (ml/m^2)	77.2 ± 13.7	68.6 ± 8.9	85.7 ± 12.4
RVESV (ml)	57.1 ± 15.1	43.5 ± 10.2	70.7 ± 14.7
Indexed RVESV (ml/m^2)	33.1 ± 9.0	27.4 ± 5.9	38.8 ± 8.0
RVSV (ml)	75.3 ± 2.4	65.3 ± 9.7	85.3 ± 12.8
Indexed RVSV (ml/m^2)	44.0 ± 6.9	41.2 ± 5.3	46.9 ± 7.4
RVCO (l/min)	5.0 ± 0.9	4.6 ± 0.8	5.4 ± 0.9
RVCi (l/min/m^2)	2.9 ± 0.5	2.9 ± 0.5	3.0 ± 0.5
RVEF, %	57.5 ± 5.9	60.2 ± 5.2	54.8 ± 5.3

Data are presented as mean ± SD

LV, left ventricle; LVCO, left ventricular cardiac output; LVCi, left ventricular cardiac output index; LVEDV, left ventricular end-diastolic volume; LVEF, left ventricular ejection fraction; LVESV, left ventricular end-systolic volume; LVSV, left ventricular stroke volume; RV, right ventricle; RVCO, right ventricular cardiac output; RVCi, right ventricular cardiac output index; RVEDV, right ventricular end-diastolic volume; RVEF, right ventricular ejection fraction; RVESV, right ventricular end-systolic volume; RVSV, right ventricular stroke volume

All RA variables were normally distributed, as confirmed by the Shapiro-Wilk test. The volumes, classified by gender and measuring methods, are shown in Table 2. RA volumes measured by the SAX method, both with and without RAA, were significantly larger than those obtained using the single-plane AL method (maximum volume including RAA: 76.9 ± 17.9 vs. 55.2 ± 13.3 ml for females, p-value < 0.001; and 92.9 ± 24.9 vs. 72.3 ± 14.0 ml for males, p-value < 0.001; minimal volume including RAA: 39.6 ± 15.0 vs. 26.8 ± 9.1 ml for females, p-value = 0.001; and 51.0 ± 15.0 vs. 42.7 ± 9.6 ml for males, p-value = 0.016). Similar findings were observed after indexing the RA volumes with BSA (indexed maximum volume including RAA: 48.0 ± 9.7 vs. 34.7 ± 8.1 ml/m^2 for females, p-value < 0.001; and 50.7 ± 12.6 vs. 39.5 ± 7.2 ml/m^2 for males, p-value < 0.001; indexed minimal volume including RAA: 24.6 ± 8.1 vs. 16.8 ± 5.4 ml/m^2 for females, p-value = 0.001; and 28.0 ± 8.2 vs. 23.3 ± 4.9 ml/m^2 for males, p-value = 0.015). RA volumes with RAA exclusion are shown in Table 2. The only parameter that did not differ significantly between the methods was RAEF (49.8 ± 8.1 vs. 51.9 ± 11.3% for females, p-value = 0.453; and 44.8 ± 8.7 vs. 40.0 ± 12.3% for males, p-values = 0.181).

To explore potential physiological influences on RA volume, we analyzed correlations with age and BMI (Supplementary Table S1). The results showed no significant correlation between age and RA volumes or RAEF ($p > 0.05$ for all comparisons). In contrast, BMI demonstrated a significant positive correlation with RA maximum and minimum volumes for both including and excluding RAA conditions ($p < 0.05$ for all comparisons).

Regarding sex differences, females had significantly smaller absolute RA volumes than males, as measured by both the SAX and single-plane AL methods. By the SAX method, RA volumes were lower in females compared to males (maximum volume including RAA: 76.9 ± 17.9 vs. 92.9 ± 24.9 mL, $p = 0.025$; minimum volume including RAA: 39.6 ± 15.0 vs. 51.0 ± 15.0 mL, $p = 0.021$; maximum volume excluding RAA: 68.1 ± 16.5 vs. 85.4 ± 23.3 mL, $p = 0.010$; minimum volume excluding RAA: 36.1 ± 14.3 vs. 48.4 ± 14.5 mL, $p = 0.010$). Similarly, using the AL method, females also had significantly smaller RA volumes (maximum volume including RAA: 55.2 ± 13.3 vs. 72.3 ± 14.0 mL, $p < 0.001$; minimum volume including RAA: 26.8 ± 9.1 vs. 42.7 ± 9.6 mL, $p < 0.001$; maximum volume excluding RAA: 45.9 ± 10.2 vs. 61.7 ± 12.3 mL, $p < 0.001$; minimum volume excluding RAA: 20.8 ± 7.1 vs. 35.7 ± 9.2 mL, $p < 0.001$).

However, when RA volumes were indexed to body surface area, significant sex differences were observed only with the AL method. Indexed RA volumes by the AL method were significantly lower in females compared to males (maximum indexed volume including RAA: 37.1 ± 7.9 vs. 39.7 ± 8.2 mL/m², $p = 0.052$; minimum indexed volume including RAA: 16.8 ± 5.4 vs. 23.3 ± 4.9 mL/m², $p < 0.001$; maximum indexed volume excluding RAA: 28.0 ± 6.4 vs. 34.3 ± 6.2 mL/m², $p = 0.003$; minimum indexed volume excluding RAA: 13.1 ± 4.3 vs. 19.5 ± 4.8 mL/m², $p < 0.001$) (Table 2).

Bland-Altman plots demonstrated substantial biases and wide limits of agreement (LoA) between the two methods, both with and without the inclusion of the RAA. The AL method consistently underestimated RA volumes, as reflected by the positive mean biases. For RA volumes including RAA, the mean biases were 21.15 ml (LoA: -14.56 to 56.85 ml) for maximum volume and 10.55 ml (LoA: -18.22 to 39.33 ml) for minimum volume. When RAA was excluded, the biases were 23.27 ml (LoA: -7.64 to 54.17 ml) and 13.97 ml (LoA: -10.16 to 38.10 ml) for maximum and minimum volumes, respectively (Figure 2). The scatterplots illustrate the moderate

Table 2 Right atrial chamber quantifications ($N=40$)

	Stack-of-short-axis method				Single-plane area-length method				*p*-value **
	Total ($n=40$)	Female ($n=20$)	Male ($n=20$)	*p*-value*	Total ($n=40$)	Female ($n=20$)	Male ($n=20$)	*p*-value*	
Include RAA									
RA maximum volume, ml	84.9 ± 22.9	76.9 ± 17.9	92.9 ± 24.9	0.025	63.7 ± 16.0	55.2 ± 13.3	72.3 ± 14.0	< 0.001	< 0.001
Indexed RA maximum volume, ml/m^2	49.4 ± 11.1	48.0 ± 9.7	50.7 ± 12.6	0.452	37.1 ± 7.9	34.7 ± 8.1	39.5 ± 7.2	0.052	< 0.001
RA minimum volume, ml	45.3 ± 15.9	39.6 ± 15.0	51.0 ± 15.0	0.021	34.7 ± 12.2	26.8 ± 9.1	42.7 ± 9.6	< 0.001	< 0.001
Indexed RA minimum volume, ml/m^2	26.3 ± 8.2	24.6 ± 8.1	28.0 ± 8.2	0.193	20.1 ± 6.1	16.8 ± 5.4	23.3 ± 4.9	< 0.001	< 0.001
RAEF, %	47.3 ± 8.7	49.8 ± 8.1	44.8 ± 8.7	0.066	45.9 ± 13.1	51.9 ± 11.3	40.0 ± 12.3	0.003	0.547
Exclude RAA									
RA maximum volume, ml	76.8 ± 21.8	68.1 ± 16.5	85.4 ± 23.3	0.010	53.5 ± 14.2	44.5 ± 10.3	62.5 ± 11.6	< 0.001	< 0.001
Indexed RA maximum volume, ml/m^2	44.6 ± 10.5	42.6 ± 9.0	46.6 ± 11.7	0.228	31.1 ± 7.0	28.0 ± 6.4	34.3 ± 6.2	0.003	< 0.001
RA minimum volume, ml	42.2 ± 15.5	36.1 ± 14.3	48.4 ± 14.5	0.010	28.3 ± 11.1	20.8 ± 7.1	35.7 ± 9.2	< 0.001	< 0.001
Indexed RA minimum volume, ml/m^2	26.3 ± 8.2	22.4 ± 7.5	26.5 ± 7.6	0.92	16.3 ± 5.6	13.1 ± 4.3	19.5 ± 4.8	< 0.001	< 0.001
RAEF, %	45.7 ± 8.7	48.4 ± 9.0	43.1 ± 7.9	0.058	48.1 ± 11.7	53.5 ± 10.4	42.7 ± 10.6	0.002	0.267

Data are presented as mean ± SD

* p-value for females vs. males

** p-value for overall stack-of-short-axis vs. single-plane area-length methods

RA, right atrium; RAA, right atrial appendage; RAEF, right atrial ejection fraction

correlation between RA volumes measured by the two methods (Fig. S2).

When RAA was included in the RA volume analysis, the intra-observer agreements for RA maximum and minimum volumes, as demonstrated by the ICC, were 0.939 (0.525, 0.987) and 0.957 (0.838, 0.989), respectively, for the SAX method, and 0.945 (0.581, 0.988) and 0.914 (0.643, 0.979), respectively, for the single-plane AL method. The inter-observer agreements for RA maximum and minimum volumes also showed excellent agreement, with ICC values ranging between 0.892 and 0.960 for both methods. However, when RAA was excluded, only the intra-observer agreements remained excellent, with ICC values ranging between 0.893 and 0.956 for both methods, while the inter-observer agreements were slightly compromised, with ICC values ranging from 0.733 to 0.897 for both methods (Table 3). We further assessed the reproducibility of RA volume measurements correlation coefficients and CoV for both intra- and inter-observer analyses. Overall, reproducibility was higher when the right atrial appendage (RAA) was included in volume measurements. For the stack-of-short-axis method, the inclusion of the RAA yielded lower inter-observer CoV (maximum volume: 9.67% vs. 13.76%; minimum volume: 27.13% vs. 23.72%) and comparable Pearson's r values (maximum volume: 0.97 vs. 0.96; minimum volume: 0.84 vs. 0.93). Similarly, for the single-plane area-length method, the inclusion of the RAA improved inter-observer CoV (13.45% vs. 18.29% for maximum volume; 21.70% vs. 27.88% for minimum volume) and showed modestly higher Pearson's r values (Table 4).

Discussion

This study provides additional normal data on RA volumes in healthy Asian participants, measured using two common CMR techniques: the standard SAX and single-plane AL methods. Our findings showed that the absolute and indexed RA volumes measured with the SAX method were larger than those measured with the single-plane AL method. However, there was no significant difference in the RAEF. Bland-Altman plots demonstrated poor agreement between both methods. Furthermore, to our knowledge, this study is the first to validate that including the RAA in the RA volume analysis provides superior inter- and intra-observe agreements, regardless of the method used.

Studies comparing RA volume measurements using the SAX and AL methods are scarce and vary in measurement techniques (e.g., including or excluding the RAA and using single-plane or biplane AL methods). In addition, the results of these publications are discrepant. One study with the 1.5T CMR showed that the RA volume and RAEF (including RAA but excluding caval veins) measured with the single-plane AL from the 4CH view were larger than those measured with the SAX method (103.2 ± 32.6 vs. 101.0 ± 30.2 ml for maximum volume, p-value < 0.001; 50.8 ± 20.2 vs. 50.3 ± 19 ml for minimum volume, p-value = 0.126; and 51.4 ± 9.2% vs. 47.2 ± 8.3% for RAEF, p-value < 0.001) [10]. On the other hand, Li et al. demonstrated that the RA volume (excluding RAA and not mentioning caval veins) measured with the single-plane AL from the 4CH view and the biplane AL from the 4CH and RV-2CH views were significantly lower than those measured with the SAX method, with RAEF being similar among the three methods [11]. The boundary of the tricuspid valve is more difficult to identify using the

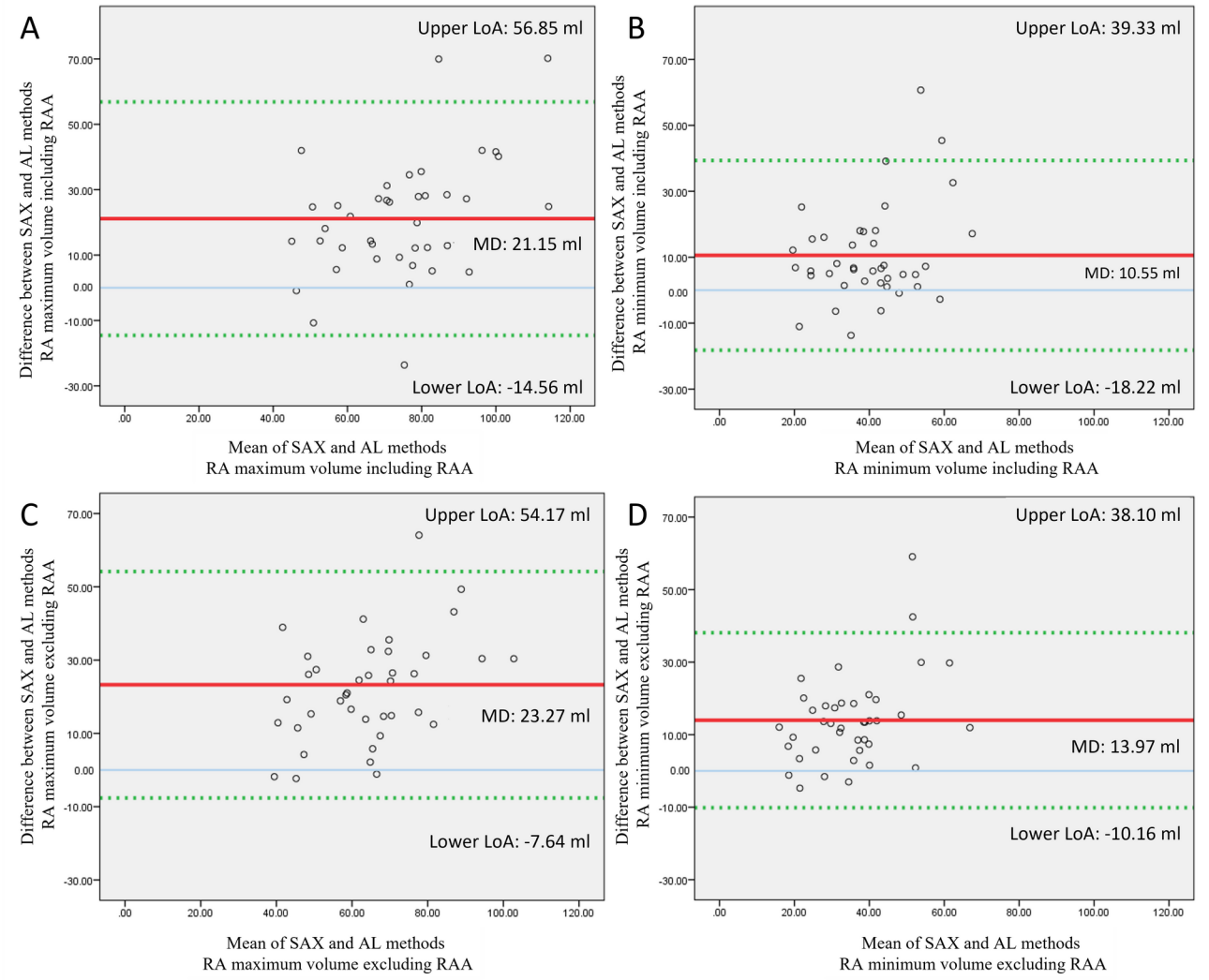

Fig. 2 Bland-Altman plots comparing RA volume measurements by SAX and AL methods (**A**) RA maximum volume including RAA; (**B**) RA minimum volume including RAA; (**C**) RA maximum volume excluding RAA; (**D**) RA minimum volume excluding RAA. The red solid line represents the mean difference (bias), and the green dotted lines indicate the upper and lower limits of agreement (LoA). AL, area-length method; LoA, limits of agreement; MD, mean difference; RA, right atrium; RAA, right atrial appendage; SAX, short-axis stack method

Table 3 Intra-observer and inter-observer variation of right atrial volumes

	Stack-of-short-axis method		Single-plane area-length method	
	Intra-observer variation (95% CI)	**Inter-observer variation (95% CI)**	**Intra-observer variation (95% CI)**	**Inter-observer variation (95% CI)**
Include RAA				
RA maximum volume	0.939 (0.525, 0.987)	0.960 (0.493, 0.992)	0.945 (0.581, 0.988)	0.892 (0.406, 0.975)
RA minimum volume	0.957 (0.838, 0.989)	0.896 (0.581, 0.974)	0.914 (0.643, 0.979)	0.896 (0.601, 0.974)
Exclude RAA				
RA maximum volume	0.938 (0.568, 0.986)	0.897 (-0.059, 0.981)	0.893 (0.205, 0.977)	0.733 (-0.240, 0.943)
RA minimum volume	0.956 (0.830, 0.989)	0.757 (-0.224, 0.950)	0.936 (0.736, 0.984)	0.848 (0.433, 0.961)

Data are presented as the mean of ICC (lower CI, upper CI)

CI, confidence interval; ICC, intraclass correlation coefficient; RA, right atrium; RAA, right atrial appendage

Table 4 Intra- and inter-observer coefficient of variation and correlation coefficient

	Stack-of-short-axis method				Single-plane area-length method			
	Intra-observer		Inter-observer		Intra-observer		Inter-observer	
	CoV (%)	Pearson (*r*)	CoV (%)	Pearson (*r*)	CoV (%)	Pearson (*r*)	CoV (%)	Pearson (*r*)
Including RAA								
RA maximum volume	13.67	0.93	9.67	0.97	8.91	0.95	13.45	0.89
RA minimum volume	20.02	0.92	27.13	0.84	20.20	0.83	21.70	0.81
Excluding RAA								
RA maximum volume	14.65	0.93	13.76	0.96	12.83	0.90	18.29	0.82
RA minimum volume	20.46	0.93	23.72	0.93	20.54	0.87	27.88	0.77

CoV, coefficient of variation; RA, right atrial; RAA, right atrial appendage; RAEF, right atrial ejection fraction

SAX method than with the AL method, which could explain the discrepancies in RA volumes measured by the SAX method. Our findings aligned with those of the later study. The Asian populations included in our study and the later study, with identical BSA, provide a plausible explanation for the similar findings. Furthermore, the RA volumes and RAEF measured by the single-plane AL method in both studies resemble those from a large-scale CMR study involving healthy adults in China [16]. In the first-mentioned study, the absolute RA volumes measured with the SAX method were higher than those in our study; however, after normalizing for BSA, the indexed RA volumes were comparable. These findings support the external validity of RA volume quantification using CMR.

The current study demonstrated that females had smaller RA volumes irrespective of the measurement methods; however, indexed RA volumes were smaller only when measured with the single-plane AL method. These results are consistent with findings from previous studies and confirmed that RA volumes are influenced by gender and BSA, with females showing smaller volumes regardless of the methods used [11, 16]. In contrast, the left atrial (LA) ejection fraction and RAEF were lower in males [6, 11, 16, 17].

The single-plane AL method is more feasible and commonly used in routine clinical practice and various clinical studies [4, 16, 18]. However, our findings indicate that the single-plane AL method significantly underestimates RA volumes compared to the SAX method, with poor agreement between the two techniques. A key reason for this discrepancy is that the AL method relies on geometric assumptions, originally developed for echocardiography, which may not accurately reflect true atrial volume. Similar limitations have been observed in studies of LA volume, where the SAX method consistently produces higher volume estimates than either the single-plane or biplane AL methods [19, 20]. These findings suggest that simplified geometric models may systematically underestimate atrial volume in both the right and left atria. Additionally, the optimal imaging plane for accurate atrial volume quantification may not align with the standard 4CH view, particularly for the RA. Given this discrepancy, the two methods should not be used interchangeably. Moreover, RA volumes should always be specified and reported with reference to the method used (e.g., SAX or AL methods and whether the RAA was included or excluded). Follow-up CMR studies should maintain consistency in measurement techniques to ensure reliable comparisons.

To the best of our knowledge, this is the first study to directly compare RA chamber quantification with and without RAA inclusion in CMR. Our findings suggest that including RAA in the RA volume measurement yielded higher reproducibility, as demonstrated by intra- and inter-observer variation. In contrast, excluding the RAA results in lower ICC values and a wider 95% confidence interval, particularly for inter-observer variation. Our additional reproducibility analysis using correlation coefficients and CoV further reinforces the benefit of including the RAA in RA volume measurements. Including the RAA consistently improved inter-observer agreement, as reflected by lower CoV across both the stack-of-short-axis and single-plane area-length methods. The overall reproducibility patterns suggest that more anatomically complete atrial volume assessments (i.e., including the RAA) enhance measurement reliability. Since the anatomical landmark of the RAA ostium is difficult to identify, the straight line used for RAA exclusion may vary with each measurement, making RA volume quantification from this method less reliable. Therefore, the RAA volume should be included in the RA volume measurement, regardless of whether the SAX or single-plane AL methods are used.

Several limitations of this study should be noted. First, cine images in this study were acquired using a retrospective ECG-gated, end-expiratory breath-holding CS technique instead of the conventional segmented breath-hold technique. Although the CS technique can sometimes result in unclear endocardial borders, many studies have shown that the breath-holding CS technique is both accurate and reliable, with good agreement in volumetric parameters when compared to standard segmented cine images [21–24]. Additionally, the range of RA volumes

measured in our study is consistent with those reported in prior studies [11, 16], further supporting the reliability of the CS technique used in this study. Second, this study did not assess the biplane AL method, which has shown a good correlation with the SAX method for LA volume quantification [25]. Unlike the biplane AL method for the LA, which can be evaluated using standard 2CH and 4CH views, the biplane AL method for RA requires a specialized RV-2CH view, leading to additional scan time. Hence, we decided to assess the single-plane AL method, which is a more practical technique for routine clinical use. We acknowledge that accurate RA volume quantification in the 4CH view may be affected by inter-examination variation in plane selection, particularly since the atrial axis is not specifically targeted during standard imaging acquisition. However, this limitation reflects real-world clinical conditions, where RA planning is not routinely performed. Third, our study focused on volume quantification techniques rather than evaluating physiological relevance. We did not assess functional indices such as RA reservoir, or conduit functions, which may provide additional clinical context. Fourth, due to the limited age range of the participants, the association between RA volumes and age was not assessed. Lastly, the current study focused on healthy volunteers; therefore, the results may not be generalizable to populations with specific health conditions [26]. Further studies are encouraged to explore these findings in patients with various diseases.

Conclusion

The single-plane AL method consistently underestimates RA volumes compared to the SAX method, with poor agreement between the two techniques. Due to this significant discrepancy, the two methods should not be used interchangeably. RA volume quantification should be interpreted using method-specific reference values, and the chosen measurement technique should be clearly specified in the CMR report. Additionally, the same technique should be used consistently in longitudinal or follow-up studies. Finally, including the RAA in RA volume quantification is recommended, as it improves reproducibility across assessments.

Abbreviation

2CH	Two chamber
3CH	Three chamber
4CH	Four chamber
AL	Area-length
BMI	Body mass index
BSA	Body surface area
CMR	Cardiovascular magnetic resonance imaging
CS	Compressed sensing
ECG	Electrocardiography
ICC	Intraclass correlation coefficient
IVC	Inferior vena cava
LV	Left ventricle
RA	Right atrium
RAA	Right atrial appendage
RAEF	Right atrial ejection fraction
SAX	Stack-of-short-axis volumes
SD	Standard deviations
SVC	Superior vena cava

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Supplementary Material 3

Supplementary Material 4

Supplementary Material 5

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Author contributions

N.N. and A.Sa. wrote the manuscript and created the figure. N.T. and P.C. were responsible for the study design. N.N., P.S., A.Su. and N.T. were involved in the data collection. N.N. and N.T. performed data analysis. A.Sa., Y.V., M.T., P.C., and N.T. were responsible for data acquisition, supervision, generated the topic of the manuscript, and took responsibility for its content. All authors have read and approved the final manuscript.

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Data availability

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at King Chulalongkorn Memorial Hospital.

Ethical approval

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki. The protocols were approved by the Faculty of Medicine, Chulalongkorn University ethical committees for research involving human subjects, and all subjects provided informed consent.

Consent for publication

No identifiable individual information was included in this study.

Informed consent

was obtained from all individual participants included in the study.

Competing interests

The authors declare no competing interests.

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