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How much are atrial volumes and ejection fractions assessed by cardiac magnetic resonance imaging influenced by the ECG gating method?

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Purpose. Most magnetic resonance imaging (MRI) centers currently use prospective electrocardiographic (ECG) triggering for image acquisition. Retrospectively gated sequences allow the coverage of the entire cardiac cycle. It has been recently shown that ventricular volumes and ejection fraction (EF) differ according to the gating method used for image acquisition. The authors sought to evaluate how much measurements of atrial volumes and EF differ depending on the gating method. *Materials and Methods.* Eighteen subjects with no cardiovascular disease were investigated by MRI using a 1.5 Tesla scanner. Images were acquired with a gradient-echo sequence with steady-state free precession (SSFP) using the standard short-axis method for volume and EF measurements. Images were acquired with 6 mm thick slices using both prospective triggering and retrospective gating. Left and right atrial volumes (end diastolic volume [EDV]; end systolic volume [ESV]; stroke volume [SV]) and EF were determined with a commercially available software package. *Results.* ESV was significantly smaller with the retrospectively gated SSFP sequence than with the prospectively triggered sequence (mean difference: ESV left 3.97 ± 1.3 ml, $p < 0.0001$; ESV right 4.34 ± 1.8 ml, $p < 0.0001$). EF and SV were significantly smaller with prospective triggering (mean difference: EF left −5.94 ± 0.9%, $p < 0.0001$; EF right −5.52 ± 1.3 %, $p < 0.0001$; SV left −3.99 ± 1.3 ml, $p < 0.0001$; SV right −4.32 ± 1.9 ml, $p < 0.0001$). EDV remained unchanged (mean difference: EDV left −0.03 ± 0.8 ml, $p = 0.902$; right EDV 0.04 ± 0.7 ml, $p = 0.882$). *Conclusion.* The gating method has a significant impact on atrial volume and EF measurements. Atrial EF is underestimated by using the prospective triggering technique.

Key Words: Cardiac magnetic resonance imaging; Steady-state free precession gradient echo sequence (SSFP); Prospective ECG triggering; Retrospective gating; Atrial volumes; Atrial ejection fractions

1. Introduction

Although a retrospectively gated gradient-echo sequence had been introduced in the late 1980s, most MRI centers still use prospective triggering for cardiac volume and EF assessment. Published reference values for MRI assessment of volumes and EF are based on calculations from short axis images acquired with prospectively triggered gradient-echo sequences (1, 2). It is known that prospectively triggered sequences do not cover the entire cardiac cycle because the acquisition window is set 10–20% below the average cardiac cycle length (Fig. 1A).

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However, retrospectively gated gradient-echo sequences do cover the entire cardiac cycle and, thus, are supposed to be more accurate in volume and EF assessment than prospectively triggered gradient-echo sequences. A fixed number of time frames is sampled (3). Because data interpolation is used, an arbitrary number of images can be reconstructed in the cine series at any time point in the cardiac cycle. The image acquisition is asynchronous with the electrocardiograph (ECG). The length of time for each phase encoding step is set by the acquisition window. A time stamp that indicates the time relative to the previous R-wave is stored with each phase encoding step. The acquisition window is defined to be longer than the maximum RR-interval to ensure data acquisition for each part of the cardiac cycle (Fig. 1B). After the acquisition, the data are sorted based on time stamps which indicate the time to the previous R-wave and are reconstructed into a series of images covering the entire cardiac cycle.

In prospectively triggered gradient-echo sequences (Fig. 1A), the same slice position is excited with a fixed

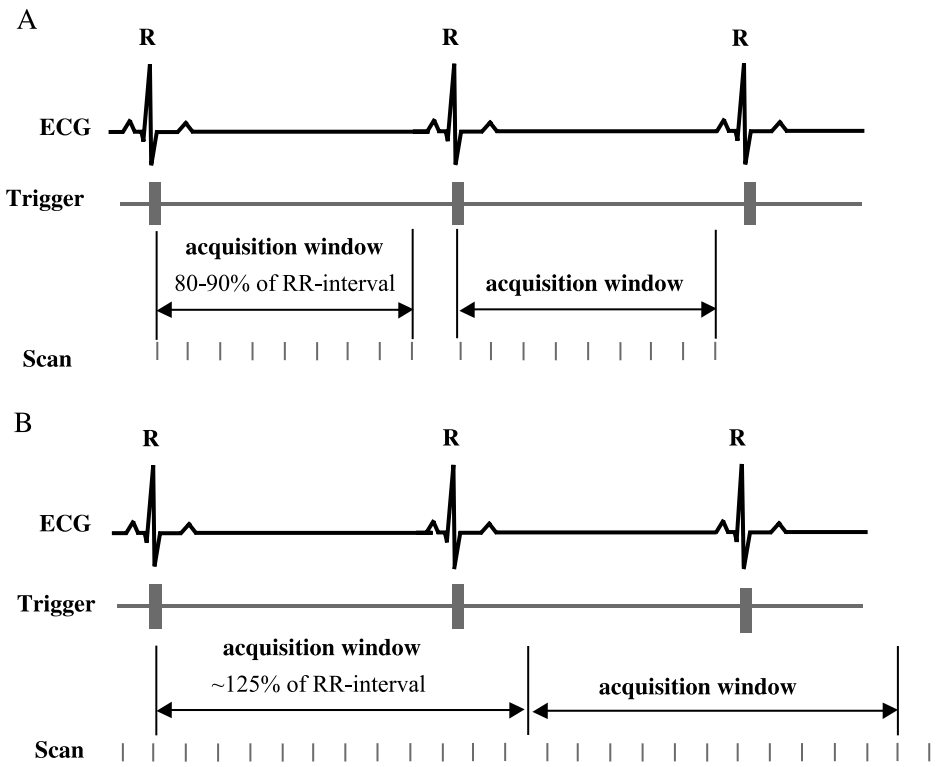

Figure 1. Timing diagram of the prospectively triggered SSFP sequence (A) and the retrospectively gated SSFP sequence (B). [Taken from Ref. (4)].

number of radio-frequency (RF) pulses (3) The number of phases depends on the repetition time (TR) and the heart rate. After a fixed number of excitations per RR-interval, the system waits until the next R-wave occurs. This gap in the late ventricular diastole/atrial systole usually disturbs the steady state and leads to an increased signal intensity, causing lightening artifact in the first images of each cine set. This can be overcome by implementing dummy pulses to bridge the gap between the last and the next excitation pulse. Dummy pulses maintain the steady-state although no data points are acquired during this time.

It has recently been shown that the gating method has a significant impact on ventricular volume and EF measurements and that EDV and global ventricular EF is underestimated by using the prospective triggering technique (4).

However, the impact of the gating method on measurements of atrial volumes and EF has not been studied yet. We therefore attempted to evaluate how much atrial volume and EF measurements are affected by the gating method.

2. Materials and methods

The study was prospectively planned and was approved by the local Institutional Review Board. Written consent was obtained in all cases.

Eighteen consecutive subjects with no prior history of cardiovascular pathology (8 women and 10 men, mean age 53.9 ± 11.2 years) underwent MRI for the evaluation of cardiac function and the determination of cardiac volumes and EF using 6 mm thick slices. All images were acquired in the same examination. Heart disease was excluded in all subjects before MRI by noninvasive diagnostic techniques (ECG, chest X-ray, echocardiography, treadmill exercise ECG, or thallium myocardial scintigraphy). None of the subjects included in the study had a history of hypertension and diabetes.

The mean heart rate during the MRI examination was 64 ± 11 bpm. All subjects had sinus rhythm.

2.1. *Image acquisition*

MRI was performed with a 1.5 Tesla Scanner (Sonata, Magnetom, Siemens, Erlangen, Germany) using an anterior and posterior surface coil array (CP Body Array Flex, CP Spine Array, Siemens, Erlangen, Germany) and prospective as well as retrospective ECG triggering. The dimensions of the coil elements were about 160 mm in the z-direction (head to feet) and about 460 mm in the x-direction (right to left). A fast imaging sequence with steady-state free precession (SSFP) and constant radiofrequency pulsing was used (5).

On the basis of scout images, cine images were acquired in the short axis and horizontal and vertical long axes. Short-axis images covering the entire left and right atrium were acquired with a 6 mm section thickness and a 4 mm gap during breath holding in end expiration using a fast gradient-echo sequence (SSFP) with both prospective and retrospective ECG

Table 1. Displayed are the left (A) and right (B) atrial volumes and EF calculated from retrospectively gated and prospectively triggered SSFP images, the mean differences, and the p-values

A				
Mean ± SD	Retrospective gating	Prospective triggering	Mean difference	P-value
EDV [ml]	66.8 ± 19.8	66.4 ± 20.1	−0.03 ± 0.8	0.902
ESV [ml]	32.3 ± 10.9	36.2 ± 12.1	3.97 ± 1.3	< 0.0001
SV [ml]	34.5 ± 11.1	30.5 ± 10.4	−3.99 ± 1.3	< 0.0001
EF [%]	51.8 ± 7.2	45.8 ± 7.9	−5.94 ± 0.9	< 0.0001
B				
EDV [ml]	75.8 ± 22.2	74.9 ± 21.3	0.04 ± 0.7	0.882
ESV [ml]	36.0 ± 11.4	40.3 ± 13.1	4.34 ± 1.8	< 0.0001
SV [ml]	39.8 ± 12.9	35.4 ± 11.6	−4.32 ± 1.9	< 0.0001
EF [%]	52.4 ± 6.5	46.9 ± 7.0	−5.52 ± 1.3	< 0.0001

Abbreviations: EDV = end-diastolic volume; ESV = end-systolic volume; SV = stroke volume; EF = ejection fraction.

triggering. Six mm thick slices were used to avoid major influences by partial volume effects.

Parameters for the prospectively triggered SSFP sequence are as follows: temporal resolution = 39 ms; echo time = 1.5 ms; slice thickness = 6 mm; inter slice gap = 4 mm; Field of View (FoV) read 380 mm; FoV phase 78%; base resolution 256; phase resolution 62%; flip angle = 65°; in-plane pixel size = 2.4 × 1.5 mm; matrix 124 × 256 pixel; number of

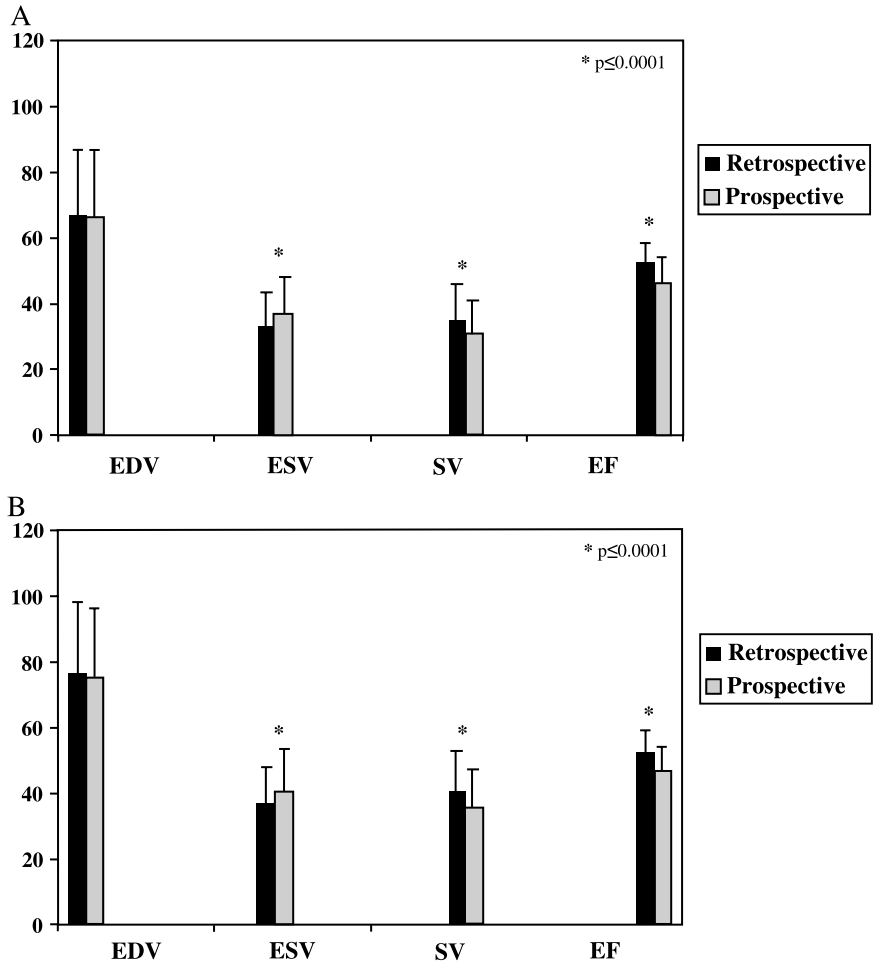

Figure 2. Mean and standard deviations of top (A) and bottom (B) atrial volumes and EF, displayed as boxplots. ESV, SV and EF differ significantly according to the gating technique used for image acquisition.

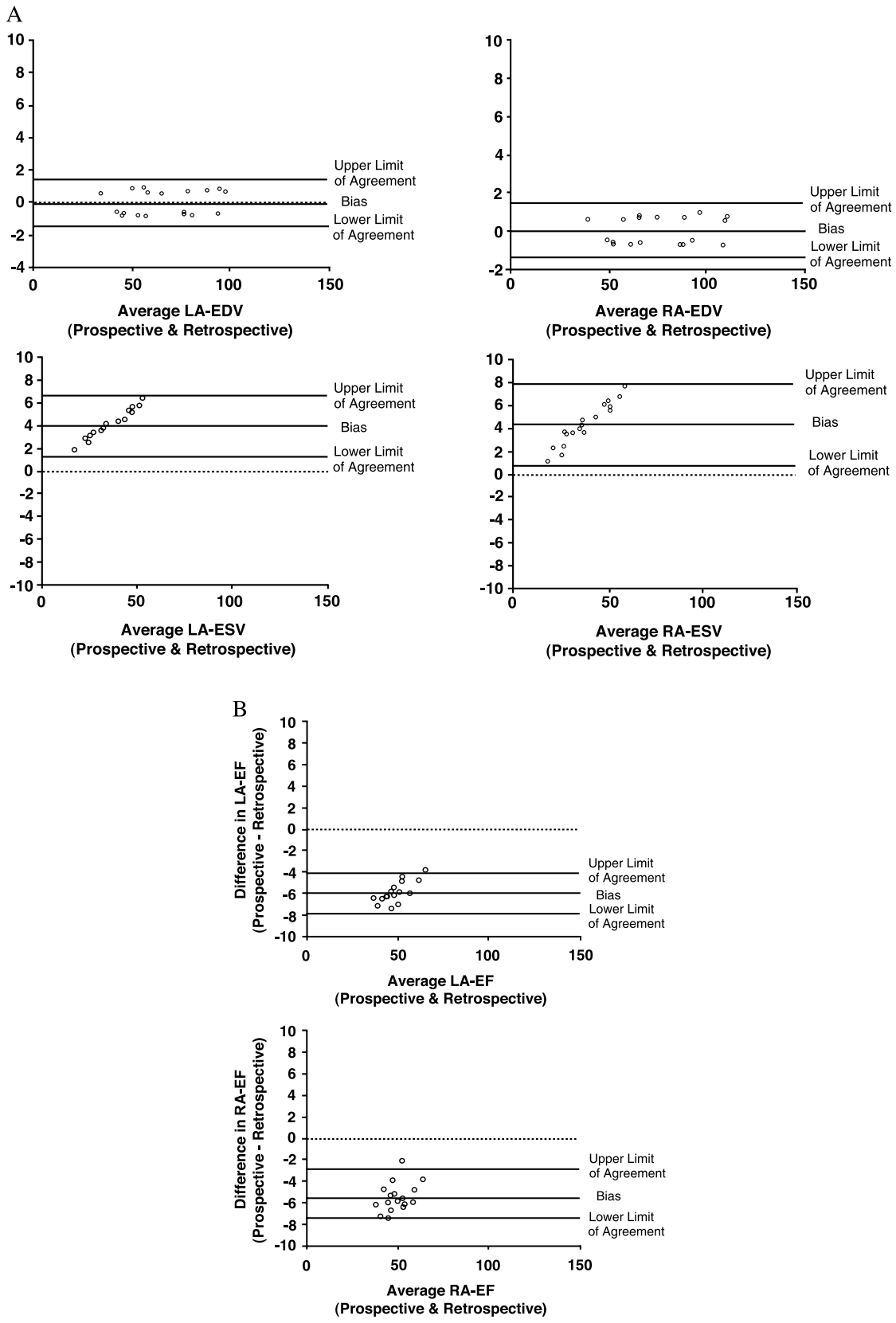

Figure 3. Band-Altman analysis of the differences between left and right atrial volumes (A) and EF (B) acquired with prospective triggering and retrospective gating.

cardiac phases = 16 (depending on heart rate); number of segments = 13; bandwidth 977 Hz/Px; scan time = 8–10 sec (depending on the heart rate).

Parameters for the retrospectively gated SSFP are as follows: temporal resolution = 42 ms; echo time = 1.4 ms; slice thickness = 6 mm; inter slice gap = 4 mm; FoV read 380 mm; FoV phase 78%; base resolution 192; phase resolution 70%; flip angle = 65°; in-plane pixel size = 2.8 × 2.0 mm; matrix 105 × 192 pixel; number of cardiac phases = 28; calculated phases = 25; number of segments = 15; bandwidth 930 Hz/Px; scan time = 11–14 sec (depending on the heart rate).

2.2. *Image analysis*

Images were analyzed in a blinded fashion and in a random order with commercially available computer software Argus (Siemens) by an experienced observer (BS). All subject identifiers and image parameters were removed from the images before analysis. Atrial volumes were assessed by the standard short axis method. Short axis slices were planned on horizontal and vertical long axis planes. At the base of the atria, slices were considered to be in the atrium if the blood was less than half surrounded by ventricular myocardium. If the blood was half or more than half surrounded by ventricular myocardium, the slice was considered to be in the ventricle. The boundary between the right atrium and the right ventricle was defined by the right atrio-ventricular groove and the septal insertion of the tricuspid valve. The slice with the largest atrial dimension was defined as atrial end diastole (at ventricular end systole before opening of the mitral valve, reflecting the maximal atrial volume). End systole was defined as the phase with the smallest atrial dimension (at ventricular end diastole, reflecting the smallest atrial volume). The endocardium of the left and right atrium was traced with a cursor in each end diastolic and end systolic slice, and the sum of the marked areas was used to calculate the total volume. Atrial end distolic volume (EDV) and end systolic volume (ESV) were calculated from the sums of the outlined areas using the Simpson's rule. Atrial stroke volume (SV) and EF were calculated from the formula SV = EDV−ESV and EF = SV/EDV × 100%.

To assess interobserver variability of the measurements a second observer (MA) measured the same data set, unaware of the results of the other observer.

2.3. *Statistical analysis*

Mean and standard deviation (SD) were derived for each of the parameters. The differences in calculated volumes and EF using different gating methods were assessed using paired *t*-test. All statistical tests were two tailed, p-value less than

Table 2. Interobserver variability of the left (A) and right (B) atrial volumes and EF measurements

A			
	Prospective triggering mean difference	P-value	95% limits of agreement
EDV [ml]	−0.16 ± 0.75	0.373	−1.7, 1.3
ESV [ml]	−0.19 ± 1.07	0.464	−2.3, 1.9
SV [ml]	0.03 ± 1.29	0.928	−2.6, 2.6
EF [%]	0.20 ± 1.99	0.677	−3.8, 4.1
	Retrospective triggering mean difference	P-value	95% limits of agreement
EDV [ml]	−0.06 ± 0.82	0.755	−1.7, 1.6
ESV [ml]	−0.12 ± 0.7	0.489	−1.5, 1.3
SV [ml]	0.05 ± 0.99	0.814	−1.9, 2.0
EF [%]	0.14 ± 1.38	0.672	−2.6, 2.9
B			
	Prospective triggering mean difference	P-value	95% limits of agreement
EDV [ml]	−0.09 ± 0.74	0.616	−1.6, 1.4
ESV [ml]	0.46 ± 1.37	0.172	−2.3, 3.2
SV [ml]	−0.55 ± 1.4	0.116	−3.3, 2.2
EF [%]	−0.76 ± 1.6	0.073	−3.9, 2.4
	Retrospective triggering mean difference	P-value	95% limits of agreement
EDV [ml]	−0.09 ± 0.81	0.627	−1.7, 1.5
ESV [ml]	0.15 ± 0.63	0.313	−1.1, 1.4
SV [ml]	−0.25 ± 1.1	0.352	−2.4, 1.9
EF [%]	−0.18 ± 1.2	0.527	−2.6, 2.2

0.05 was regarded as significant. Interobserver variability was defined with the formula (observer A − observer B)/(mean observer A and B). Bland-Altman plots were performed from the measurements obtained by the two observers (6).

3. Results

Differences in left and right atrial volumes and EF are displayed in Table 1 and Fig. 2. Left and right ESV were significantly smaller with the retrospectively gated SSFP sequence than with the prospectively triggered SSFP sequence (mean difference: ESV left 3.97 ± 1.3 ml, $p < 0.0001$; ESV right 4.34 ± 1.8 ml, $p < 0.0001$). Left and right EF and SV were significantly smaller with prospective triggering (mean difference: EF left −5.94 ± 0.9%, $p < 0.0001$; EF right −5.52 ± 1.3 %, $p < 0.0001$; SV left −3.99 ± 1.3 ml, $p < 0.0001$; SV right −4.32 ± 1.9 ml, $p < 0.0001$). As the left and right ESV increase, the difference between the volumes calculated from images acquired with prospective triggering and images acquired with retrospective gating gets larger, Fig. 3A. Left and right EDV remained unchanged (mean difference: EDV left −0.03 ± 0.8 ml, $p = 0.902$; right EDV 0.04 ± 0.7 ml, $p = 0.882$).

The Bland-Altman analysis of the differences between left and right atrial volumes and EF acquired with prospective triggering and retrospective gating is displayed in Fig. 3.

The interobserver variability for the left and right atrial volumes and EF is shown in Table 2.

4. Discussion

MRI is known to be accurate and reproducible for left and right ventricular function assessment and determination of cardiac volumes and EF (7–12). Up to present, prospective triggering has been routinely used for image acquisition. Published data for volume and EF assessment are mostly related to this gating technique (1, 2).

Using prospectively triggered image sequences, the acquisition window has to be set 10–20% below the average cycle length. Therefore, only 80–90% of the entire cardiac cycle is covered and available for data analysis (Fig. 1). Due to the fact that no data is recorded for the remaining 10–20% of the cardiac cycle, ventricular EDV and SV calculated from images acquired with a prospectively triggered gradient-echo sequence are underestimated. This results in significant differences in ventricular EF (4).

During ventricular systole, the left and right atrium is in diastole. Thus, changes of atrial volumes due to the gating technique used for image acquisition are expected to be different from changes observed for ventricular volumes. It is known that atrial volumes have a significant predictive value for the recurrence of atrial fibrillation after cardioversion (13, 14) and prognostic value for future cardiac events (15). Therefore, it is important to get the most accurate measurements for left and right atrial volumes and EF.

Up to present, it has not been studied how much atrial volumes and EF measurements are influenced by the gating method.

We found that ESV, SV, and EF differ significantly depending on the gating method used for image acquisition. SV and EF were underestimated by the prospective triggering method. The values for EDV remained unchanged for both atria regardless of the gating method used for image acquisition. The difference of the results between the two gating methods is due to the fact that prospective triggering does not cover the atrial late systole, whereas the entire cardiac cycle is covered by retrospective gating. Therefore, left and right atrial ESV are overestimated by using prospective triggering for image acquisition.

5. Conclusion

It can be concluded that the gating method has a significant impact on atrial volume and EF measurements. These findings might be of clinical value in settings where different imaging sequences and gating techniques are available. Imaging and sequence parameters need to be taken into account to distinguish between normal and abnormal and when using published data for reference values. For the most accurate volume and EF assessment, retrospectively gated gradient-echo cine sequences should be routinely used, in clinical practice and for research purpose.

5.1. *Limitations*

The spatial resolution was better in the prospectively triggered sequence than in the retrospectively gated sequence. The matrix size of the retrospectively gated sequence was reduced to avoid breath-hold durations intolerable to the majority of patients. The scan parameters were optimized for the sequence and gating method to get the best image quality within a reasonable breath hold time. However, the differences in the parameter setting could potentially have affected the results.

The authors did not study the differences in volumes and EF in patients with enlarged atria and irregular cardiac cycles. The authors wanted to elucidate the difference in volumes and EF using two different gating methods for image acquisition. The authors did not attempt to show the difference in various patient population.

References

1. Salton CJ, Chuang ML, O'Donnell CJ, Kupka MJ, Larson MG, Kissinger KV, Edelman RR, Levy D, Manning WJ. Gender differences and normal left ventricular anatomy in an adult population free of

hypertension. A cardiovascular magnetic resonance study of the Framingham Heart Study Offspring cohort. J Am Coll Cardiol 2002; 39:1055–1056.
2. Alfakih K, Plein S, Thiele H, Jones T, Ridgway JP, Sivananthan MU. Normal human left and right ventricular dimensions for MRI as assessed by turbo gradient echo and steady-state free precession imaging sequences. J Magn Reson Imaging 2003; 17:323–329.
3. Lenz GW, Haacke EM, White RD. Retrospective cardiac gating: a review of technical aspects and future directions. Magn Reson Imaging 1989; 7(5):445–455.
4. Sievers B, Addo M, Kirchberg S, Bakan A, John-Puthenveettil B, Franken U, Trappe HJ. Impact of the ECG gating method on ventricular volumes and ejection fractions assessed by cardiovascular magnetic resonance imaging. J Cardiovasc Magn Reson 2004; 7(2):441–446.
5. Brown MA, Semelka RC. MR imaging abbreviations, definitions and descriptions: a review. Radiology 1999; 213:647–662.
6. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1(8476):307–310.
7. Pattynama PM, Lamb HJ, Van der Velde EA, Van der Geest RJ, van der Wall EE, de Roos A. Reproducibility of magnetic resonance imaging-derived measurements of right ventricular volumes and myocardial mass. Magn Reson Imaging 1995; 13:53–63.
8. Sakuma H, Fujita N, Foo TK, Caputo GR, Nelson SJ, Hartiala J, Shimakawa A, Higgins CB. Evaluation of left ventricular volume and mass with breath-hold cine MR imaging. Radiology 1993; 188:377.
9. Dulce MC, Mostbeck GH, Friese KK, Caputo GR, Higgens CB. Quantification of the left ventricular volumes and function with cine MR imaging: comparison of geometric models with three-dimensional data. Radiology 1993; 188:337–371.
10. Sakuma H, Globits S, Bourne MW, Shimakawa A, Foo TK, Higgens CB. Improved reproducibility in measuring LV volumes and mass using multicoil breath-hold cine MR imaging. J Magn Reson Imaging 1996; 1:124–127.
11. Grothues F, Smith GC, Moon JC, Bellenger NG, Collins P, Klein HU, Pennell DJ. Comparison of interstudy reproducibility of cardiovascular magnetic resonance with two-dimensional echocardiography in normal subjects and in patients with heart failure or left ventricular hypertrophy. Am J Cardiol 2002; 90:29–34.
12. Grothues F, Moon JC, Bellenger NG, Smith GS, Klein HU, Pennell, DJ. Interstudy reproducibility of right ventricular volumes, function, and mass with cardiovascular magnetic resonance. Am Heart J 2004; 147:218–223.
13. Tsang TS, Barnes ME, Bailey KR, Leibson CL, Montgomery SC, Takemoto Y, Diamond PM, Marra MA, Gersh BJ, Wiebers DO, Petty GW, Seward JB. Left atrial volume: important risk marker of incident atrial fibrillation in 1655 older men and women. Mayo Clin Proc 2001; 76:467–475.
14. Barnes ME, Miyasaka Y, Seward JB, Gersh BJ, Rosales AG, Bailey, KR, Petty GW, Wiebers DO, Tsang TS. Left atrial volume in the prediction of first ischemic stroke in an elderly cohort without atrial fibrillation. Mayo Clin Proc 2004; 79:1008–1014.
15. Rossi A, Cicoira M, Zanolla L, Sandrini R, Golia G, Zardini P, Enriquez-Sarano M. Determinants and prognostic value of left atrial volume in patients with dilated cardiomyopathy. J Am Coll Cardiol 2002; 40:1425.