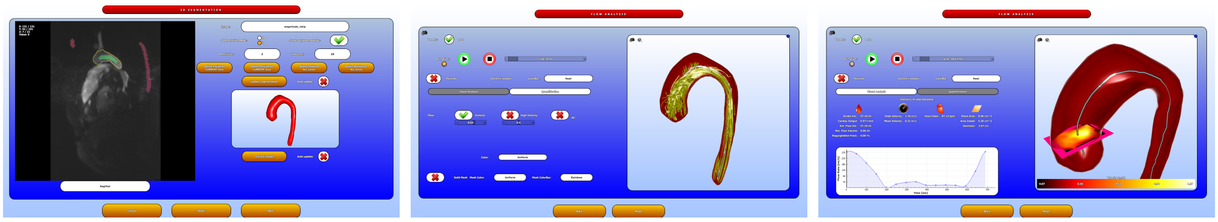
Guided Analysis of Cardiac 4D PC-MRI Blood Flow Data

Benjamin Köhler[1], Uta Preim[2], Matthias Grothoff[3], Matthias Gutberlet[3], Katharina Fischbach[4], Bernhard Preim[1]

[1] Department of Simulation and Graphics, Otto-von-Guericke University, Magdeburg, Germany
[2] Department of Diagnostic Radiology, Hospital Olvenstedt, Magdeburg, Germany
[3] Department of Diagnostics and Interventional Radiology, Heart Center, Leipzig, Germany
[4] Department of Radiology and Nuclear Medicine, University Hospital, Magdeburg, Germany

ben.koehler@isg.cs.uni-magdeburg.de



(a) Graph cut-assisted vessel segmentation. (b) Semi-automatic vortex extraction. (c) Cardiac function assessment.

Figure 1: Screenshots of the presented software *Bloodline* for cardiac 4D PC-MRI data evaluation.

Abstract

Four-dimensional phase-contrast magnetic resonance imaging (4D PC-MRI) allows the non-invasive acquisition of temporally resolved, three-dimensional blood flow information. Quantitative and qualitative data analysis helps to assess the cardiac function, severity of diseases and find indications of different cardiovascular pathologies. However, various steps are necessary to achieve expressive visualizations and reliable results. This comprises the correction of special MR-related artifacts, the segmentation of vessels, flow integration with feature extraction and the robust quantification of clinically important measures. A fast and easy-to-use processing pipeline is essential since the target user group are physicians. We present a system that offers such a guided workflow for cardiac 4D PC-MRI data. The aorta and pulmonary artery can be analyzed within ten minutes including vortex extraction and robust determination of the stroke volume as well as the percentaged backflow. 64 datasets of healthy volunteers and of patients with variable diseases such as aneurysms, coarctations and insufficiencies were processed so far.

Categories and Subject Descriptors (according to ACM CCS): I.4.9 [Computing Methodologies]: Image Processing and Computer Vision—Applications

1. Introduction

Cardiovascular diseases (CVDs) are the most frequent cause of death in the world. Understanding their origin and evolution may improve diagnosis and the choice of appropriate treatments. Vortex flow has been determined as an atypical flow pattern that is caused by, e.g., heart valve defects or an altered vessel morphology. Quantitative measures such as stroke volumes facilitate the assessment of the present cardiac function and the tracking of disease progression by evaluating follow-up examinations.

Four-dimensional phase-contrast magnetic resonance imaging (4D PC-MRI) gained increasing importance in the last decade. Its 2D equivalent measures the flow in only one preangulated slice. Unsatisfactory results make a new acquisition necessary, which is stressful for the patient. In contrast, 4D PC-MRI datasets contain the full spatio-temporal blood flow information and thus allow a more flexible analysis. Recent advances greatly reduced acquisition times to levels that are feasible for the clinical routine. Although it has the potential to replace 2D PC-MRI, 4D flow scans are mainly performed for research purposes at the moment. This points out the need for standardized and guided techniques to analyze these highly complex data. Software solutions that integrate such methods into easy-to-use workflows are of equal importance. We present a tool that facilitates data analysis within ten minutes. This includes an automated data preprocessing, a graph cut-assisted vessel segmentation, semi-automatic vortex flow extraction and analysis of the stroke volume as well as percentaged backflow. Resulting visualizations can easily be saved and shared using the provided one-click solutions for videos of the animated flow and screenshots of the 3D view or GUI.

2. Previous and Related Work

Markl et al. [MFK*12] provide an overview of 4D PC-MRI acquisitions, Calkoen et al. [CRvdG*14] document its high flexibility by describing recent applications. Line predicates were used by Born et al. [BPM*13] to extract flow features and employed in a previous work to extract vortex flow [KGP*13]. Relevant quantitative measures such as stroke volumes are described by Hope et al. [HSD13]. We developed a method to robustly determine stroke volumes and percentaged backflow (regurgitation fractions) [KPG*14].

MeVisFlow by Hennemuth et al. [HFS*11] and *FourFlow* by Heiberg et al. [HSU*10] are software systems that provide a pipeline including preprocessing, segmentation and interactive data exploration. The *Siemens Flow Demonstrator* is a similar prototype [SCG*14]. The *Quantitative Flow Explorer* by van Pelt et al. [vPBB*10] encompasses interactive, illustrative visualizations for data exploration. *Ensight* and *GyroTools GTFlow* are commercial tools that, however, do not focus on cardiac blood flow.

3. Medical Background

A goal of current medical research papers is to correlate cardiovascular diseases with specific flow behaviors, i.e. vortex flow patterns. For instance, Hope et al. [HHM*10] found systolic vortex flow in 75% of their patients with *bicuspid aortic valves* – a defect where the aortic valve consists of only two instead of three leaflets. Altered vessel morphology can be another important factor that promotes the formation of vortices. Slight dilations are called *ectasia*, severe dilations are referred to as *aneurysm*. Pathological narrowings are called *stenosis* or, in case of the aortic arch, *coarctation*.

The *stroke volume* is the amount of pumped blood per heart beat in ml and can be determined as flow that passes a plane, usually located above the valve, orthogonally. It is calculated as integral of the time-dependent *flow rate* which is given in ml/s throughout the cardiac cycle. The *cardiac output* is the *stroke volume* multiplied with the *heart rate* and thus describes the heart's pumping capacity in l/min. These measures help to assess the cardiac function. *Regurgitation fraction* denotes the percentaged amount of blood that flows back into the ventricle during systole due to improperly closing valves. It is below 5% in a healthy person. High values of 20% and more can indicate a valve replacement surgery if the patient shows severe symptoms.

3.1. Data Acquisition

Most of our datasets were acquired with a 3 T Magnetom Verio (Siemens Healthcare, Erlangen, Germany). A 4D PC-MRI dataset consists of each three (x-, y-, z-dimension) magnitude and flow images that represent the flow strength and direction, respectively, per voxel. The grid size is 132×192 in the plane with 15 to 23 and between 14 and 21 temporal positions. The spatio-temporal resolution is 1.77 mm $\times$ 1.77 mm $\times$ 3.5 mm $\times$ 50 ms. The *velocity encoding* (V_{ENC}) – an a priori MR parameter that describes the maximum expected velocity – was set to 1.5 m/s, which is a common choice for aortic blood flow [MFK*12].

4. Requirement Analysis

The use of (semi-)automatic methods is essential to establish a fluent workflow. Exploitation of the GPU's computational power is desirable to speed up the data processing. Required input should fit into the mental model of our target user group with a medical background. Thus, employed algorithms should allow to make use of physicians' expert knowledge. Reasonable default parameters have to be provided for everything that is unintuitive from their perspective. It is necessary that results of evaluated datasets can easily be shared via screenshots or videos.

5. Bloodline

In this section, we describe our developed software named *Bloodline*, shown in Figure 1. It is written in C++ and uses OpenGL for rendering, embedded in a Qt/QML-based GUI.

5.1. Data Import

The raw data – one file per slice per temporal position – are converted to 4D images using information from the DICOM headers. An eddy current correction is then applied to the flow image using the method by Walker et al. [WCS*93] with their suggested default parameters.

5.2. Vessel Segmentation

A temporal maximum intensity projection (tMIP) of the magnitude images is computed, which yields a high-contrast 3D image. Graph cuts require the specification of regions in- and outside the target structure as input. The user provides these information by drawing on the tMIP slices (see Figure 1a). The better the image quality, the less input is necessary to achieve satisfactory results. Though, detail corrections can be performed if the segmentation includes unwanted or excludes wanted parts. Due to the employed *3D graph cut* with a 26-neighbourhood per voxel, input is not required on every slice. Edge weights in the graph are set to $exp(-\alpha \cdot ||\nabla I||)$, where I are the $[0,1]$-scaled intensities from the tMIP and α is a tolerance parameter with 1000 as experimentally determined default value. Noise in the resulting segmentation is reduced with a $3 \times 3 \times 3$ morphological opening and closing.

Phase wraps occur when the measured velocity exceeds the V_{ENC}. In this case, values flip to the other end of the domain. We correct phase wraps within the obtained segmentations according to Dìaz et al. [DR04]. The rest of the flow image is not processed to save time.

5.3. Surface Mesh and Centerline Extraction

Marching cubes is employed to automatically extract the vessel surface from the segmentation. We apply a *low-pass filter* [TZG96] and reduce the mesh via *quadric decimation* [Hop99]. The user marks a start and end point on the vessel surface for the subsequent *centerline extraction* [AEIR03]. Multiple end points are allowed to create centerlines in branching vessels such as the pulmonary artery. An aorta is, on average, represented by 2500-3000 triangles with a mean edge length of 4.9 mm. For comparison, a voxel diagonal is 4.3 mm long. This mesh resolution is sufficient because of the non-complex shape of the aorta and pulmonary artery.

An adapted graph cut enables the semi-automatic 4D vessel segmentation from time-resolved anatomical images, e.g., from an SSFP cine sequence. An explicit moving surface is automatically extracted for visualization purposes and optional quantification with increased accuracy [KPG*15a].

5.4. Qualitative Analysis

Flow Integration: Runge-Kutta-4 with adaptive step size is implemented on the GPU to integrate the full set of pathlines. Velocity vectors $\vec{u} \in \mathbb{R}^3$ in the 4D flow field $\mathbb{V}$ at the spatio-temporal position $\vec{x} = (x,y,z,t)^T$ are obtained via quadrilinear interpolation. The temporally adjacent vectors $u_{\vec{\lfloor t \rfloor}} = \mathbb{V}(x,y,z,\lfloor t \rfloor)$ and $u_{\vec{\lceil t \rceil}} = \mathbb{V}(x,y,z,\lceil t \rceil)$, both obtained via hardware-accelerated trilinear interpolation, are used to perform a last linear interpolation manually. We ensure that each voxel of the segmentation is visited at least once in every temporal position. For this purpose, we seed one pathline at a random position inside each segmentation voxel at the first temporal position. For each remaining time step, in succession, we determine the voxels that were not visited, create new seeds and integrate the pathlines.

Vortex Extraction: During the full flow integration, we also calculate the λ_2 vortex criterion for each pathline point. To alleviate the impact of the low data resolution and noise, we smooth the values along each pathline using a 1D binomial filter with kernel size 3. Contrary to our previous work [KGP*13], we do not crop away parts of the pathlines. Instead, we provide the option to flexibly hide all non-vortex parts using a slider that adjusts the λ_2 threshold (see Figure 1b). Filtering flow velocities is possible in the same way. For the aorta, a circular 2D plot can be generated as overview of present vortices [KMP*15].

Visualization: The vessel front is culled and only hinted at with a ghosted viewing [GNKP10]. The back faces are rendered with Phong illumination. Pathlines with halos are created in the geometry shader as view-aligned quads. Illuminated streamlines are implemented in the subsequent fragment shader. In the animation mode, cone-shaped particles with trails are drawn on every position where the current animation time matches a pathline's temporal component. Order-independent transparency ensures correct alpha blending. The default line width, particle width and particle length are set according to the dataset's voxel diagonal. The standard trail length depends on the temporal resolution and number of time steps. Real-time adjustment of all visualization parameters is possible via sliders.

Media: Results can easily be shared by taking a high-resolution screenshot of the GUI or render window. The animated flow can be exported to a 1080p video with a single click. Patient and dataset information are automatically added to the top left corner.

5.5. Quantitative Analysis

Measuring planes are automatically oriented orthogonal to the centerline and their size is automatically determined so that they fit the vessel (see Figure 1c). The user can drag a plane along the centerline or adjust the angulation, i.e. rotate it. A diagram shows the time-dependent flow rate determined for this plane configuration. Additionally, the stroke volume, cardiac output, regurgitation fraction, mean as well as peak velocity and the vessel diameter are provided. Unfortunately, the calculations are highly sensitive towards the plane's angulation. Therefore, a robust stroke volume and regurgitation fraction analysis can be performed [KPG*14]. This work received an *honorable mention* and was invited to be submitted in an extended version to the Computer Graphics Forum [KPG*15b]. Another quantifiable measure on the vessel surface is the vectorial wall shear stress.

6. Application

Bloodline is used by the Heart Center in Leipzig, Germany, where also a Siemens prototype is used, and by the University Hospital in Magdeburg, Germany. 64 datasets were evaluated for research purposes so far in close collaboration with radiologists specialized in the cardiovascular system. Besides 36 healthy volunteers, the following pathologies were present: 1 aneurysm in the left subclavian artery, 3 aortic insufficiencies, 3 ectasias / aneurysms in the ascending aorta, 15 bicuspid aortic valves, some of them with ectatic ascending aortas, 1 tetralogy of Fallot with pulmonary insufficiency, 3 vascular prostheses and 2 coarctations.

After familiarization, physicians are able to perform a standard evaluation, i.e. vortex flow extraction and stroke volume as well as regurgitation fraction analysis, in less than ten minutes, which was rated as feasible for the clinical routine. The robust quantification is most expensive and takes about 30 s using an Intel i7-3930K and a GeForce GTX 680. Other costly computations such as the full flow integration including vortex extraction are each performed within 10 s.

The graph cut-assisted segmentation shows high acceptance due to the exploitation of the physicians' anatomy knowledge. The option to hide vessels in order to reduce occlusions and the independence of specific MRI scanners were appreciated. A suggestion was to let the program perform pending automatic operations such as pathline integrations for all new datasets at once. This way, the concentrated waiting time could be used for other things.

7. Conclusion and Future Work

We presented the cardiac 4D PC-MRI data evaluation software *Bloodline* that allows to process datasets within ten minutes. It integrates a full preprocessing pipeline as well as a quantitative and qualitative data analysis. The use of (semi-)automatic methods enables a fluent workflow. Carefully selected defaults strongly reduce the necessity to adjust parameters. State-of-the-art visualizations can easily be created and saved in order to share results.

Special functionality for the ventricles shall be provided in the future. Another goal is to automatically generate clinical reports. Hence, larger studies can be better evaluated and gender- and age-specific norm values may be determined.

References

[AEIR03] Antiga L., Ene-Iordache B., Remuzzi A.: Centerline Computation and Geometric Analysis of Branching Tubular Surfaces with Application to Blood Vessel Modeling. In *Proc Winter School Comput Graph (WSCG)* (2003). 3

[BPM*13] Born S., Pfeifle M., Markl M., Gutberlet M., Scheuermann G.: Visual Analysis of Cardiac 4D MRI Blood Flow Using Line Predicates. *IEEE Trans Vis Comput Graph 19* (2013), 900 – 912. 2

[CRvdG*14] Calkoen E. E., Roest A. A., van der Geest R. J., de Roos A., Westenberg J. J.: Cardiovascular Function and Flow by 4-Dimensional Magnetic Resonance Imaging Techniques: New Applications. *J Thorac Imag 29*, 3 (2014), 185 – 196. 2

[DR04] Dìaz C., Robles L. A.: Fast Noncontinuous Path Phase-Unwrapping Algorithm Based on Gradients and Mask. In *Proc Iberoameric Cong Patt Recog (CIARP)* (2004), pp. 116 – 123. 3

[GNKP10] Gasteiger R., Neugebauer M., Kubisch C., Preim B.: Adapted Surface Visualization of Cerebral Aneurysms with Embedded Blood Flow Information. In *Proc Eurographics Vis Comput Biol Med* (2010), pp. 25 – 32. 3

[HFS*11] Hennemuth A., Friman O., Schumann C., Bock J., Drexl J., Huellebrand M., Markl M., Peitgen H.-O.: Fast Interactive Exploration of 4D MRI Flow Data. *Proc of SPIE Med Imag 7964* (2011). 2

[HHM*10] Hope M. D., Hope T. A., Meadows A. K., Ordovas K. G., Urbania T. H., Alley M. T., Higgins C. B.: Bicuspid Aortic Valve: Four-Dimensional MR Evaluation of Ascending Aortic Systolic Flow Patterns. *Radiology 255*, 1 (2010), 53 – 61. 2

[Hop99] Hoppe H.: New Quadric Metric for Simplifying Meshes with Appearance Attributes. In *Proc IEEE Vis* (1999), pp. 59 – 66. 3

[HSD13] Hope M. D., Sedlic T., Dyverfeldt P.: Cardiothoracic Magnetic Resonance Flow Imaging. *J Thorac Imaging 28*, 4 (2013), 217 – 230. 2

[HSU*10] Heiberg E., Sjögren J., Ugander M., Carlsson M., Engblom H., Arheden H.: Design and Validation of Segment - Freely Available Software for Cardiovascular Image Analysis. *BMC Med Imag 10* (2010), 1. 2

[KGP*13] Köhler B., Gasteiger R., Preim U., Theisel H., Gutberlet M., Preim B.: Semi-Automatic Vortex Extraction in 4D PC-MRI Cardiac Blood Flow Data Using Line Predicates. *IEEE Trans Vis Comput Graph 19*, 12 (2013), 2773 – 2782. 2, 3

[KMP*15] Köhler B., Meuschke M., Preim U., Fischbach K., Gutberlet M., Preim B.: Two-Dimensional Plot Visualization of Aortic Vortex Flow in Cardiac 4D PC-MRI Data. In *Proc Bildverarb Med* (2015), p. to appear. 3

[KPG*14] Köhler B., Preim U., Gutberlet M., Fischbach K., Preim B.: Robust Cardiac Function Assessment in 4D PC-MRI Data. In *Proc Eurographics Vis Comput Biol Med* (2014), pp. 1 – 10. 2, 3

[KPG*15a] Köhler B., Preim U., Grothoff M., Gutberlet M., Fischbach K., Preim B.: Motion-Aware Stroke Volume Quantification and Vessel Visualization in 4D PC-MRI Data of the Human Aorta. *Int J Comp Assist Radiol Surgery* (2015). submitted. 3

[KPG*15b] Köhler B., Preim U., Grothoff M., Gutberlet M., Fischbach K., Preim B.: Robust Cardiac Function Assessment in 4D PC-MRI Data of the Aorta and Pulmonary Artery. *Comp Graph Forum* (2015). invited submission. 3

[MFK*12] Markl M., Frydrychowicz A., Kozerke S., Hope M. D., Wieben O.: 4D Flow MRI. *J Magn Reson Imag 36*, 5 (2012), 1015 – 1036. 2

[SCG*14] Semaan E. M., Carr M., Gulsun M., van Ooij P., Stalder A. F., Carr J., Collins J., Markl M., Spottiswoode B.: Evaluation of an Optimized Post-processing Tool for 4D Flow MRI Data Analysis in Healthy Volunteers and Patients with Aortic Stenosis, Aortic Insufficiency, and Aortic Aneurysm. In *Proc Intl Soc Mag Reson Med* (2014), p. 3948. 2

[TZG96] Taubin G., Zhang T., Golub G.: Optimal Surface Smoothing as Filter Design. In *Proc Europ Conf Comput Vis*. 1996, pp. 283 – 292. 3

[vPBB*10] van Pelt R., Bescos J. O., Breeuwer M., Rachel E. C., Gröller M. E., ter Haar Romenij B., Vilanova A.: Exploration of 4D MRI Blood Flow Using Stylistic Visualization. *IEEE Trans Vis Comput Graph 16*, 6 (2010), 1339 – 1347. 2

[WCS*93] Walker P. G., Cranney G. B., Scheidegger M. B., Waseleski G., Pohost G. M., Yoganathan A. P.: Semiautomated Method for Noise Reduction and Background Phase Error Correction in MR Phase Velocity Data. *J Magn Reson Imag 3*, 3 (1993), 521 – 530. 2