# Two-Dimensional Plot Visualization of Aortic Vortex Flow in Cardiac 4D PC-MRI Data

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**Abstract.** Aortic vortex flow is a strong indicator for various cardiovascular diseases. The correlation of pathologies like bicuspid aortic valves to the occurrence of such flow patterns at specific spatio-temporal positions during the cardiac cycle is of great interest to medical researchers. Dataset analysis is performed manually with common flow visualization techniques such as particle animations. For larger patient studies this is time-consuming and quickly becomes tedious. In this paper, we present a two-dimensional plot visualization of the aorta that facilitates the assessment of occurring vortex behavior at one glance. For this purpose, we explain a mapping of the 4D flow data to circular 2D plots and describe the visualization of the employed $\lambda_2$-vortex criterion. A grid view allows the simultaneous investigation and comparison of multiple datasets. After a short familiarization with the plots our collaborating cardiologists and radiologists were able distinguish between patient and healthy volunteer datasets with ease.

## 1 Introduction

Four-dimensional phase-contrast magnetic resonance imaging (4D PC-MRI) made great advances in the last decade [1,2]. It enables the non-invasive acquisition of time-resolved, three-dimensional information about the intravascular hemodynamics. The gained insight supports diagnosis and severity assessment of different cardiovascular diseases (CVD). Vortex flow in the great mediastinal vessels such as the aorta is presumed to be a strong indication of several pathologies. Therefore, studies with homogeneous patient groups are performed to quantify the probability of vortex occurrence in specific vessel sections during the cardiac cycle.
Common pathline visualizations [3] of the highly complex 4D PC-MRI datasets allow qualitative analysis. Köhler et al. [4] adapted the line predicates technique to semi-automatically filter vortex flow. Such methods are essential to make 4D PC-MRI viable for the clinical routine. Nevertheless, when the pathlines are displayed all at once by ignoring their temporal component, heavy visual clutter remains. Particle animations alleviate this problem, but increase the required

evaluation time per dataset.
Different works established simplified visualizations of the cardiovascular morphology. Cerqueira et al. [5] proposed the nowadays widely used 2D Bull's Eye Plot (BEP) of the left ventricle that is based on a standardized segmentation. The plot is simple, unambiguous and thus a convincing reduction of the 3D information. Angelelli et al. [6] introduced a straightening of tubular structures and applied it to the aorta in order to enhance flow analysis with reference to the main flow direction, which usually is the centerline. Yet, when the whole cardiac cycle is to be analyzed, numerous such visualizations with different temporal positions are required.
In this work, we introduce a circular 2D plot that is adaptable to various flow characteristics. We focus on vortex flow due to the strong correlation to cardiovascular pathologies. The plot provides detailed information about the temporal position and reasonably approximates the corresponding vessel section. A grid view of different datasets enables the fast assessment of vortex behavior in a user-defined database. A scalar parameter controls the plots' sensitivity towards vortex flow. The possibility to set already analyzed datasets as references enhances the classification of new cases. After a brief training our collaborating cardiologists and radiologists were able to reliably find pathologic cases in the grid view.

### 1.1 Medical Background

The aorta is the largest artery of the body with a vessel diameter of about 2-3 cm. Oxygenated blood comes from the left ventricle (LV), passes the aortic valve (AV) and is then supplied to the body. Systole denotes the phase of LV contraction, when the AV is opened. During diastole, when the LV is relaxed, the AV is closed and prevents retrograde flow. A pathologic dilation of the aorta is called ectasia. If the vessel diameter is above 1.5 the original size, it is referred to as aneurysm. The altered morphology promotes the formation of vortex flow in the corresponding vessel section. The AV normally consists of three leaflets. In bicuspid aortic valve (BAV) patients two of them adhere. Hope et al. [7] detected systolic vortex flow in the ascending aorta, the vessel section directly behind the valve, in 75% of their BAV patients. For furthers details about the relation between vortex flow and cardiovascular pathologies we refer to [4].

## 2 Material and Methods

In the following, the 4D PC-MRI dataset acquisition and preprocessing pipeline are described. We proceed with a detailed explanation of the 4D data to 2D plot projection, the employed $\lambda_2$-vortex measure and grid view as solution to one of its drawbacks.

### 2.1 Data Acquisition and Preprocessing

The 4D PC-MRI data were acquired using a 3 T Siemens Verio MR scanner with a maximum expected velocity ($V_{ENC}$) of 1.5 m/s per dimension. A dataset contains each three (x-, y- and z-dimension) time-resolved flow and magnitude images that describe the flow direction and strength (i.e. the velocity), respectively. All temporal positions together represent one full heartbeat. The spatio-temporal resolution is 1.77 mm $\times$1.77 mm in a 132 $\times$ 192 grid with 3.5 mm distance between the 15 to 23 slices and about 50 ms between the 14 to 21 time steps. Artifact reduction in the flow images was performed using eddy current correction and phase unwrapping [8]. A maximum intensity projection over time (tMIP) of the magnitude images is calculated as basis for the graph cut-assisted segmentation.[1] The resulting three-dimensional binary vessel mask is postprocessed using morphological closing and opening. A surface mesh is obtained via marching cubes, subsequently low-pass filtered as well as reduced and then used to extract a centerline.[2] The GPU is utilized to integrate pathlines using an adaptive step size Runge-Kutta-4 scheme with quadrilinear interpolation of the flow velocity vectors and to calculate the $\lambda_2$-criterion for the line predicate-based vortex extraction [4]. It is ensured that each voxel in every temporal position is visited at least once.

### 2.2 Aortic Vortex Plot

*Mapping:* Intravascular positions $\boldsymbol{x} = (x, y, z, t)$ in the 4D PC-MRI dataset consist of a three-dimensional spatial and a one-dimensional temporal component. The circular plot visualization, however, offers merely an angle $\phi$ and a distance $d$ to the center as degrees of freedom.
Medical research papers, which correlate the presence of vortex flow patterns to specific pathologies, have two central questions: *When* (during the cardiac cycle) does the vortex occur and in *what vessel section*? We decided to map a vortex' temporal position to the plot's angle as an analogy to a clock and due to the cyclic nature of the data. The first time step is located 12 o'clock, the direction is clockwise. Now there is only the center distance $d$ left to map the spatial position. The idea is to employ the centerline for this purpose. The projection $\boldsymbol{p}$ of a spatial position in the vessel onto the centerline is determined and used to obtain $d \in [0, 1]$ as $\sqrt{\text{length (centerline until } \boldsymbol{p})\ /\ \text{length (centerline)}}$. Thus, the plot center corresponds to the approximate aortic valve location, where the centerline starts. Increasing $d$ encode positions in the aortic arch and descending aorta. The square root is used to ensure that inner and outer parts of the plot are represented with equally large areas. Figure 1 depicts the mapping.

*Vortex Processing:* Each centerline point stores $T$ values, where $T$ is the number of time steps in the dataset. These buckets are used to accumulate a quantitative measure, in our case the $\lambda_2$-criterion since it is well suited for vortex

[1] GridGraph_3D_26C (GridCut)
[2] vtkMarchingCubes, vtkWindowedSincPolyDataFilter, vtkQuadricDecimation (VTK) and vmtkcenterlines (VMTK)

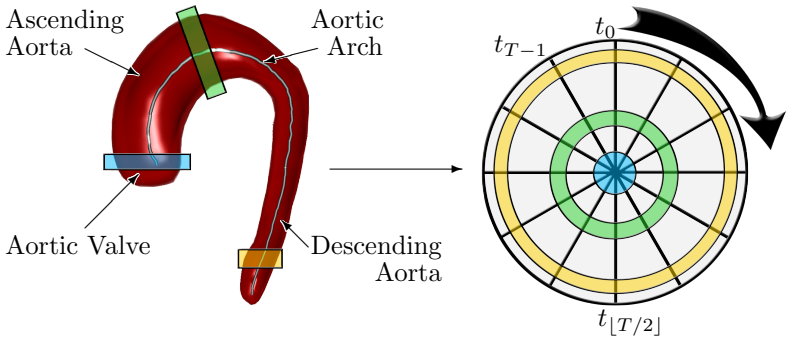



**Fig. 1.** Mapping intravascular positions to the plot. The temporal position corresponds to the angle – analogous to a clock. The first time step is at 12 o'clock, the direction is clockwise. The distance from the plot center encodes the position on the centerline. Central areas (blue, green) present vessel sections near the aortic valve, whereas increasing distances (yellow) show the descending aorta.

extraction in the cardiac 4D PC-MRI context [4]. As a preprocessing the centerline is equidistantly resampled in 0.5 mm steps via cubic spline interpolation[3] in order to have the same distances in different datasets and a sufficient amount of buckets. Since our employed Runge-Kutta-4 integration uses adaptive step sizes, the vortex representing pathlines are resampled as well in the same manner. Afterwards, every point of each pathlines is processed. The closest spatio-temporal projection onto the centerline is determined and the $\lambda_2$-value of the pathline vertex is split among the 2 neighboring centerline buckets weighted by their inverse distance to the projection. After evaluating all pathlines the mean $\lambda_2$-value is calculated for each bucket. A binomial smoothing of the accumulated values is performed as postprocessing. Vortices are present where $\lambda_2 < 0$. The smaller $\lambda_2$ is, the stronger is the vortex flow. Unfortunately, the criterion has no fixed minimum, which negatively affects the comparability between different datasets. As a remedy, we let the user define a minimum $\lambda_2$-value as parameter $\alpha$ within 0 and the minimal occurring $\lambda_2$-value. The closer $\alpha$ is to 0, the more sensitive the visualization is towards vortex flow. The parameter is used to scale as well as clamp the $\lambda_2$-values to $[0, 1]$. The scaled values are then mapped to an arbitrary color scale. We employ the rainbow scale since this a common choice in the clinical context.

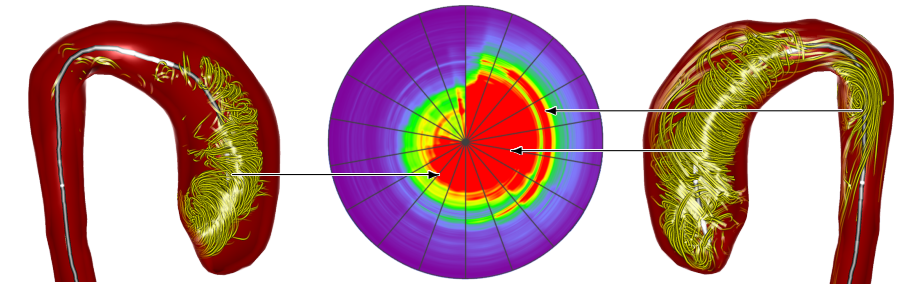
*Dataset Comparison:* A grid view is provided to enable the efficient comparison of multiple datasets. The sensitivity parameters $\alpha$ is used globally for all plots. The user has the option to choose known cases as reference plots in addition to the actual cases that are selected for evaluation.

## 3 Results

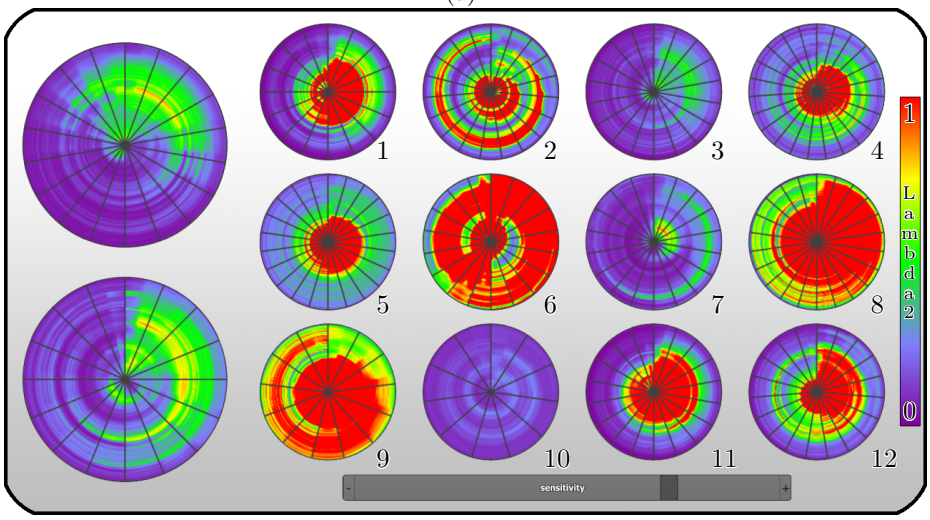
We used 14 datasets for the evaluation: 5 healthy volunteers, 2 patients with an ectatic ascending aorta and 7 BAV patients. Each patient has prominent systolic

[3] spline1dbuildcubic (ALGLIB)

vortex flow in the ascending aorta. The computation time per case is between 2 and 5 s on an Intel i7-3930K depending on the amount of pathlines. Figure 2(a) shows one of the patients with a dilated ascending aorta and depicts the relation between occurring vortex flow and the resulting plot. Figure 2(b) shows the proposed grid view with all datasets. The two larger plots on the left are healthy volunteers that were selected as references. The sensitivity parameter $\alpha$ was interactively adjusted so that these two plots merely indicate the slight physiologic helix in the aortic arch during systole. In an informal evaluation our collaborating radiologists and cardiologists were easily able to spot the remaining three healthy volunteers without pathologic vortex flow.



(a)




(b)

**Fig. 2.** (a) Diastolic (left) and systolic vortex flow (right) and the resulting vortex plot of a patient with an ectatic ascending aorta. (b) Two healthy volunteers are shown as larger reference plots on the left. Three more healthy volunteers (3, 7, 10) are among 2 patients with an ectatic ascending aorta (1, 11) and 7 BAV patients.

## 4 Discussion

We presented a two-dimensional circular plot visualization of aortic vortex flow. Domain experts were able to quickly assess whether or not pathologic vortices are present in a dataset and could estimate their positions and temporal extents. Presenting the temporal position based on a clock analogy was considered as intuitive, whereas the mapping of spatial positions using the centerline required a short briefing. A possible application of our method is to get a quick overview of datasets in larger studies. Tasks such as counting the BAV patients with systolic vortex flow in the ascending aorta can be performed comfortably. In addition, our method could support the clinical report generation and serve as a summary of a patient's vortex flow behavior. Our method provides no information about a vortex' wall closeness, which might be interesting due to the association with high shear forces [9]. However, a visualization or integration of other measures in the plot derived from arbitrary flow properties or line predicates is conceivable. The comparability of datasets acquired with different scanners and/or MR sequences has to be analyzed in a future work. Potential problems may arise due to differently scaled $\lambda_2$-values. Our proposed plot uses exactly one centerline to project the spatial intravascular positions. Another future topic could be the adaption for branching vessels like the pulmonary artery.

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