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Assessment of Left Atrial Volumes at 1.5 Tesla and 3 Tesla Using FLASH and SSFP Cine Imaging

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ABSTRACT

***Purpose*: To investigate left atrial volumes and function and their variability in healthy volunteers using steady state free precession (SSFP) and fast low angle shot (FLASH) sequences at both 1.5 and 3 T using both the short-axis and biplane area-length methods. *Materials and Methods:* Ten healthy volunteers underwent CMR at both 1.5 and 3 Tesla. The biplane area-length method utilized volumes from the horizontal and vertical long axis images. *Results*: There were no significant differences between left atrial short-axis volumes or function between 1.5 and 3 T assessed using either FLASH or SSFP sequences. The biplane area-length method underestimated maximal left atrial volume using FLASH by 12 mL at 3 T (18%) and by 10 mL (14%) at 1.5 T ($p = 0.003$ and $p = 0.05$ respectively). Variability was larger for left atrial measurements using the biplane area-length method. *Conclusion*: Field strength had no effect on left atrial volume and function assessment using either FLASH or SSFP. The use of the short-axis method for the acquisition of left atrial parameters is more reproducible than the biplane area-length for serial measurements.**

INTRODUCTION

Cardiovascular magnetic resonance (CMR) is a well-tolerated, accurate and reproducible method for the serial monitoring of patients and has become the gold standard method for the characterization of cardiac anatomy, mass and function (1). The technique of choice for the assessment of ventricular volumes and mass in current clinical practice is steady state free precession (SSFP) cine imaging at 1.5 Tesla (T). Left atrial size is related to cardiovascular morbidity and mortality and is important in the assessment of mitral valvular disease, cardiomyopathies and diastolic function (2–4). Increased atrial size is positively correlated to the risk of developing atrial fibrillation, the most common arrhythmia affecting 10% of the elderly population, and reduces the success of recovery from cardioversion (5). Echocardiography is currently the gold standard method for assessing left atrial volumes, but this method relies upon a number of geometric assumptions and obtaining accurate imaging planes and has previously been shown to underestimate left atrial volumes by up to 47% when compared with CMR (6). However, the assessment of left atrial volumes using CMR has not yet become routine because acquisition and analysis of a full stack of atrial short-axis slices can be time-consuming. Sievers et al have demonstrated that the biplane area-length method for ellipsoid bodies is a rapid and reproducible alternative method for assessment of the left atrium in both healthy volunteers and patients although it does rely on geometric assumptions (7, 8).

The availability of 3 T cardiovascular imaging is increasing because the signal-to-noise (SNR) increases linearly with the magnetic field strength and hence is benefiting CMR applications that are currently limited by low temporal and spatial resolution at 1.5 T (9, 10).

Before the use of SSFP in clinical practice, a cine gradient echo sequence (fast low angle shot, FLASH [(11)] was used which underestimated LV volumes because of inferior border definition (12). Previous CMR studies of left atrial volumes have used either SSFP or FLASH sequences respectively

Keywords: Steady state free precession, fast low angle shot, 3 Tesla, left atrium, biplane are-length method.
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at 1.5 T or 1.0 T, but none have compared these directly, and none have been performed at very high field strengths of 3 T.

Thus, we aimed to investigate left atrial volumes and function in healthy volunteers using SSFP and FLASH sequences at both 1.5 and 3 T and to compare the short-axis and biplane area-length methods for the assessment of left atrial volumes and function.

We hypothesized that the measurements of left atrial volumes and function would be independent of field strength, the systematic differences in ventricular volume between SSFP and FLASH would also be evident in left atrial volumes, and the short-axis method would have improved reproducibility compared to the biplane area-length method because of the reduced dependence on geometric assumptions.

MATERIALS AND METHODS

Study population

Ten healthy volunteers (5 male and 5 female, mean age 28 ± 5 years, mean height 171 ± 9 cm, mean weight 70 ± 16 kg, mean heart rate 60 ± 9 bpm and mean blood pressure 116 ± 10/74 ± 6 mm Hg) with normal left and right ventricular ejection fractions, no history of cardiac disease, hypertension or other cardiac risk factors and a normal baseline electrocardiogram (ECG) were recruited. Volunteers with contraindications to CMR were not enrolled. The study was carried out according to the principles of the Declaration of Helsinki and was approved by our institutional ethics committee. Each subject gave written informed consent.

Cardiovascular magnetic resonance protocol

All CMR examinations were performed using a 1.5 T (Sonata, Siemens Medical Solutions, Erlangen, Germany) and a 3 T MR system (Trio, Siemens Medical Solutions) on the same day with anterior phased array surface coils, and either a posterior phased array surface coil (3 T) or 2 elements of the integrated spine coil (1.5 T), retrospective electrocardiographic gating and in the supine position. After localizing images, piloting was performed in the vertical long axis (VLA), horizontal long axis (HLA) and short-axis planes. SSFP and FLASH cines were acquired in the VLA and HLA views after the acquisition of a SSFP frequency pilot (13). The parameters for FLASH cines were TR 5.48 ms, TE 2.75 ms, 2.28 × 2.82 mm resolution, using parallel imaging (GRAPPA) (14) with × 2 acceleration, 9 lines per segment, sampled temporal resolution of 49.3 ms, with 350 Hz/pixel bandwidth, FOV 350 × 306 mm, flip angle 20° and a breath-hold time of 9 heartbeats. The SSFP parameters were TR 3.12 ms (3.47 ms at 3 T), TE 1.42 ms (1.47 ms at 3 T), sampled temporal resolution of 43.7 ms (44.38 ms at 3 T), 1.82 × 1.82 resolution, using parallel imaging (GRAPPA) ×2 acceleration, 930 Hz/pixel bandwidth, flip angle 60° (mean at 3 T, 56 ± 4) with a breathhold time of 7 heartbeats. Atrial slices were planned parallel to the atrioventricular groove. The left atrium was covered by 4 to 8 slices of 7 mm with an interslice gap of 3 mm.

Image analysis

CMR image analysis was performed with Argus software (Version 25A, Siemens Medical Solutions, Erlangen, Germany) by two experienced investigators.

Short-axis method

Manual tracing of the endocardial borders of successive short-axis slices at ventricular end-diastole (Fig. 1) and end-systole was performed. Left atrial end-diastole was defined as the slice with the largest left atrial dimension, just prior to left atrial contraction and at ventricular end-systole. Volumes were included as atrial if less than 50% of the blood volume was surrounded by ventricular myocardium. Blinded investigators were free to select the end-diastolic and end-systolic frame. Maximal left atrial volume (end-systole) and minimal atrial volume (end-diastole) were used to calculate atrial stroke volume and ejection fraction.

Biplane area-length method

Maximal left atrial volume (end-systole) and minimal atrial volumes (end-diastole) were traced using both the horizontal and vertical long axis images (7, 15). The end-systolic and end-diastolic width and length in both views was also measured (Fig. 2). Left atrial volumes, ejection fraction and stroke volume were then calculated using the biplane-area length method for ellipsoid bodies (7).

The left atrial appendage was included in the atrial volume, but the pulmonary veins were excluded for both methods.

Reproducibility

A second investigator analyzed 4 of the data sets with both the short-axis and biplane area-length methods to provide a measure of inter-observer variability. To assess intra-observer variability, one observer analyzed all the images of the first 4 volunteers twice, leaving at least a 2 week gap and being blinded to the previous results.

To assess inter-study reproducibility, 4 volunteers underwent a second identical scan on both 1.5 T and 3 T systems, on a different day from the first study.

Statistical analysis

All data are presented as mean ± standard deviation (SD) unless stated otherwise. A univariate general linear model with fixed effects for sequence (SSFP and FLASH) and field strength (1.5 T and 3 T) was used to test whether differences between sequences were specific to the field strength. To compare the two methods of measuring left atrial volume and function (short-axis and biplane area-length method), a paired t-test was used. Throughout the analyses, a two sided p value of <0.05 was considered statistically significant. Inter-study reproducibility and inter- and intra-observer variability were assessed using the method of Bland and Altman (16). The coefficient of variability was calculated as the SD of the differences between the two sets

Table 1. Left atrial volume and function using SSFP and FLASH techniques at 1.5 T and 3 T in healthy volunteers with the short-axis method.

	SSFP		FLASH		p value		
	1.5 T	3 T	1.5 T	3 T	Sequence	Field strength	Interaction
LA ejection fraction (%)	54 ± 8	48 ± 14	50 ± 10	50 ± 14	0.85	0.43	0.43
LA maximal volume (mL)	81 ± 27	78 ± 25	82 ± 26	77 ± 26	0.99	0.96	0.45
LA minimal volume (mL)	37 ± 13	40 ± 16	42 ± 18	37 ± 13	1.0	0.63	0.88
LA stroke volume (mL)	44 ± 18	38 ± 17	42 ± 18	40 ± 21	0.99	0.47	0.71

All data are mean ± standard deviation. Univariate general linear model with fixed effects for sequence and field strength was used. SSFP = steady state free precession, FLASH = fast low angle shot.

of measurements divided by the mean. All computations were performed with SPSS 11.5 (SPSS Inc., Chicago, Illinois, US).

RESULTS

CMR at 1.5 and 3 T was well-tolerated by all volunteers, and all images could be included in the study. There were no image artifacts that affected analysis. A typical short-axis slice acquisition of a healthy volunteer using FLASH and SSFP at both 1.5 T and 3 T with endocardial border contours is shown in Fig. 1.

LA volumes and function

There were no significant differences between the left atrial volumes or function between 1.5 and 3 T assessed using either FLASH or SSFP sequences with the short-axis method ($p > 0.05$ for field strength for all parameters, Table 1). Furthermore, there was no significant difference in the left atrial volumes, ejection fraction or stroke volume between the FLASH and SSFP sequences with the short-axis method ($p > 0.05$ for sequence, Table 1).

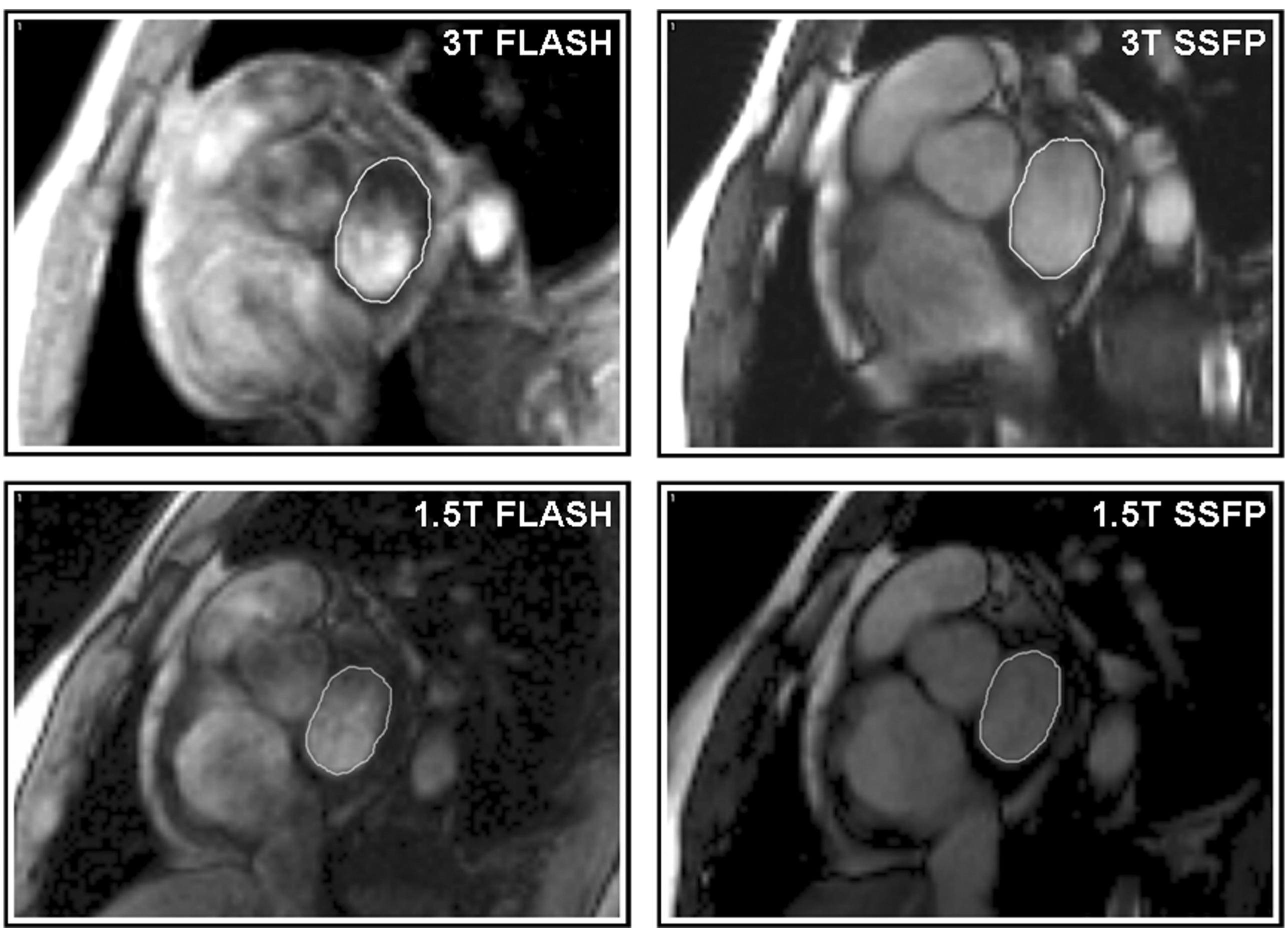

Figure 1. SSFP and FLASH left atrial images at 1.5 and 3 T in a male healthy volunteer showing the endocardial border contours.

Table 2. Comparison of the biplane area-length and short axis methods for left atrial volume and function measurements

	Short-axis	Biplane area-length	*p* value
LA EF(%)			
FLASH 1.5 T	50 ± 10	52 ± 13	0.57
SSFP 1.5 T	54 ± 8	54 ± 6	0.89
FLASH 3 T	50 ± 14	48 ± 10	0.66
SSFP 3 T	48 ± 14	53 ± 7	0.21
Maximal LA volume (mL)			
FLASH 1.5 T	82 ± 26	72 ± 18	0.05
SSFP 1.5 T	81 ± 27	75 ± 22	0.24
FLASH 3 T	77 ± 26	65 ± 27	0.003
SSFP 3 T	78 ± 25	80 ± 27	0.60
Minimal LA volume (mL)			
FLASH 1.5 T	40 ± 13	35 ± 15	0.06
SSFP 1.5 T	37 ± 13	34 ± 10	0.27
FLASH 3 T	37 ± 13	34 ± 14	0.34
SSFP 3 T	40 ± 16	38 ± 13	0.49

All data are mean ± standard deviation. Paired student's t test was used to compare analysis methods. p values <0.05 were considered significant. SSFP = steady state free precession, FLASH = fast low angle shot.

Influence of method of analysis

When comparing the short-axis and biplane area-length method for assessing left atrial parameters, the biplane area-length method significantly underestimated the maximal left atrial volume using FLASH by 12 mL (18%) at 3 T, $p = 0.003$ and by 10 mL (14%) 1.5 T, $p = 0.05$ (Table 2). There was no statistically significant difference between the left atrial ejection fractions calculated using either method ($p > 0.05$ for all). While there was a trend for minimal left atrial volumes at 1.5 T using FLASH to be underestimated by the biplane area-length method, ($p = 0.06$), there were no significant differences between either method of analysis using SSFP images (Fig. 3).

Reproducibility

The intra-observer variability of the left atrial ejection fraction using the short-axis method for the two sequences at both field strengths ranged from 3.0% (SSFP at 1.5 T) to 7.4% (FLASH at 1.5 T) as shown in Table 3. As expected, the inter-observer and inter-study variability was higher than the intra-observer values, with 1.5T SSFP being the most consistently reproducible sequence. Variability was larger for left atrial measurements assessed using the biplane area-length method than for the short-axis method. With this method, 1.5 T SSFP again tended to show the lowest variability.

DISCUSSION

We have assessed left atrial volumes in healthy volunteers with both FLASH and SSFP sequences at 1.5 and 3 T using both the short-axis and biplane area-length method.

Our results for left atrial maximal and minimal volumes, stroke volume and ejection fraction using the short-axis method are quantitatively similar to previous values acquired in healthy volunteers at 0.5 to 1.5 T using transverse ECG gated multi-slice spin-echo sequences, gradient echo, FLASH and SSFP sequences (7, 15, 17–19).

There were no significant differences between left atrial parameters acquired at 1.5 or 3 T using the short-axis method with either FLASH or SSFP, respectively. Thus, our data does not demonstrate a systematic over-estimation of left atrial volumes as shown for ventricular volumes with FLASH compared to SSFP at 1.5 T (12). The difference in left ventricular endocardial contours in the paper by Moon et al were mostly affected by trabeculations and papillary muscles and, hence, the absence of these within the atria along with greater contrast at the atrial endocardial border may explain this discrepancy (12).

When comparing the short-axis and biplane area-length methods of analysis, there was no significant difference in the

Table 3. Reproducibility of measurements for left trial ejection fraction

	Intraobserver		Interobserver		Interstudy	
	Bias (95% Limits of Agreement)	CoV	Bias (95% Limits of Agreement)	CoV	Bias (95% Limits of Agreement)	CoV
Short axis method						
1.5 T FLASH	−3.0 (−8.0 to 8.0)	7.4	4.2 (−15.5 to 16.3)	14.8	2.5 (−12.6 to 17.6)	14.0
1.5 T SSFP	0.6 (−3.0 to 4.2)	3.0	4.3 (−4.6 to 13.30)	8.3	1.7 (−2.9 to 6.3)	4.0
3 T FLASH	3.7 (1.6 to 6.9)	3.0	2.7 (−2.5 to 8.0)	5.1	−2.1 (−24 to 19)	19.0
3 T SSFP	0.5 (6.9 to 3.3)	6.0	−0.8 (7.1 to 5.5)	6.2	−9.7 (−12.2 to 10.3)	12.0
Biplane area-length method						
1.5 T FLASH	−1.1 (−20.7 to 18.5)	18.4	−1.0 (−13.9 to 23.5)	16.7	−2.5 (−19.8 to 14.9)	17.8
1.5 T SSFP	−0.6 (−8.2 to 6.9)	6.7	−3.9 (−24.6 to 16.7)	17.8	−0.3 (−8.5 to 7.8)	7.9
3 T FLASH	−1.7 (−12.8 to 9.3)	11.6	8.6 (−2.9 to 20.2)	18.2	1.9 (−20.5 to 24.4)	24.0
3 T SSFP	−0.3 (−8.4 to 7.7)	7.6	−3.6 (−20.6 to 13.6)	15.8	−0.5 (−16.7 to 15.6)	16.2

CoV = Coefficient of Variability.

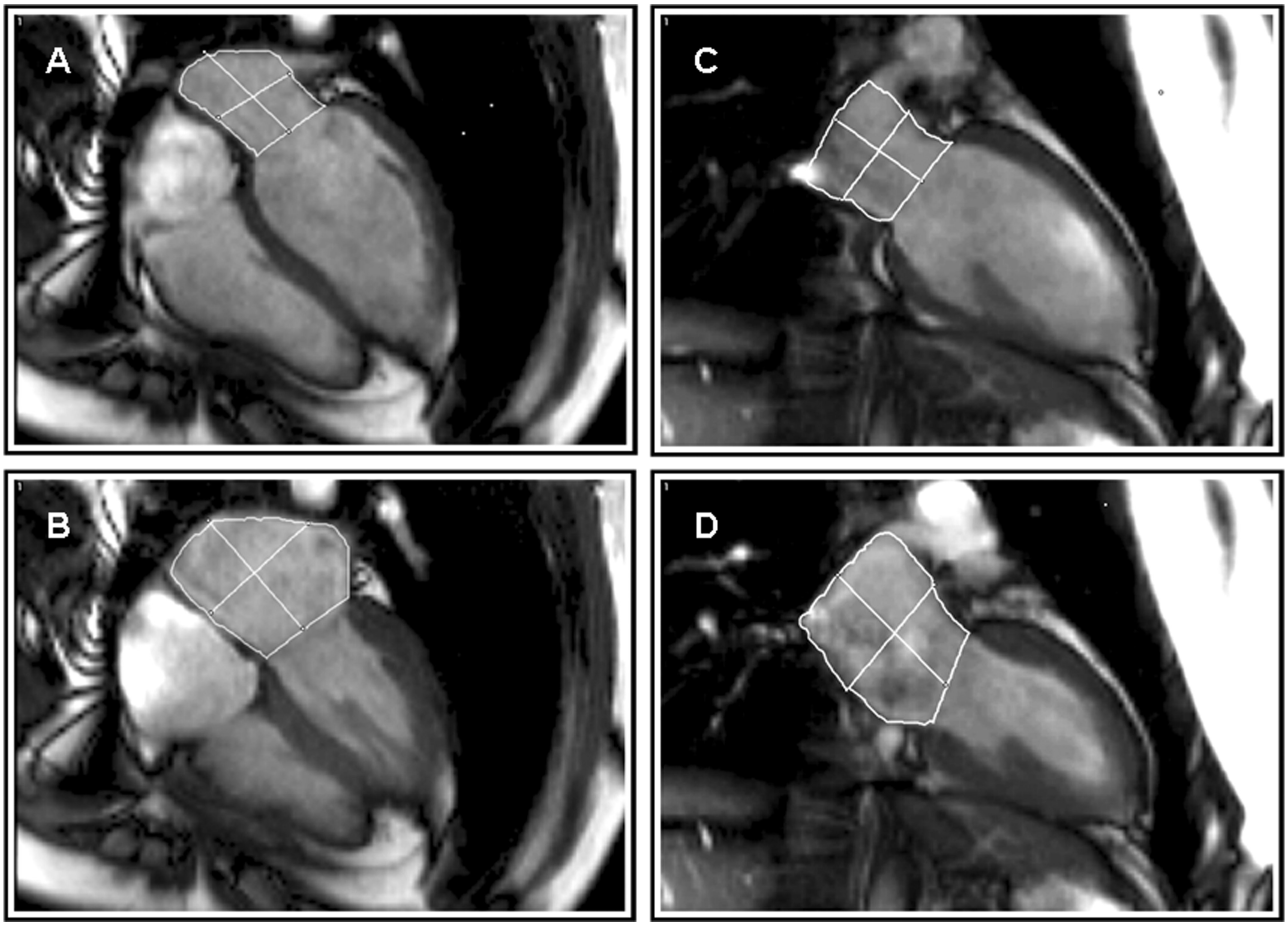

Figure 2. Horizontal long axis (HLA) in ventricular end-diastole (A) and end-systole (B), vertical long axis (VLA) in end-diastole (C) and end-systole (D) using SSFP images at 3 T illustrating the contours for the biplane are-length method for left atrial volumes and ejection fraction. The upper panel demonstrates the minimal left atrial volume and the lower panel shows the maximal volume. The left atrial appendage was included in the atrial volume, but the pulmonary veins were excluded.

left atrial ejection fraction, demonstrating that either method can be used to accurately calculate left atrial function. However, the biplane area-length method significantly underestimated the maximal LA volume using FLASH at both field strengths, in this case probably reflecting the reduced border definition with this sequence, as there was no significant difference in the atrial volumes using SSFP with both analysis methods. Any small underestimation with the traced contour is then translated into a larger difference with the biplane area-length method as a result of geometric assumptions.

The variability for the left atrial volumes using the short-axis method ranged from 3.0% to 7.4% for intraobserver, 5.1% to 14.8% for interobserver and 4.0 to 19.0% for interstudy variability. These values for left atrial volume reproducibility are larger than those published for the left or right ventricle, reflecting the difficulty in selection of the basal slice and in excluding the pulmonary vein volumes (20–22). Reproducibility for the biplane area-length method was lower than for the short-axis method. This again reflects the contribution of geometric assumptions with a small difference in measurements resulting in a large effect on volume calculation. Therefore, we would recommend the use of the short-axis method in preference to the biplane area-length method to provide the most reproducible and accurate method for serial assessment of the left atrium, albeit with an increase in scan time of up to 5 minutes. An increase in field strength did not afford any improvement in reproducibility in either sequence, and all CMR scans were well tolerated with no image artifacts affecting image analysis, and, hence, we have shown that imaging of atrial volumes is feasible at the higher field strength of 3 T.

Atrial fibrillation is a common arrhythmia affecting an ever aging population, and the assessment of the left atrium can provide information about prognosis and predicted response to therapeutic interventions (5, 23–31). The assessment of left atrial volumes using CMR has not yet become routine despite the current clinical method of choice for this echocardiography, relying upon on a number of geometric assumptions. However, left atrial enlargement using echocardiography has been shown to reflect diastolic dysfunction and to correlate with increased incidence of heart failure as well as mortality in patients with

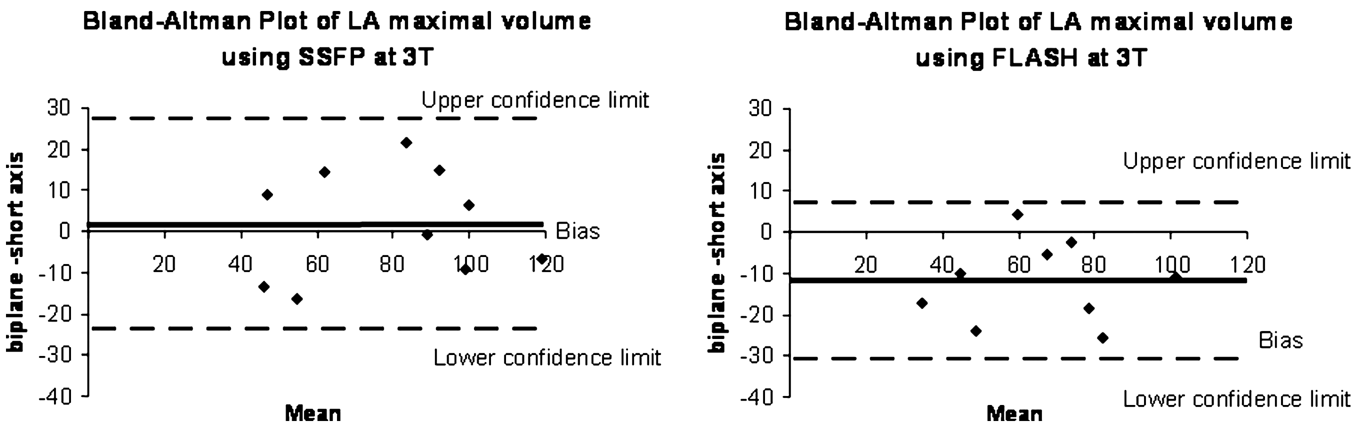

Figure 3. Bland-Altman plot between the biplane area-length method and short-axis method for left atrial maximal volume in 10 healthy volunteers using SSFP and FLASH at 3 T. Solid lines represent the mean (bias) and dotted lines represent the limits of agreement (95% limits of agreement).

dilated cardiomyopathy (32) and valvular heart disease (27). To optimize the application of left atrial volume and function for patient risk stratification, the most reproducible, available and accurate imaging method should be used, and we would recommend the use of CMR for this.

Limitations

Although we have demonstrated the assessment of left atrial volumes in a small study group of 10 healthy volunteers at 1.5 and 3 T, we have not investigated this method systematically in patients with coronary stents, valve replacements, impaired left ventricular function or atrial fibrillation to assess the effect of these factors on image quality and analysis. We have investigated the use of the short-axis technique using 7 mm slices with a 3 mm interslice gap, our standard acquisition protocol, and it is possible that a 3 mm gap may influence left atrial volumes to a small extent (33). Further comparison of variability for short-axis acquisition with long-axis slices as well as with the biplane area-length method may also prove interesting.

In conclusion, field strength does not have any effect on left atrial volume and function assessment using either FLASH or SSFP. We would recommend the use of the short-axis method in preference to the biplane area-length at 1.5 T with SSFP for the acquisition of left atrial volumes and function because of the improved reproducibility of this approach.

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