

Reference Values for Pediatric Atrial Volumes Assessed by Steady-State Free-Precession Magnetic Resonance Imaging Using Monoplane and Biplane Area-Length Methods

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Background: Measurement of atrial volumes by MRI is becoming increasingly important in pediatric cardiac disorders. However, MRI normal values for atrial volumes in children are lacking.

Purpose: To establish pediatric reference values for atrial volumes.

Study Type: Retrospective.

Subjects: A total of 155 healthy children from two large institutions (103 male, age 13.9 ± 2.8 years, range 4–18 years).

Field Strength/Sequence: A 1.5 T; balanced steady-state free precession (bSSFP) sequence.

Assessment: The monoplane and biplane area-length methods were used to measure minimal and maximal left and right atrial volumes (LA_{\min} , LA_{\max} , RA_{\min} , and RA_{\max}) from four-chamber (4ch) and two-chamber (2ch) MR cine images. Centile charts and tables for atrial volumes were created.

Statistical Tests: Descriptive statistics, lambda-mu-sigma (LMS)-method of Cole and Green, univariable and multivariable linear regression models. A P value < 0.05 was considered to be statistically significant.

Results: In the multivariable linear model, body surface area was significantly associated with all atrial volumes and sex was significantly associated with RA volumes, LA volumes measured in the 2ch-view as well as biplane LA_{\max} . Average atrial volumes measured: monoplane 4ch: LA_{\min} 13.1 ± 4.8 mL/m², LA_{\max} 33.4 ± 8.8 mL/m², RA_{\min} 18.5 ± 6.8 mL/m², RA_{\max} 33.2 ± 9.6 mL/m²; monoplane 2ch: LA_{\min} 12.7 ± 4.9 mL/m², LA_{\max} 30.5 ± 9.5 mL/m²; biplane: LA_{\min} 12.3 ± 4.5 mL/m², LA_{\max} 30.9 ± 8.7 mL/m².

Data Conclusion: Pediatric MRI reference values for atrial volumes have been provided.

Technical Efficacy: 2

Evidence Level: 4

J. MAGN. RESON. IMAGING 2023;57:532–542.

View this article online at wileyonlinelibrary.com. DOI: 10.1002/jmri.28230

Received Feb 28, 2022, Accepted for publication Apr 27, 2022.

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Atrial size and function are gaining increasing importance in the prognostic assessment of various cardiac conditions.^{1–3} This is not only true for conditions that mainly develop in adulthood but also for diseases in the pediatric population.^{4–6}

MRI is well suited for the assessment of cardiac volumes and mass⁷ and is considered the reference standard for the measurement of ventricular volumes and systolic function.⁸ MRI also allows assessment of atrial volumes, typically by using the Simpson's or the faster biplane area-length method,^{9,10} and the measurement of atrial size and ejection fraction from MR images is increasingly used in routine clinical practice. In this context, normal values are of importance and several publications with reference values for atrial volumes and function in the adult population exist.^{10–13} However, atrial reference values for children and adolescents are sparse and have been derived from transaxial cine stacks using the Simpson's method.⁹ The Simpson's method is likely to be more accurate, although there is no final consensus in the literature regarding the measurement method as stated in a recently published review on normal values.¹⁴ However, measuring atrial volumes from a transaxial or short axis cine stack with the Simpson's method is more time-consuming and requires more experience from the observer compared to the biplane-area length method. In addition, a study by Nacif et al showed that left atrial (LA) volumes derived from the biplane-area length method correlated well with LA volumes measured with the Simpson's method.¹⁵

Thus, the aim of this study was to establish pediatric reference values for atrial volumes and function. Specifically, by using the area-length method, it was our goal to provide reference values that would allow a fast assessment in daily clinical routine.

Methods

Study Population

A general informed consent for the use of routinely acquired clinical data for retrospective research studies was available for all parents or legal guardians, as appropriate.

The study was approved by the local ethics committee and was performed in accordance with the Declaration of Helsinki.

In a retrospective study-design, 155 MR data sets from healthy individuals with an age-range between 4 and 18 years (103 male; mean age 13.9 ± 2.8 years) were evaluated. A histogram showing the patients age and sex is shown in Fig. 1. Weight was 55.2 ± 15.0 kg (male: 55.3 ± 15.3 kg, female: 54.9 ± 13.6 kg), height was 162.3 ± 16.0 cm (male: 163.1 ± 18.2 cm, female: 160.7 ± 10.4 cm), BSA was 1.6 ± 0.3 m² (male: 1.6 ± 0.3 m², female: 1.6 ± 0.2 m²), and heart rate was 74.2 ± 13.1 beats per minutes (male: 73.6 ± 14.3 beats per minute, female: 75.6 ± 10.3 beats per minute). Children between 0 and 18 years, who were scheduled for a clinical MRI scan, were included. Most children were of Caucasian ethnicity. Indications for MRI were described previously by our group¹⁶ and included: 1) nondiagnostic echocardiographic examination, 2) uncertainty about the cardiac anatomy and myocardial structure on echocardiography, 3) syncope or 4) chest pain with low prescan probability of being cardiac in origin. MRI and clinical findings as well as clinical follow-up did not show any evidence for a cardiovascular pathology. In all children, MRI and clinical follow-up data demonstrated normal cardiac findings.

Exclusion criteria were any kind of congenital or acquired heart disease, arterial hypertension, intake of antihypertensive medication or any other disease that may lead to structural or functional alterations of the heart. All probands were in sinus rhythm. Body surface area (BSA) was calculated

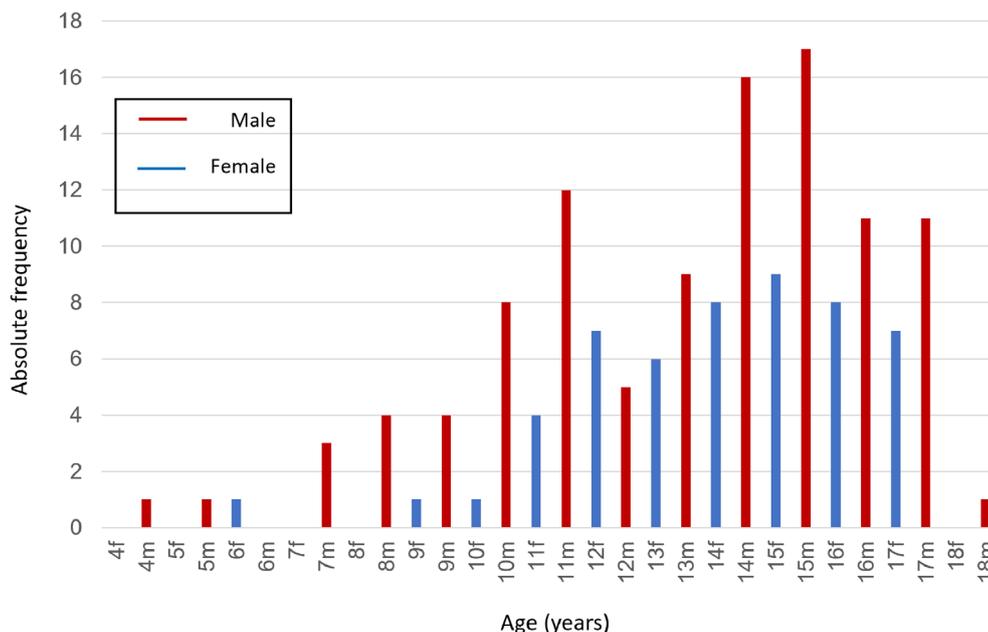


FIGURE 1: Histogram of patient age and sex is shown. f = female; m = male.

	All (<i>n</i> = 155) Mean ± SD	Males (<i>n</i> = 103) Mean ± SD	Females (<i>n</i> = 52) Mean ± SD
Age (years)	13.9 ± 2.8	13.6 ± 3.0	15.9 ± 2.3
Weight (kg)	55.2 ± 15.0	55.3 ± 15.8	54.9 ± 13.6
Height (cm)	162.3 ± 16.0	163.1 ± 18.2	160.7 ± 10.4
BSA (m ²)	1.6 ± 0.3	1.6 ± 0.3	1.6 ± 0.2
Heart rate (1/min)	74.2 ± 13.1	73.6 ± 14.3	75.6 ± 10.3

BSA = body surface area; SD = standard deviation.

using the Mosteller formula.¹⁷ Characteristics of the study population are shown in Table 1.

Magnetic Resonance Imaging

MRI studies were performed with a 1.5 T scanner (Magnetom Avanto fit and Magnetom Aera, Siemens Healthcare GmbH, Erlangen, Germany) using a balanced

steady-state free precession (bSSFP) sequence. A total of 145 MRI data sets were acquired at one center and 10 data sets at the other site. Four-chamber (4ch-) and 2-chamber (2ch-) ECG-gated cine images were acquired retrospectively with the following sequence parameters: echotime (TE) 1.04–1.37 msec, repetition time (TR) 31.44–86.7 msec, field of view (FOV) 96 mm–440 mm, matrix size 192 × 156 mm,

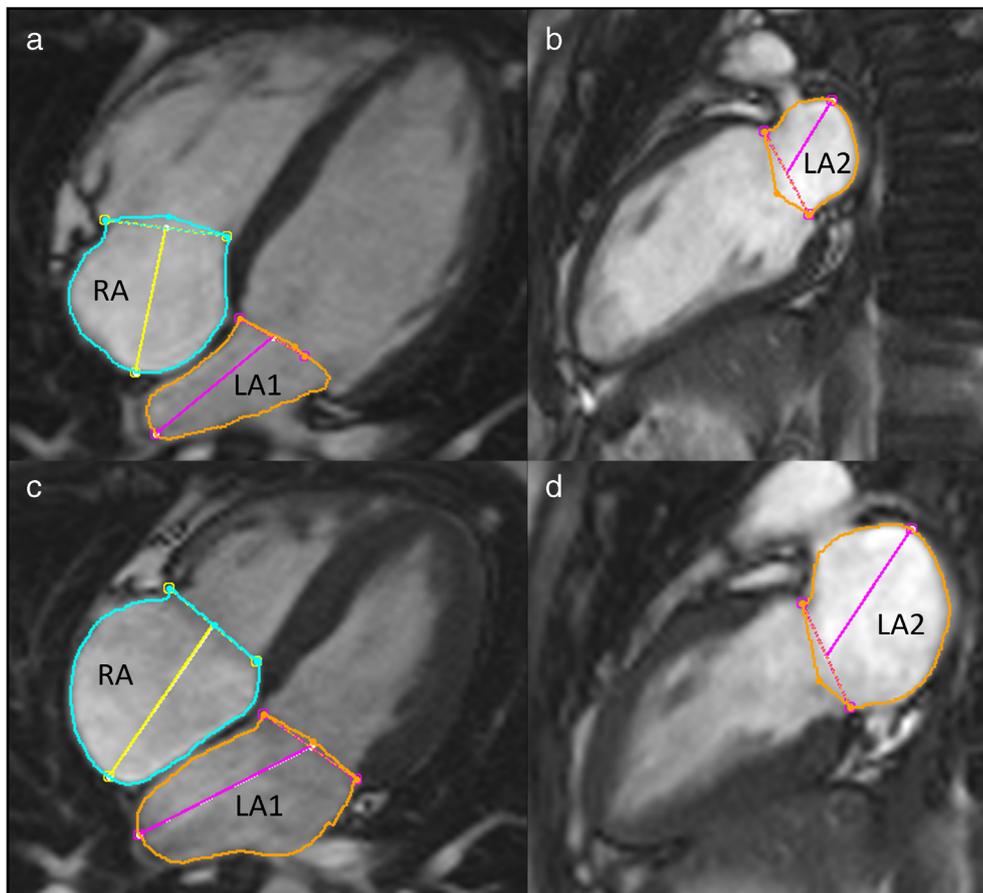


FIGURE 2: The upper row shows the measurement of minimal monoplane right atrial volumes (RA; a) and minimal biplane left atrial volumes (LA1 and LA2; a,b). The lower row shows the measurement of maximal monoplane RA volumes (c) and maximal biplane LA volumes (LA1 and LA2; c,d). The pink and yellow lines represent the length of the left and right atrium. The following formulas were used: (a) biplane area-length formula for the measurement of left atrial volumes²⁷: $8/3\pi[(LA1)(LA2)/L]$.²⁷ LA1 and LA2 are the areas of the left atrium in the 4-chamber and 2-chamber view. L is the shortest length of either LA1 or LA2. (b) Monoplane area-length formula for the measurement of right atrial volumes²⁷: $8(RA)^2/3\pi L$.

TABLE 2. Left and Right Atrial Volumes

	All (<i>n</i> = 155) Mean ± SD	Males (<i>n</i> = 103) Mean ± SD	Females (<i>n</i> = 52) Mean ± SD
LA _{min} 4ch (mL/m ²)	13.1 ± 4.8	13.3 ± 6.6	12.7 ± 5.1
LA _{max} 4ch (mL/m ²)	33.4 ± 8.8	34.3 ± 8.9	31.5 ± 8.4
RA _{min} 4ch (mL/m ²)	18.5 ± 6.8	19.9 ± 7.3	15.9 ± 4.8
RA _{max} 4ch (mL/m ²)	33.2 ± 9.6	35.0 ± 10.0	29.6 ± 7.4
LA _{min} 2ch (mL/m ²)	12.7 ± 4.9	13.1 ± 5.3	11.8 ± 4.2
LA _{max} 2ch (mL/m ²)	30.5 ± 9.5	31.2 ± 10.4	28.5 ± 8.1
LA _{min} biplane (mL/m ²)	12.3 ± 4.5	12.4 ± 4.8	11.8 ± 4.1
LA _{max} biplane (mL/m ²)	30.9 ± 8.7	31.4 ± 9.9	29.3 ± 7.0

Results are expressed as mean and standard deviation (SD).
4ch = four-chamber; LA_{max} = maximal volume of the left atrium; LA_{min} = minimal volume of the left atrium; 2ch = two-chamber.

number of segments 13, slice thickness 7–8 mm (in children below 9 years of age 5 mm), interslice gap 0 mm, 25–30 phases per heart cycle, breath-hold technique.

MR Image Analysis

MRI data sets were analyzed with the software cvi42 (Version 5.12.1, Circle Cardiovascular Imaging Inc., Calgary, Alberta, Canada). All measurements were carried out by one observer with 1–2 years of experience in cardiac MRI (SH) and reviewed by a pediatric cardiologist with 15 years of experience in cardiac MRI (IV). If necessary, changes by the pediatric cardiologist (IV) were made.

LA and right atrial (RA) endocardial contours were drawn on 4ch-views at the times in the cardiac cycle when the atria reached the maximum and minimum size. Maximal and minimal atrial volumes (LA_{min}, LA_{max}, RA_{min}, and RA_{max}) were then automatically calculated by the software using the monoplane area-length method. By using the combination of a 4ch- and a 2ch-view, LA_{min} and LA_{max} were also estimated using the biplane area-length method (Fig. 2). Endocardial contouring was performed semi-automatically with manual correction. Atrial appendages and pulmonary veins were excluded from the atrial volume creating smooth contours along atrial cavities.

To determine interobserver variability, 25 randomly chosen data sets were analyzed by an independent observer (S.B.G.) with 3 years of experience.

Statistical Analysis

Statistical analysis was performed using the software R, version 3.6.2¹⁸ and MedCalc (MedCalc Software Ltd, Ostend, Belgium). All tests were performed two-sided, and the significance level was set at 0.05. Normal distribution was assessed

with a Shapiro–Wilk test. Parametric tests were used because data were normally distributed.

The influence of sex, BSA, age, height, and weight on atrial measurements was analyzed using Pearson's correlation coefficient (*r*) as well as univariable and multivariable linear models, with and without interactions. Backward model selection was performed with a *P* value threshold of 0.05.

Reference curves were created using the LMS (lambda-mu-sigma) method.¹⁹ If sex showed an influence in the multivariable linear models, these curves were sex specific. Otherwise, curves were generated for girls and boys together. For the present analysis, the extended version of this method in the R package gamlss was used.²⁰

To assess interobserver variability, intraclass correlation coefficients (ICC) were calculated.

Results

Mean volumes of the left and right atrium are shown in Table 2.

Results from statistical analysis showed strong significant correlations between atrial volumes and age, BSA, body weight, and body height. In the univariable linear analyses, age, BSA, weight, and height were significantly correlated with LA and RA volumes (Table 3). Sex had a significant effect on RA volumes, LA volumes measured in the 2ch-view and LA_{max} derived from the biplane area-length method (Table 3). In the multivariable linear model, BSA remained significantly associated with all atrial variables, while only LA_{max} measured in the 4-ch-view was significantly associated with height and weight. Sex remained significantly associated with RA volumes, LA volumes measured in the 2ch-view and biplane LA_{max} but not LA_{max} and LA_{min} measured in the 4-ch view as well as biplane LA_{min} (Tables 3).

TABLE 3. Results From Univariable and Multivariable Linear Regression Analysis

Influence Variable	Correlation Coefficient*	Regression Coefficient	Standard Error	P Value
LA_{min} 4ch				
Sex (reference male)	NA	-1.58	1.55	0.31
BSA	0.54	17.51	2.20	<0.001
Body height	0.56	0.32	0.038	<0.001
Body weight	0.49	0.29	0.043	<0.001
Age	0.45	1.48	0.24	<0.001
LA_{max} 4ch				
Sex (reference male)	NA	-5.54	3.05	0.072
BSA	0.63	40.78	4.03	<0.001
Body height	0.63	0.71	0.071	<0.001
Body weight	0.59	0.71	0.078	<0.001
Age	0.51	3.29	0.45	<0.001
RA_{min} 4ch				
Sex (reference male)	NA	-7.17	2.21	0.0015
BSA	0.61	29.24	3.05	<0.001
Body height	0.60	0.50	0.054	<0.001
Body weight	0.57	0.51	0.059	<0.001
Age	0.50	2.38	0.34	<0.001
RA_{max} 4ch				
Sex (reference male)	NA	-9.53	3.29	0.0043
BSA	0.61	46.86	4.26	<0.001
Body height	0.60	0.77	0.079	<0.001
Body weight	0.57	0.83	0.082	<0.001
Age	0.50	3.66	0.49	<0.001
LA_{min} 2ch				
Sex (reference male)	NA	-3.35	1.51	0.029
BSA	0.54	17.33	2.18	<0.001
Body height	0.52	0.29	0.039	<0.001
Body weight	0.51	0.30	0.042	<0.001
Age	0.39	1.25	0.24	<0.001
LA_{max} 2ch				
Sex (reference male)	NA	-6.76	3.09	0.030
BSA	0.61	39.85	4.18	<0.001
Body height	0.56	0.64	0.077	<0.001
Body weight	0.59	0.71	0.080	<0.001
Age	0.43	2.81	0.48	<0.001
LA_{min} biplane				
Sex (reference male)	NA	-2.42	1.42	0.090
BSA	0.58	17.19	1.96	<0.001

TABLE 3. Continued

Influence Variable	Correlation Coefficient*	Regression Coefficient	Standard Error	P Value
Body height	0.58	0.30	0.034	<0.001
Body weight	0.53	0.29	0.038	<0.001
Age	0.44	1.32	0.22	<0.001
LA _{max} biplane				
Sex (reference male)	NA	-6.27	2.89	0.032
BSA	0.67	40.47	3.68	<0.001
Body height	0.63	0.67	0.068	<0.001
Body weight	0.63	0.72	0.072	<0.001
Age	0.49	2.99	0.43	<0.001

Influence variables that remained significant in the multivariable linear model are shown in bold.

BSA = body surface area; 4ch = four-chamber; LA_{max} = maximal volume of the left atrium; LA_{min} = minimal volume of the left atrium; 2ch = two-chamber.

*Pearson correlation coefficient.

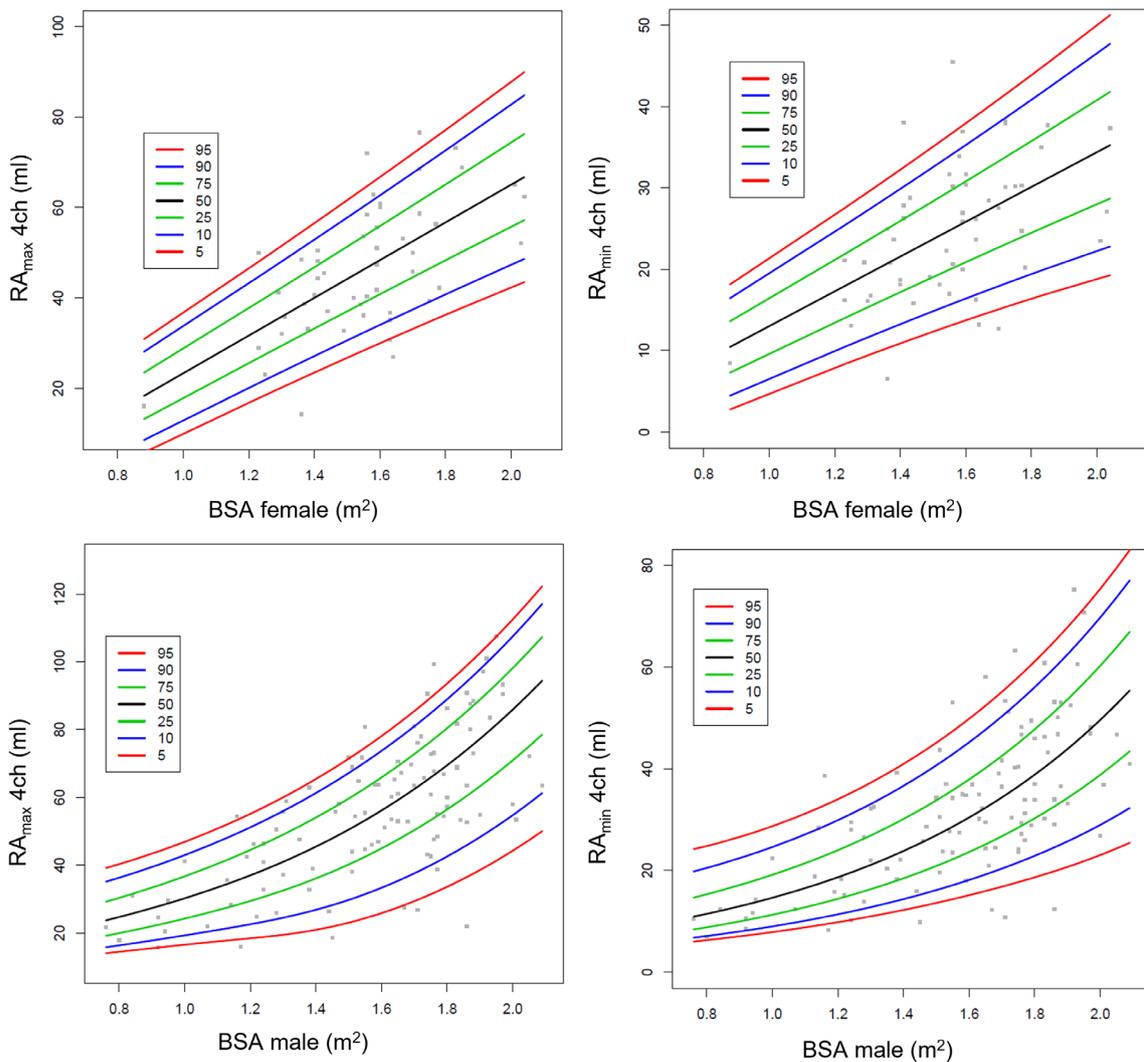


FIGURE 3: Sex-specific centile graphs for RA_{max} derived from 4-chamber (4ch) views.

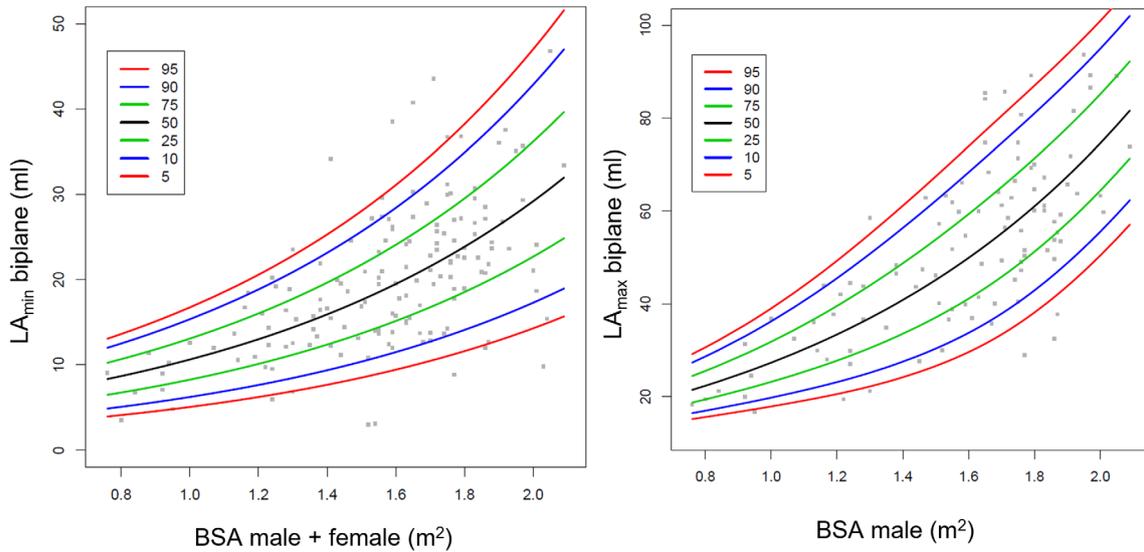


FIGURE 4: Sex-specific centile graphs for LA_{min} and LA_{max} measured by the biplane area-length method.

TABLE 4. Centiles (C) of the RA_{min} (in mL) for Girls

BSA (m^2)	C5	C10	C25	C50	C75	C90	C95
1	4.71	6.55	9.61	13.02	16.43	19.49	21.33
1.1	6.32	8.27	11.53	15.16	18.79	22.05	24
1.2	7.89	9.97	13.44	17.3	21.16	24.63	26.71
1.3	9.41	11.63	15.33	19.44	23.55	27.25	29.47
1.4	10.9	13.26	17.2	21.58	25.96	29.9	32.26
1.5	12.34	14.85	19.05	23.72	28.38	32.58	35.09
1.6	13.74	16.42	20.89	25.86	30.83	35.3	37.98
1.7	15.09	17.94	22.7	28	33.29	38.06	40.91
1.8	16.39	19.42	24.5	30.14	35.78	40.85	43.89
1.9	17.63	20.86	26.27	32.28	38.28	43.69	46.92
2	18.81	22.26	28.02	34.42	40.81	46.57	50.02

As BSA was significantly associated with all atrial volumes, centile curves, and tables were created with regard to BSA (Figs. 3 and 4, Supplementary Fig. S1; Tables 4–9, Supplementary Tables S1–S5).

For LA_{min} measured in the 2-ch-view and LA_{max} derived from the biplane method, no convergence was achieved for females; therefore, the results are only shown for males.

Indexed RA volumes and indexed LA volumes measured in the 4-ch-view and indexed biplane LA_{min} correlated significantly with age. Indexed LA volumes measured in the 2-ch-view and indexed biplane LA_{max} did not correlate with age (LA_{min} [2ch]: $r = 0.11$, $P = 0.13$; LA_{max} [2ch]: $r = 0.12$, $P = 0.13$; biplane LA_{max} : $r = 0.16$, $P = 0.05$).

Interobserver variability was good for the following parameters: LA_{min} (4ch), ICC = 0.84, LA_{max} (4ch), ICC = 0.88, LA_{min} (2ch), ICC = 0.85 and LA_{min} (biplane), ICC = 0.87. Excellent interobserver variability was found for RA_{min} (ICC = 0.94), RA_{max} (ICC = 0.95), LA_{max} (2ch) (ICC = 0.92), and LA_{max} (biplane) (ICC = 0.92).

Discussion

Pediatric MRI normal values are important for clinical interpretations. In this study, we analyzed volumes of the left and right atrium in a large cohort of healthy children using the biplane and monoplane area length-method and provided corresponding reference values.

TABLE 5. Centiles (C) of the RA_{min} (in mL) for Boys

BSA (m ²)	C5	C10	C25	C50	C75	C90	C95
0.8	6.27	7.09	8.8	11.44	15.3	20.48	24.79
0.9	7.02	7.97	9.95	12.93	17.1	22.4	26.57
1	7.85	8.97	11.26	14.61	19.13	24.59	28.69
1.1	8.78	10.09	12.73	16.51	21.41	27.07	31.16
1.2	9.81	11.35	14.41	18.65	23.97	29.88	34.01
1.3	10.94	12.76	16.3	21.07	26.86	33.06	37.26
1.4	12.2	14.34	18.44	23.81	30.11	36.64	40.94
1.5	13.59	16.12	20.87	26.91	33.77	40.67	45.12
1.6	15.11	18.11	23.61	30.41	37.89	45.2	49.83
1.7	16.79	20.35	26.72	34.36	42.53	50.31	55.14
1.8	18.63	22.86	30.24	38.83	47.75	56.05	61.11
1.9	20.68	25.7	34.24	43.88	53.64	62.5	67.84
2	23.01	28.95	38.8	49.61	60.27	69.77	75.41

TABLE 6. Centiles (C) of the RA_{max} (in mL) for Girls

BSA (m ²)	C5	C10	C25	C50	C75	C90	C95
1	9.92	12.88	17.82	23.31	28.8	33.74	36.7
1.1	13.37	16.49	21.7	27.48	33.27	38.48	41.6
1.2	16.78	20.07	25.56	31.66	37.76	43.25	46.54
1.3	20.15	23.61	29.4	35.84	42.27	48.06	51.52
1.4	23.47	27.12	33.23	40.01	46.79	52.9	56.55
1.5	26.74	30.59	37.03	44.19	51.34	57.78	61.63
1.6	29.96	34.03	40.82	48.36	55.91	62.7	66.76
1.7	33.13	37.42	44.58	52.54	60.49	67.65	71.94
1.8	36.25	40.77	48.32	56.71	65.1	72.66	77.18
1.9	39.31	44.08	52.04	60.89	69.74	77.7	82.47
2	42.31	47.33	55.73	65.06	74.4	82.79	87.82

The measurement of atrial volumes has gained increasing importance in the treatment and follow-up of various cardiac diseases including pediatric cardiac disorders. Particularly in patients with cardiomyopathies and patients with atrioventricular valve disease but also congenital heart disease, serial measurement of atrial volumes can be of importance in clinical practice.^{4,21,22} In this context, several studies have reported MR reference values for atrial volumes in the adult population using different analysis techniques, most

commonly the area-length method.^{10–13} Sarikouch et al have provided atrial reference values for children.^{9,14} Compared to the data presented here, the study cohort was smaller ($n = 115$) and atrial measurements were performed on axial cine stacks using the more time-consuming Simpson's method.⁹ The Simpson's method used by Sarikouch et al⁹ is likely to give more accurate results, especially if the analysis is performed by an experienced MRI reader. However, acquisition of transaxial cine stacks and atrial volume analysis from

TABLE 7. Centiles (C) of the RA_{max} (in mL) for Boys

BSA (m ²)	C5	C10	C25	C50	C75	C90	C95
0.8	14.45	16.34	19.95	24.7	30.35	36.3	40.3
0.9	15.5	17.77	21.99	27.32	33.37	39.45	43.39
1	16.54	19.29	24.23	30.23	36.71	42.96	46.88
1.1	17.52	20.88	26.71	33.44	40.4	46.85	50.79
1.2	18.43	22.57	29.44	37	44.49	51.17	55.15
1.3	19.46	24.49	32.53	40.98	49.01	55.96	60.01
1.4	20.93	26.83	36.09	45.46	54.06	61.28	65.42
1.5	23.03	29.76	40.21	50.5	59.66	67.19	71.43
1.6	25.85	33.33	44.95	56.15	65.89	73.73	78.09
1.7	29.38	37.6	50.34	62.45	72.78	80.96	85.46
1.8	33.62	42.57	56.43	69.47	80.41	88.94	93.6
1.9	38.57	48.27	63.28	77.26	88.83	97.76	102.58
2	44.25	54.75	70.93	85.89	98.14	107.48	112.5

TABLE 8. Centiles (C) of the LA_{min} Biplane (in mL) for Boys and Girls Together

BSA (m ²)	C5	C10	C25	C50	C75	C90	C95
0.8	4.1	5.07	6.75	8.67	10.66	12.5	13.61
0.9	4.55	5.62	7.46	9.6	11.81	13.85	15.09
1	5.05	6.22	8.26	10.62	13.07	15.34	16.73
1.1	5.61	6.89	9.14	11.75	14.47	17	18.55
1.2	6.22	7.63	10.11	13	16.02	18.84	20.57
1.3	6.9	8.46	11.18	14.38	17.74	20.88	22.81
1.4	7.66	9.37	12.37	15.92	19.64	23.14	25.29
1.5	8.5	10.37	13.69	17.61	21.75	25.64	28.04
1.6	9.43	11.49	15.14	19.48	24.08	28.41	31.09
1.7	10.46	12.73	16.75	21.56	26.66	31.49	34.47
1.8	11.61	14.09	18.54	23.85	29.51	34.89	38.23
1.9	12.87	15.61	20.51	26.38	32.68	38.66	42.39
2	14.28	17.29	22.69	29.19	36.18	42.85	47

these stacks are more time-consuming. Therefore, atrial volume analysis from mono- or biplane area-length method for the often-lengthy analysis of pediatric MRI scans might be preferred. Although previous studies have indicated that the reference standard for volumetric assessment of atria is from a short-axis stack,^{12,23} the area-length method is easier to perform and does not require short-axis images of the entire

heart. The latter might be of importance in children as they might struggle with repeated breath-hold maneuvers in short succession. Atrial volumes derived from MRI long-axis images using the mono- and biplane area-length might not be directly compared to atrial volumes measured from short-axis stacks. Li et al reported that the area-length method underestimated atrial volumes compared to the short-axis

TABLE 9. Centiles (C) of the LA_{max} Biplane (in mL) for Boys

BSA (m ²)	C5	C10	C25	C50	C75	C90	C95
0.8	15.61	16.98	19.41	22.35	25.55	28.66	30.62
0.9	16.72	18.33	21.22	24.71	28.52	32.23	34.57
1	17.89	19.79	23.19	27.32	31.84	36.22	39
1.1	19.16	21.38	25.36	30.21	35.51	40.65	43.91
1.2	20.57	23.14	27.77	33.4	39.55	45.52	49.29
1.3	22.2	25.16	30.48	36.94	43.97	50.78	55.07
1.4	24.19	27.54	33.56	40.84	48.73	56.35	61.13
1.5	26.61	30.37	37.08	45.15	53.86	62.21	67.44
1.6	29.61	33.75	41.12	49.92	59.34	68.34	73.94
1.7	33.4	37.89	45.81	55.19	65.16	74.61	80.47
1.8	38.14	42.9	51.24	61.02	71.32	81.01	87
1.9	43.83	48.8	57.43	67.46	77.94	87.72	93.73
2	50.42	55.55	64.39	74.58	85.14	94.94	100.93

method,¹² whereas Zemrak et al found only a minimal mean difference between the biplanar and the short-axis method for the assessment of LA volumes.²³

Recent studies have shown the benefit of artificial intelligence for the automatic calculation of atrial volumes from cross-sectional images.^{24,25} To our knowledge, similar studies for pediatric patients are still lacking but would improve cardiac MRI postprocessing, more particularly if automated calculation processes could be implemented in commercially available cardiac MRI postprocessing software.

In this study, univariable and multivariable linear models were used to evaluate the impact of demographic parameters on atrial volumes. The results showed that BSA was a strong determinant for all atrial volumes, with only LA_{max} measured in the 4-ch-view being strongly associated with height and weight rather than with BSA. Our reference centile curves and tables are therefore presented with respect to BSA although we acknowledge that this might underestimate atrial volumes in obese children and adolescents.²⁶ We believe that atrial volumes measured by the area-length method can be easily added to a routine pediatric MRI report. As the biplane area-length method is thought to be more accurate compared to the monoplane area-length method and we found good-to-excellent ICC values for LA volumes derived from the biplane area-length method, we recommend using the reference values derived from the biplane area-length method for LA volumes.

Limitations

This is a retrospective study with a smaller number of girls than boys which might have impacted on the results. In

particular, we were unable to provide centile tables and curves for LA_{min} (2ch) and LA_{max} biplane in girls. Nevertheless, mean values for absolute and indexed atrial volumes for girls are given.

Furthermore, children younger than 4 years of age were not included and only Caucasian children were included but no other ethnicities. The retrospective study design is also responsible for the large range of spatial and temporal resolution. Our results therefore should be carefully used in this context with the awareness that they are probably not generalizable.

Another limitation is that we did not include atrial function parameters and cross-sectional areas in our analysis.

Conclusion

We provide pediatric MRI reference values for atrial volumes. These may be useful in the diagnosis and follow-up of congenital or acquired heart disease in children and for research purposes.

Acknowledgment

Open access funding enabled and organized by Projekt DEAL.

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