Left atrium MRI 4D-flow in atrial fibrillation: association with LA function

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Abstract

Left atrium (LA) is a principal site of thrombus formation inducing thromboembolic events, which have been associated with LA low flow velocities. Recent developments in magnetic resonance imaging (MRI) 4D flow analysis enable a non-invasive visualization of LA flow patterns. Our main objective was to investigate modifications of the main vortices in the LA with regards to LA functional indices in 4 patients with atrial fibrillation (AF) and 6 healthy volunteers. Vorticity threshold and Q-criterion indices were computed from the centered vorticity calculation on filtered 4D velocity MRI images. Phasic LA longitudinal strains were computed on cine MRI images using LA feature tracking algorithm. LA dilation in AF came along with a drop in LA longitudinal strains. Best correlations between LA flow and functional changes were found for velocity vs. longitudinal strains corresponding to reservoir and LA contraction phases (r=0.69 and r=0.81, p<0.03). Similarly, the highest correlation was found during LA contraction phase for associations between LA longitudinal strains and Q-criterion (r=0.52). In AF, LA functional changes are tightly associated with flow disorganization during the cardiac cycle especially during LA contraction phase.

1. Introduction

Left atrium (LA) has been described as a major site of thrombosis formation leading to stroke, particularly in case of atrial fibrillation (AF). Indeed, Virchows triad highlighted hemodynamic changes where stasis and turbulence are responsible for thrombosis formation in the LA. Several studies using either echo particle image velocimetry (echoPIV) or MRI [1–3] highlighted the differences in LA flow between patients with AF and healthy subjects. Furthermore, LA dilation is reported to be induced by increased LA pressures [4]. To the best of our knowledge, associations between LA flow and LA function, which could help understanding the mechanism of stasis appearance, have not been investigated yet. This might be due to the difficulty of studying LA phasic function, which is now rendered feasible using the recently proposed feature tracking [5]. Furthermore, hemolysis has been related to instantaneous energy dissipation and relationships between vortices and such energy dissipation are still to be investigated [6]. Vortex detection was studied in a echoPIV cohort, which highlighted that additional indices for quantifying LA flow organization are required [1, 3].

MRI, with its 4D flow and cine sequences, offers new perspectives in terms of studying the interplay between LA flow and functional changes. Besides, as a part of MRI 4D-flow analysis and intrinsically linked to turbulence, the detection of vortices would highlight a new understanding of flow using fluid mechanics vorticity criteria methods [7–9]. Q-criterion was considered and tested here for the vortex detection in the LA. Accordingly, the objectives of this study were :

- To detect LA flow modifications through velocities distribution and vortices quantitative measurements.
- To assess ability of such quantitative indices to characterize patients with AF, as compared to healthy controls.
- To investigate associations between LA flow vortices development and LA myocardial function.

2. Methods

2.1. Population

Six healthy volunteers (24.7±2.4 y.) and 4 patients with AF (55.8±9.9 y. in sinus rhythm during MRI) underwent MRI exams including 4D flow sequences covering the whole LA volume (Figure 1). Acquisition parameters were: acquisition matrix of 170x178.7±6.2x93.4±8.2 with slice thickness of 2±0.2mm oriented according to patient anatomy, repetition time of 40.3±11.75 ms, echo time of 2.64±0.12ms, flip angle of 8deg, voxel size of 1.94±0.8 mm^2x2±0.2 mm and temporal resolution ranged between 37.5 and 45ms (mean 40.2±1.7ms).

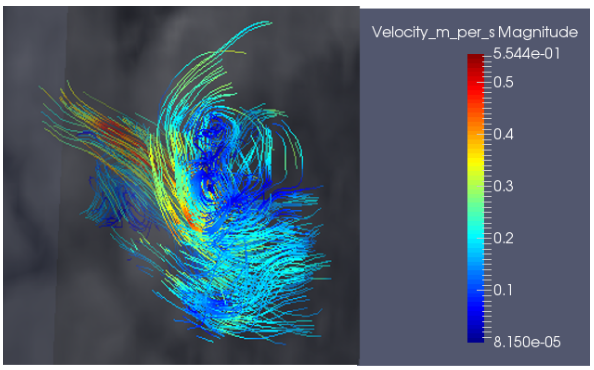

Figure 1. Streamlines in left atrium for a healthy volunteer at reservoir peak strain.

Additionally, cine steady state free precession (SSFP) images corresponding to the 2 chamber, 3 chamber and 4 chamber views were used to determine global longitudinal strain as in [5] (Figure 2). Briefly, the endocardial contour of the LA was manually defined on a single phase for each view and then automatically propagated using a feature tracking algorithm through the cardiac cycle. Such endocardial border tracking enabled the estimation of LA myocardial strain for different LA phases: reservoir (LV systole), conduit (LV active filling) and LA contraction (LV passive filling).

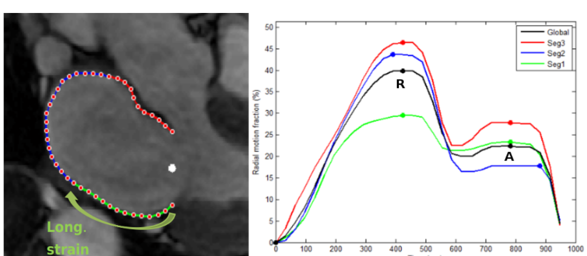

Figure 2. Left atrial longitudinal strain: reservoir (R), conduit (R-A) and LA contraction (A) phase.

2.2. Velocity and vorticity criteria

3D Vorticity is defined for 4D CMR velocity components using the rotational operator and described a local rotating constraint sustained by the flow :

$$\omega_{i,j} = \begin{pmatrix} \frac{\partial V_z}{\partial y} - \frac{\partial V_y}{\partial z} \\ \frac{\partial V_x}{\partial z} - \frac{\partial V_z}{\partial x} \\ \frac{\partial V_y}{\partial x} - \frac{\partial V_x}{\partial y} \end{pmatrix} \quad (1)$$

with each derivative approximated by

$$\frac{\partial V_x}{\partial y} = \frac{V_x i-1,j - V_x i+1,j}{2 * \partial y}. \quad (2)$$

Two criteria have been defined for the identification of vortices [8]

- direct thresholding of vorticity modulus map, using the first and second tertiles, to detect vortex center
- Q-criteria.

From the Jacobian matrix J, S is defined as: $S = \frac{1}{2} * (J + J^T)$ and $\Omega = \frac{1}{2} * (J - J^T)$.
$Q = \frac{1}{2} * (||S^2|| + ||\Omega^2||)$ with $||G|| = [tr(GG^T)]^{1/2} > 0$ defined by [10] for vortex center. Q-criterion, $Q > 0$, is defined in a spatial region where fluid strain rate is dominated by the Euclidian norm of the vorticity tensor [7]. Since, vorticity thresholding was reported to be subjective by Jeong et al., Q-criterion could be seen as an alternative for vortices detection. Under appropriate assumptions, it determines spatial location of pressure minimum in a two-dimensional plane for Navier-Stokes flows.

In order to analyze LA flow automatically as well as to provide macroscopic indices of vortices formation during each LA phase, the two vorticity criteria were defined for reservoir, conduit and LA contraction phases. First and second tertiles during each phase were used as threshold values for vortices detection.

3. Results

3.1. Subject characteristics

Table 1. Subjects characteristics and LA volumes.

	Healthy sub. (n=6)	AF Patients (n=4)
BSA (m2)	1.8± 0.2	2.1± 0.2
BMI (kg/m2)	22.2± 1.8	26.8± 2.9
Ind. LADV (mL/m2)	38± 10.3	57.3± 11.9
Ind. LASV (mL/m2)	16.6± 6.6	45± 19.7

Subjects basic characteristics and LA volumes are summarized in Table 1. Along with the expected LA dilation in AF, our strain analysis revealed a reduction of all LA functional parameters in AF patients: reservoir longitudinal strains were 33±44% in controls and 14±15% in AF, conduit longitudinal strains were 16±5% and 7±8% and LA contraction longitudinal strains were 17±2% and 8±7%, respectively.

3.2. Flow in LA

Percentage of velocities under 20cm/s have been shown to be significantly different between healthy volunteers and AF patients [2]. Our results were similar although significance was not reached due to the small number of subjects (Table 2). Velocity mean values were substantially reduced in AF patients, as compared to healthy subjects. Indeed a drop in mean velocity in AF of 40% was found during reservoir phase, of 44% during conduit phase and 31% during LA contraction phase. Vorticity mean values decreased in AF as compared to healthy subjects by 13% during reservoir phase, 6% during conduit phase and 27% during LA contraction phase.

Table 2. Velocity and vorticity mean values during LA functional phases. Res for reservoir, Cond. for conduit and LA cont. for LA contraction phase.

	Healthy sub. (n=6)	AF Patients (n=4)
Age (y.)	24.7± 2.4	55.8± 9.9
Vel. $>$ 20cm/s (%)	26.5± 10.1	10.2± 11.4
Res. Vel. (cm/s)	18.1± 4.0	10.8± 5.2
Cond. Vel. (cm/s)	17.6± 4.1	9.8± 4.9
LA cont. Vel. (cm/s)	15.9± 3.8	11.0± 4.6
Res. Vor. (1/s)	25 038± 8 240	21 919± 10 224
Cond. Vor. (1/s)	7 131± 1 850	6 699± 2 895
LA cont. Vor. (1/s)	17 793± 3 699	12 927± 7 001
Res. Q-crit.	4 342e6± 3 480e6	4 016e6± 3 584e6
Cond. Q-crit.	188.9e6± 123.6e6	303.7e6± 383.8e6
LA cont. Q-crit.	23.7e6± 18.8e6	77.4e6± 99.9e6

Q-criterion decreased in AF as compared to controls by 7.5% in average for reservoir phase and increased by 60.8% for conduit phase and by 226.5% for LA contraction phases. Overall highest vorticity values were found for reservoir function for both AF and controls.

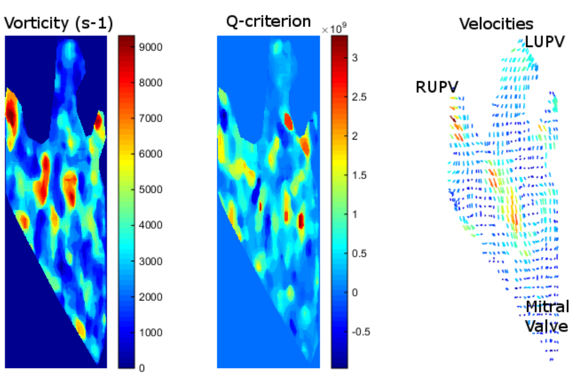

Figure 3. Vorticity, Q-criterion and velocity vectors in LA in healthy volunteer at end of reservoir phase. Right (RUPV) and left (LUPV) upper pulmonary veins.

3.3. LA flow-function interplay

Associations between LA functional parameters and LA flow indices during each phase of the LA function (Fig. 4) were investigated while considering both AF patients and controls. The strongest correlations were found for LA contraction longitudinal strains with Q criterion values. Additionally, longitudinal strain corresponding to LA contraction correlated highly with velocity index (r=0.81).

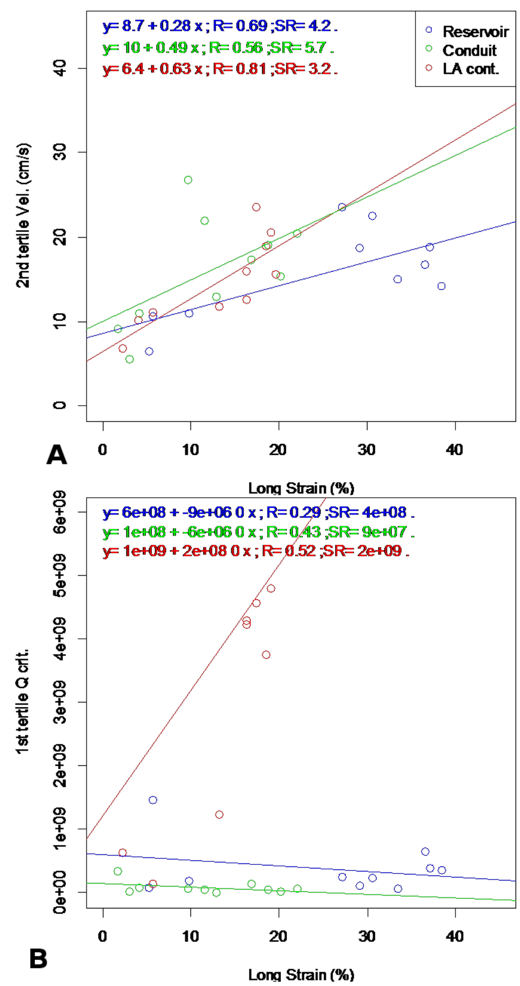

Figure 4. Correlations between longitudinal strains corresponding to the LA reservoir, conduit and contraction phases and velocity (A) and Q criterion (B) indices.

4. Discussion

As previously described, percentage of velocities under 20cm/s was increased in AF patients resulting in LA stasis development which could lead to thrombus formation. Mean velocity values were mostly altered during reservoir and conduit phases whereas mean vorticity values and Q-criterion values were mostly altered during conduit and LA contraction phases.

The decrease of Q-criterion in AF patients during reservoir phase could suggest absence of vortices during this phase in patients as previously described in [11]. The rise of Q-criterion values during both conduit and LA contraction phases would on the contrary suggest an increase of vortices formation during both phases.

LA flow and functional indices correlated for active LA phases (reservoir, contraction) in terms of velocities, as higher longitudinal strain depicted substantial LA relaxation or contraction inducing higher velocities. The correlation found between Q-criterion values and longitudinal strain were stronger during LA contraction phase, as compared to reservoir and conduit phases. Such finding suggests that vortices during LA contraction phase were created by LA motion whereas reservoir and conduit vortices may result from pulmonary veins inflow and LV suction, respectively, rather than from LA deformation.

Our results show that vortices mainly developed in AF as compared to controls during both conduit and LA contraction phases and that modifications in flow organization are related to LA functional alterations not only in terms of velocity but also in terms of vorticity and vortices formation.

Velocity, vorticity and Q-criteria analysis provided a comprehensive view and understanding of modifications of flow in LA in case of AF.

Q-criterion appeared to provide interesting input for vortices detection during LA contraction phase. The definition of an adapted threshold for each of the criteria previously used for the detection of flow alteration needs further investigation. In our data, the use of the second tertile, as a Q-criterion threshold value rather than the first tertile resulted in better correlations with LA functional indices.

The first limitation of our study is the limited number of subjects. However one might remind that 4D flow imaging is still time consuming and thus not easy to include in clinical MRI workflow. Besides, despite the small number of subjects, the data studied here are highly original since LA flow and function were studied non-invasively and quantitatively in the same subjects during the same exam. Another limitation is the absence of studying timings of vortices formation. This was not done here to avoid drawing erroneous conclusions because of the insufficient temporal resolution of 4D flow MRI.

5. Conclusion

LA flow quantitative analysis through velocity distribution and vorticity criteria enabled to characterize flow changes in AF. LA flow and function interplay at each phase of the LA function revealed the association between LA contraction alteration and the development of vortices and stasis.

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