Altered left ventricular vortex ring formation by 4-dimensional flow magnetic resonance imaging after repair of atrioventricular septal defects

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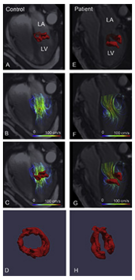
ABSTRACT

Objectives: During normal left ventricular (LV) filling, a vortex ring structure is formed distal to the left atrioventricular valve (LAVV). Vortex structures contribute to efficient flow organization. We aimed to investigate whether LAVV abnormality in patients with a corrected atrioventricular septal defect (AVSD) has an impact on vortex ring formation.

Methods: Whole-heart 4D flow MRI was performed in 32 patients (age: 26 ± 12 years), and 30 healthy subjects (age: 25 ± 14 years). Vortex ring cores were detected at peak early (E-peak) and peak late filling (A-peak). When present, the 3-dimensional position and orientation of the vortex ring was defined, and the circularity index was calculated. Through-plane flow over the LAVV, and the vortex formation time (VFT), were quantified to analyze the relationship of vortex flow with the inflow jet.

Results: Absence of a vortex ring during E-peak (healthy subjects 0%, vs patients 19%; $P = .015$), and A-peak (healthy subjects 10% vs patients 44%; $P = .008$) was more frequent in patients. In 4 patients, this was accompanied by a high VFT (5.1-7.8 vs 2.4 ± 0.6 in healthy subjects), and in another 2 patients with abnormal valve anatomy. In patients compared with controls, the vortex cores had a more-anterior and apical position, closer to the ventricular wall, with a more-elliptical shape and oblique orientation. The shape of the vortex core closely resembled the valve shape, and its orientation was related to the LV inflow direction.

Conclusions: This study quantitatively shows the influence of abnormal LAVV and LV inflow on 3D vortex ring formation during LV inflow in patients with corrected AVSD, compared with healthy subjects. (J Thorac Cardiovasc Surg 2015;150:1233-40)



Different vortex core orientation and shape in patient with corrected AVSD compared with control.

Central Message

Atrioventricular valve morphology and abnormal vortex formation in the left ventricle are closely related in patients who have undergone correction for AVSD.

Perspective

Vortex structures that form in the LV during diastolic filling contribute to efficient flow organization. The 4D flow MRI shows abnormalities of the 3-D vortex cores, which relate to LAVV and inflow abnormalities, in patients who have had AVSD corrected. This study stresses the relationship between LAVV morphology and surgery and abnormal vortex formation.

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E.E. Calkoen is supported by a grant from the Willem-Alexander Kinder-en Jeugdfonds; M.S.M. Elbaz and J.J.M. Westenberg are supported by a grant from the Dutch Technology Foundation (STW), project number 11626.

E.E. Calkoen and M.S.M. Elbaz contributed equally to this work. A.A.W. Roest and R.J. van de Geest contributed equally to this work.

Received for publication May 7, 2015; revisions received July 1, 2015; accepted for publication July 15, 2015; available ahead of print Aug 14, 2015.

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0022-5223/$36.00

http://dx.doi.org/10.1016/j.jtcvs.2015.07.048

Supplemental material is available online.

Patients with an atrioventricular septal defect (AVSD) require corrective surgery early in life to prevent pulmonary overflow and heart failure. Compared with a normal mitral valve, the mural (posterior) leaflet of the left atrioventricular valve (LAVV) is smaller, and the anterolateral papillary muscle is positioned more laterally in AVSD hearts.[1,2] Furthermore, the presence of a single papillary muscle and double orifice are described.[3] Moreover,

Abbreviations and Acronyms

- AVSD = atrioventricular septal defect
- A-peak = peak early filling
- EDV = end-diastolic volume
- E-peak = peak late filling
- ESV = end-systolic volume
- LAVV = left atrioventricular valve
- LV = left ventricle
- VFT = vortex formation time
- 3D = 3-dimensional
- 4D flow = 4-dimensional (3-directional and time)

surgical correction of an AVSD, including closure of the ‘‘cleft,’’ may result in restricted opening of the LAVV[4] and a more-lateral inflow,[5] which might affect efficiency of cardiac blood flow in the left ventricle (LV).

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Survival after surgical correction is excellent in the current era, but the reoperation rate due to valve regurgitation is high.[6,7] Long-term follow-up data on cardiac function or exercise capacity after AVSD correction are lacking. However, deterioration of cardiac function and New York Heart Association class is described during pregnancy, when cardiac flow increases.[8]

Recently, the formation of a vortex within the LV during diastole was related to the inflow area through the mitral valve in healthy subjects.[9] The formation of vortex structures (ie, compact regions of swirling blood flow) in LV blood flow patterns during diastolic filling has recently emerged as a potential novel index for characterizing efficient LV blood flow and evaluating cardiac chamber (dys) function.[10] During LV filling, a vortex ring structure distal to the mitral valve leaflets and enclosing the inflow jet is observed. This vortical flow is considered an efficient mechanism for transporting a significant portion of LV-filling volume toward the aorta,[11] minimizing energy loss, and helping mitral valve closure.[12,13] Recently, 3-directional, 3-dimensional (3D) and time-resolved velocity-encoded MRI (magnetic resonance imaging; 4D flow MRI) has been introduced to assess vortex ring formation during LV filling in vivo,[9] because it has the advantage of a 3D evaluation of the vortex ring.

Given the relationship between the vortex ring properties and the mitral valve morphology and LV inflow,[9,14-17] we hypothesized that LAVV abnormalities, and associated abnormal lateral inflow[5] after surgical AVSD correction, may result in disturbed vortex flow during LV filling. Therefore, we used 4D flow MRI to identify and quantitatively characterize the geometric properties and anatomic location of vortex ring cores during early and late LV filling, allowing quantitative assessment of 3D vortex ring properties in AVSD-corrected patients and comparison with healthy controls.

METHODS

Study Population

The study was approved by the ethical committee of the Leiden University Medical Center, and written informed consent was obtained from all participants or their parents. Thirty-two patients with a history of corrected AVSD were prospectively enrolled from a surgical database.[18] Thirty healthy subjects of similar age, without a history of cardiac disease, were included for comparison.

Participants in the current study were included in previous studies with the aim of characterizing and quantifying diastolic transatrioventricular flow.[5,19] Twenty-four of the 30 healthy subjects were included in a study that provided reference values for 3D vortex LV flow.[9] None of the previously published papers addresses vortex formation in corrected AVSD patients. For clarity, we use the term ‘‘left atrioventricular valve’’ (LAVV) in patients and controls, instead of referring to the mitral valve in healthy subjects, and the LAVV in patients.

Magnetic Resonance Imaging Acquisition and Analysis

Whole-heart 4D flow was obtained on a 3T MRI scanner (Ingenia; Philips Medical Systems International, Best, The Netherlands), with a maximal gradient amplitude of 45 mT/m for each axis, and a slew rate of 200 T/m/s, using a combination of FlexCoverage Posterior coil in the table top with a dStream Torso coil, providing up to 32 coil elements for signal reception. Imaging details are reported elsewhere.[5]

In short, a 3D volume acquisition of the heart was performed with a velocity encoding of 150 cm/s in all 3 directions, and spatial resolution of $2.3 \times 2.3 \times 3.0 - 4.2\ mm^3$; 30 cardiac phases were retrospectively reconstructed to represent 1 average heartbeat, with a maximal true temporal resolution of 31 ms. Furthermore, to quantify LV volumes and ejection fraction, a left 2-chamber and 4-chamber cine view, and a short-axis cine stack of slices, was acquired with steady-state free-precession sequences as reported elsewhere.[5] Spatial resolution was $1.0 \times 1.0 \times 8.0\ mm^3$; in addition, for these acquisitions, 30 phases were retrospectively reconstructed.

All acquisitions were performed with free breathing and no respiratory motion control. The cine steady-state free-precession acquisitions were all performed with 3 signal averages to suppress breathing artifacts. After manual segmentation of LV endocardial boundaries, the LV end-diastolic volume (LVEDV), end-systolic volume (ESV), and ejection fraction were calculated. The sphericity index of the LV was calculated as LVEDV/(π/6 $\times$ long-axis at end-diastole[3]).

A 3D Vortex Core Analysis Based on the Lambda2 Method

Using the image analysis workflow described elsewhere,[9] the cores of vortex structures within the LV blood flow during diastole, as acquired from the 4D flow MRI data, were identified by a single observer using the Lambda2 method.[20] In short, the Lambda2 method is a fluid-dynamics–based method that uses the gradient properties of the velocity field to identify vortex cores in the flow. For each subject, the vortex cores were identified at the early (E-peak) and late (A-peak) filling, defined from the trans-LAVV flow quantification, described later, and visualized as isosurfaces.

Qualitative visual inspection of the shape of detected vortex cores was performed to determine whether a 3D ring-shaped vortex core was present, defined as a vortex core with a donut-like (torus) shape (Figure 1). If a vortex ring core was detected during E-peak and/or A-peak, its 3D position (in normalized cylindrical coordinates), orientation, and shape were quantitatively characterized, as illustrated in Figure 1.

Trans–Left Atrioventricular Valve Flow

Trans-LAVV flow was quantified using the 4D flow MRI data and retrospective valve tracking.[21] From the through-plane LAVV velocity map, a