Exploration of 4D MRI Blood-Flow using Stylistic Visualization

Roy van Pelt, Javier Oliván Bescós, Marcel Breeuwer, Rachel E. Clough,
M. Eduard Gröller *Member, IEEE*, Bart ter Haar Romeny and Anna Vilanova *Member, IEEE*

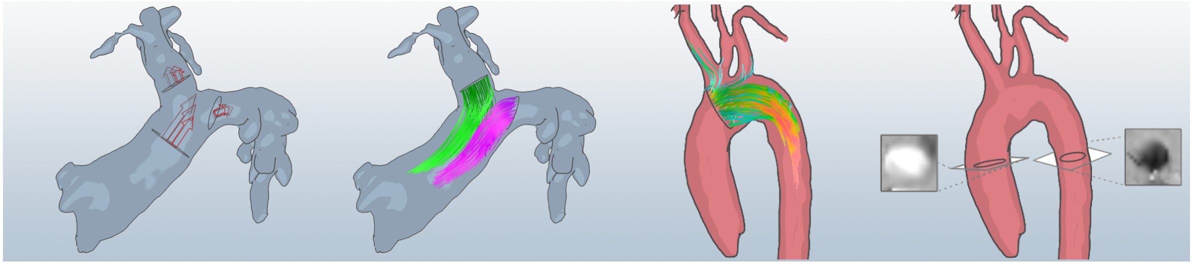

Fig. 1: Various techniques to explore and stylistically depict cardiovascular 4D MRI blood-flow data.

Abstract— Insight into the dynamics of blood-flow considerably improves the understanding of the complex cardiovascular system and its pathologies. Advances in MRI technology enable acquisition of 4D blood-flow data, providing quantitative blood-flow velocities over time. The currently typical slice-by-slice analysis requires a full mental reconstruction of the unsteady blood-flow field, which is a tedious and highly challenging task, even for skilled physicians. We endeavor to alleviate this task by means of comprehensive visualization and interaction techniques. In this paper we present a framework for pre-clinical cardiovascular research, providing tools to both interactively explore the 4D blood-flow data and depict the essential blood-flow characteristics. The framework encompasses a variety of visualization styles, comprising illustrative techniques as well as improved methods from the established field of flow visualization. Each of the incorporated styles, including exploded planar reformats, flow-direction highlights, and arrow-trails, locally captures the blood-flow dynamics and may be initiated by an interactively probed vessel cross-section. Additionally, we present the results of an evaluation with domain experts, measuring the value of each of the visualization styles and related rendering parameters.

Index Terms—4D MRI blood-flow, Probing, Flow visualization, Illustrative visualization, Phase-contrast cine MRI

1 Introduction

Cardiovascular disease (CVD) is a class of conditions affecting the heart and blood vessels, with an estimated overall prevalence of over thirty percent of the American population [1]. CVD is currently the leading cause of death worldwide.

Assessment of CVD is facilitated by various imaging modalities, acquiring data related to the cardiovascular morphology, function and hemodynamics. Diagnosis of CVD typically involves an evaluation of both the anatomical structure and function, while the behavior of blood-flow is still rarely inspected. The flow behavior is, nevertheless, of vital importance to the cardiovascular system and potentially harbors a considerable value for both diagnosis and risk assessment. A wide range of pre-clinical research indicates that atypical flow behavior directly relates to medical conditions [3, 12, 26].

- *Roy van Pelt, Anna Vilanova and Bart ter Haar Romeny are with the department of Biomedical Engineering, within the group of Biomedical Image Analysis at Eindhoven University of Technology, E-mail: {r.f.p.v.pelt, a.vilanova, b.m.terhaarromeny}@tue.nl.*
- *Javier Oliván Bescós and Marcel Breeuwer are with the department of Clinical Sciences and Advanced Development at Philips Healthcare, E-mail: {javier.olivan.bescos, marcel.breeuwer}@philips.com.*
- *Rachel E. Clough is with the division of Imaging Sciences and the department of Vascular Surgery, NIHR Comprehensive Biomedical Research Centre of Guy's and St Thomas' NHS Foundation Trust and King's College London, E-mail: rachel.clough@kcl.ac.uk*
- *M. Eduard Gröller is with the department of Computer Science, within the group of Computer Graphics and Algorithms at Vienna University of Technology, E-mail: groeller@cg.tuwien.ac.at.*

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For information on obtaining reprints of this article, please send email to: tvcg@computer.org .

In current clinical practice, UltraSound (US) is the reference standard, offering a non-invasive and cost-efficient modality to inspect the dynamics of blood-flow. However, diagnosis of more complex conditions often requires a better image quality, including higher spatial resolutions, more contrast and a larger field of view. The necessary imaging quality can be provided by present-day Magnetic Resonance Imaging (MRI) techniques. Moreover, advances in MRI acquisition sequences over the last twenty years skillfully utilize the intrinsic sensitivity of MRI to flow.

In particular, phase-contrast (PC) MRI sequences enable acquisition of flow data that is linearly related to the actual blood-flow velocities, capturing both speed and direction. This linear relation is described by the velocity encoding (VENC) acquisition parameter, representing the largest speed that can be measured unambiguously. Choosing a suitable VENC, and hence avoiding specific imaging artefacts, provides a data set with great correspondence to the actual blood-flow velocity field [11]. As a consequence, the acquired data allows for quantitative analysis of the blood-flow behavior.

A quantitative 3D blood-flow data set can be obtained by acquiring the data in multiple directions, and reconstructing the data to represent three orthogonal directions. In addition, PC cine MRI sequences support acquisition of 3D blood-flow data throughout the cardiac cycle, generating a 4D blood-flow data set [17, 20, 29]. There are two customary approaches to reconstruct the acquired raw data to the desired flow images [2]. Figure 2 depicts a single slice of the reconstructed 4D flow data, at a certain point in time. The top row, figures 2 (a) - (c), represents the blood-flow data in the three patient-oriented orthogonal directions, encoding both speed and directions of the blood-flow quantitatively. This data is commonly referred to as the *phase* (PC-P) reconstruction. The bottom row, figures 2 (d) - (f), represents the blood-flow data in three directions, encoding only speed. This data is commonly referred to as the *magnitude* (PC-M) reconstruction. Even though the blood-flow direction cannot be resolved from the PC-M reconstruction, the resulting data is inherently less prone to the uncorrelated noise that is typical for the PC-P reconstructed data.

Analyzing this 4D flow data on a slice-by-slice basis becomes a defiant and tedious task. While skilled physicians are able to mentally reconstruct a spatial image from 3D scalar data, this becomes significantly more difficult for 3D vector-valued data. A 4D flow data set currently consists of twenty to thirty 3D vector-valued data sets over time, which is virtually impossible to grasp for the human mind.

A limited number of visualization tools have strived to convey the 4D PC-MRI blood-flow data, aiming to apprehensively depict the data by reducing the amount of visual information. To that end, physicians are generally required to define one or more regions-of-interest, typically involving a process of extensive manual labor. Time constraints may consequently force physicians to inspect only a fraction of the information contained within the 4D blood-flow data set.

Furthermore, visualization techniques are still unable to sufficiently communicate the relevant information required by the physicians, even when the amount of visual information is reduced by selecting a region-of-interest. Capturing the unsteady flow dynamics from the blood-flow data remains a significantly challenging task, additionally impeded by the limitations imposed by the MRI acquisition process.

Generally, the 4D PC-MRI data includes a considerable amount of uncorrelated noise, inherent to the reconstruction process. In addition, both the temporal and spatial resolution are currently limiting factors (figure 2), causing severe discontinuities of the flow-field over time and various partial volume effects at the edges of the flow.

We endeavor to provide the physicians with the necessary tools to visualize and interact with the 4D flow data, supporting their need to understand the patient-specific hemodynamics. To this end, we contemplate the work from the established field of flow visualization, comprising a multitude of techniques to capture the complex behavior of unsteady flow. These techniques are commonly applied to simulated blood-flow data.

A considerable amount of research has been conducted in the field of computational fluid dynamics (CFD), aiming to closely mimic the behavior of fluids. Although apt results have been produced over the past few decades, a simulation by definition relies on a vast amount of model assumptions. Instead, flow visualization techniques can now be applied to quantitative measurements, such as the 4D PC-MRI acquired blood-flow information.

Summarizing, the main contributions of this paper are:

- Interactive techniques that allow physicians to explore 4D PC-MRI blood-flow data in real-time. This includes a fast and interactive selection of vessel cross-sections and real-time parametrization of visualization styles.
- Specialized flow visualization techniques, inspired by medical illustrations, depicting the dynamics of the blood-flow. We present several improvements to existing techniques, specifically geared towards cardiovascular applications and the challenging 4D MRI blood-flow modality. The presented novelties include exploded planar reformats, line trace animated highlights, and flow-rate arrow-trails.
- An evaluation with domain experts, assessing the interactive exploration and visualization styles with diversified parameters.

2 Related work

A relatively small community of physicians pioneers the potential of MRI acquired 4D flow information. Within this community, a limited set of visualization techniques prevails.

In many cases, data analysis is performed based on multi-planar reformats (MPR). Either the speed or the separate components of the velocity vectors are inspected, based on various color codings. For example, Sørensen et al. [26] present color-coded planar reformats, combined with a translucent direct volume-rendered visualization to indicate the anatomical context. Different MPR visualizations, as presented by Uribe et al. [29], depict a red-green-blue color coding of the velocity vector, similar to the color Doppler approach.

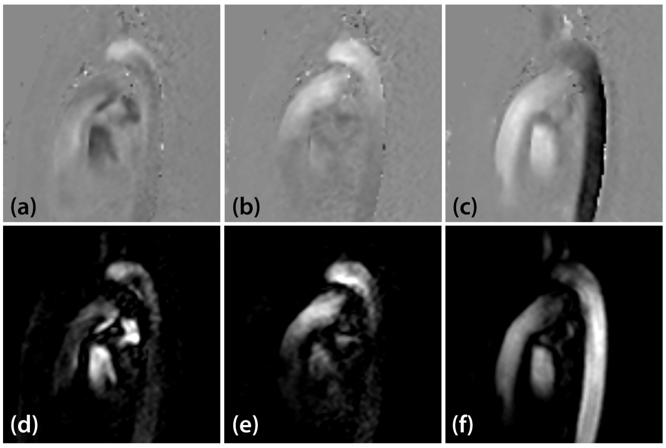


Fig. 2: The PC flow data set consists of 20 phases in time, for both PC-P and PC-M. Each phase in the series comprises a velocity vector volume with a resolution of $144 \times 144 \times 144$ voxels of $2.0 \times 2.0 \times 2.7$ mm. (a) PC-P right to left (b) PC-P anterior to posterior (c) PC-P head to feet (d) PC-M right to left (e) PC-M anterior to posterior (f) PC-M head to feet.

Other blood-flow visualizations presented in pre-clinical research literature, adopt techniques put forth by the flow visualization community. Typical examples are vector plots [17], particle traces [32] and line traces. A review of these visualization approaches is presented by Unterhinninghofen et al. [28].

A range of flow visualization techniques has been applied to blood-flow simulations, employing different visualization styles. For example, flow profiles are presented by mesh deformations over time [24], as well as local vector plots at cross-sections of the vessel model [13].

The CFD community, however, addresses a much wider range of applications, for which a multitude of flow visualizations have been proposed. In general, techniques can be categorized into either dense and texture based approaches, or feature extraction and line tracing approaches [22].

In this paper, we present a visualization framework called Quantitative Flow Explorer (QFE). This framework encompasses a variety of interactive visualizations, depicting 4D MRI blood-flow for cardiovascular applications. Visual styles from the field of illustrative rendering [6, 10] have been adopted, as well as improved techniques from the field of flow visualization.

The following section will introduce the interactive probing approach, included in the QFE system, providing a basis for the presented flow visualization techniques. Before elaborating on these flow visualizations in subsection 4.2, the illustrative visualization of the anatomical context will be described in subsection 4.1. This will be followed by the results of the user evaluation in section 5, a discussion in section 6, and lastly the conclusions and future work in section 7.

3 Probing and interaction

In section 1, the difficulties involved with analyzing the MRI acquired 4D blood-flow data were discussed. Any direct visual representation of the full-scale data would result in an excessive visual overload. For example, direct 3D representations, such as hedgehogs or vector-plots are difficult to interpret, because of the considerable amount of visual clutter. To a lesser extent, this drawback also holds for 3D texture-based approaches, generally requiring well specified opacity modulation. Moreover, direct representations are typically susceptible to the uncorrelated noise that is present in the MRI measurement.

In order to reduce the quantity of visual information, QFE includes a probing technique that allows physicians to inspect just parts of the blood-flow in the main vessels surrounding the heart. This technique comprises a single mouse-click interaction, selecting a cross-section of the vessel of interest.

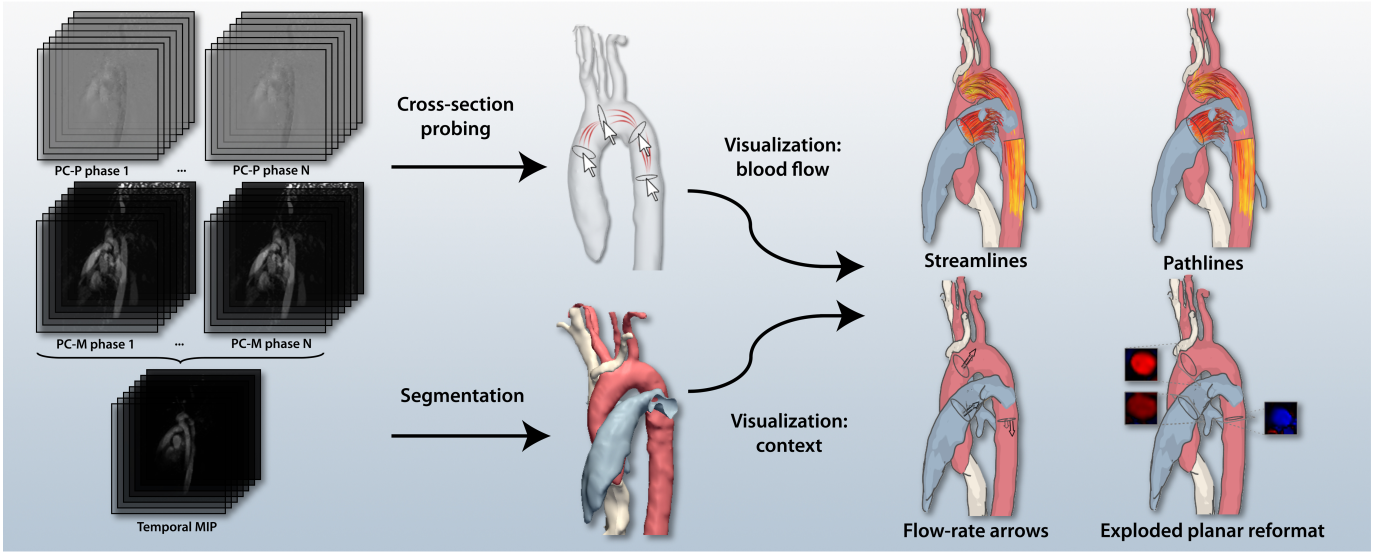


Fig. 3: The Quantitative Flow Explorer (QFE) framework, enabling interactive exploration and stylistic depiction of 4D MRI blood-flow data. The 4D PC-MRI data is pre-processed by a temporal MIP, providing data for the semi-automatic vessel segmentation. After interactively probing vessel cross-sections, a variety of flow visualizations can be presented in combination with the anatomical context.

Locating the area to be inspected and probing the vessel cross-section requires a visual representation of the anatomical context, for which we present our approach in section 4.1. Using conventional viewpoint interaction, the physician is able to navigate through the anatomical structures and locate the region-of-interest. A single mouse click on the depicted vessel structure will initiate the computation of the cross-sectional plane at the indicated position.

On each mouse click, the depth buffer is queried at the window coordinates of the designated position, obtaining a 3D position in the camera coordinate frame. After transformation to the patient coordinate frame, the orientation of the vessel is determined from the MRI acquired data, involving an eigen-decomposition of the structure tensor [15]. Subsequently, the cross-sectional perimeter is determined in a 2D plane, based on a full-width at half-max edge detector [4]. This detector determines the best contour fit for a limited number of scales, robustly detecting vessels with varying diameters. The approach assumes tubular structures, and can not reliably probe cross-sections of the heart chambers.

Generally, the vessel cross-section probing approach relies on a data set that represents the anatomy. In practice, whenever anatomical data is acquired, this is usually not a cine data set representing a full cardiac cycle. Instead, anatomical data is acquired for one, or at most two phases of the cardiac cycle. For current pre-clinical research, often no anatomical data is acquired at all, saving valuable acquisition time.

Employing the cross-section probing functionality without anatomical data available requires the acquired flow data to be pre-processed using a temporal maximum intensity projection (TMIP). The TMIP results in a new volumetric scalar-valued data set, representing a coarse static approximation of the anatomical structures. For each voxel position $\vec{x}$ of the new volume, the maximum speed is determined along the time axis of the 4D flow data $v_{t_i}(\vec{x})$. For N cardiac phases, this is defined as:

$$\text{TMIP}(\vec{x}) = \max_{t_i}(\|v_{t_i}(\vec{x})\|) \quad \text{for } i = 0, \ldots, N-1.$$

Within the volume obtained by the TMIP, each voxel with a bright intensity indicates that a flow velocity with a substantial speed has occurred there at least once during the cardiac cycle. Hence, the voxel is contained within a vascular structure at least at one phase of the heart-beat. The process of generating a TMIP volume is presented on the left-hand side of the system overview in figure 3, and the cross-section probing is indicated by a moving mouse cursor on top of the depicted vessel structure.

The following section presents the variety of visualization styles, adapted and included in QFE. Various styles depend on the generated TMIP volume, as well as a number of selected vessel cross-sections. All the styles can be interactively parameterized.

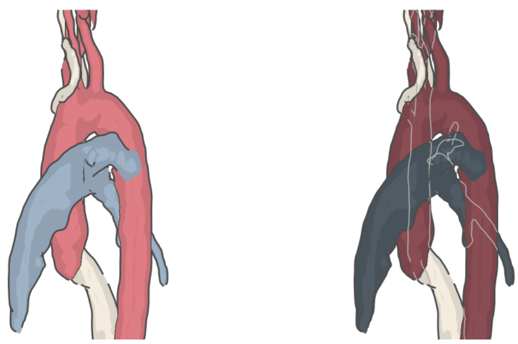
4 4D FLOW VISUALIZATION

This section describes the QFE visualization styles, starting with the depiction of the anatomical context. Subsequently, the various blood-flow visualization approaches are presented. An overview of the QFE system, including the presented visual styles, is depicted in figure 3.

4.1 Anatomical context

Exploration of the 4D flow data requires a patient-specific depiction of the anatomy, facilitating navigation to the regions-of-interest. With the primary interest in blood-flow dynamics, we allow an approximate representation of the anatomical structures. The anatomical context can be extracted from either a data set representing the anatomical structures, or the pre-processed TMIP volume, presented in section 3.

For our purpose, the depiction of the anatomical structures requires a surface representation, typically extracted from the TMIP data. A conventional segmentation technique, such as the marching cubes algorithm, suffices to extract the desired surface geometry from the



(a) (b)

Fig. 4: Anatomical context visualization (a) Cel shaded silhouettes and occluding contours (b) Hidden contours during viewpoint interaction

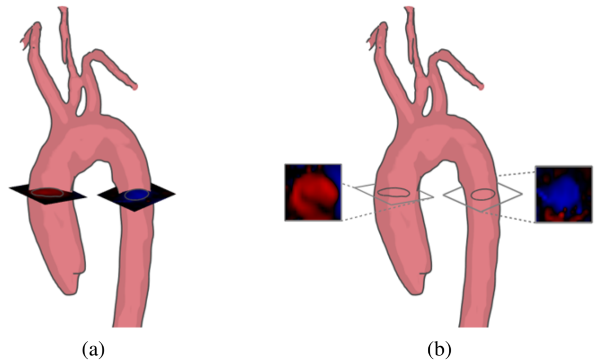


Fig. 5: MPR visualization (a) Integrated planes at cross-section positions (b) Exploded view of planes at cross-section positions

TMIP data. For the figures in this paper, third party software [33] was used to improve the automated segmentation. The vessel boundaries were manually retouched on a slice-by-slice basis. Furthermore, the vessel structures were separated, facilitating visibility changes of the structures and hence avoiding occlusion if necessary. With the focus on visualization, we have tolerated this laborious segmentation approach. In literature, other methods endeavor extraction of the full surface geometry from the MRI blood-flow data [14, 21].

With the anatomy being presented as a contextual aspect of the visualization, details should be omitted without losing the necessary morphological information. To that end, we employ illustrative techniques to depict the anatomical context, capturing the desired outline of the approximate anatomical representation.

Figure 4a depicts our anatomical context visualization, inspired by medical illustrations. The visualization is based on cel shaded silhouettes [10], combined with superimposed occluding contours [6]. The silhouettes are generated by view-dependently rendering the rearmost surface of the segmented vessel structure, continually depicting the inside of the vessel-wall. The cel shading provides the desired visual simplification, retaining a cue for visual depth and an outline of the morphological structure.

The outline of the anatomical structures is emphasized using contour lines. In the past, extensive research has been conducted, investigating the variety of line structures that are effective at conveying shape [6]. QFE includes occluding contours, defined as the boundary between the visible and the hidden parts of the surface. These contours are generated by the set of points where the surface normal is perpendicular to the view direction. Complementary contour lines, such as suggestive contours, are deliberately omitted for the representation of the anatomical context. As mentioned, this context is a coarse approximation of the anatomical structure. Highlighting details of this structure would not provide any relevant information to the physician.

The presented stylistic visualization of the anatomical context simplifies the representation, reducing depth perception and increasing insight into the spatial relations of the structures. In order to facilitate the vessel cross-section probing process, we introduce hidden contours that are visible during viewpoint interaction (figure 4b), bypassing occlusion and clarifying spatial relations. The interaction is initiated as soon as the left mouse button is pressed, and ends when the button is released, leaving an uncluttered representation of the anatomical context. After positioning the vessel cross-sections, the hidden contours may be occluded by the blood-flow depictions. However, they do not impede the resulting flow visualization.

4.2 Blood-flow dynamics

With the anatomical context in place, the quantitative blood-flow field can be inspected. Various visualization styles depict the flow field at the vessel cross-section locations, which are positioned by the physician using the probing technique presented in section 3. This subsection describes the blood-flow visualization techniques, incorporated in the QFE framework. The techniques are interactively parameterizable and can be combined without notable loss of performance.

4.2.1 Planar reformat

The first technique is based on the customary MPR, depicting separate components of the blood-flow velocity vectors, speed or a color Doppler inspired through-plane flow component. From literature, we observe that the MPR is an essential tool for 4D flow analysis [17, 29].

Instead of using a full planar reformat, slicing the bounding box of the volume, we propose smaller reformats at the designated vessel cross-sections. This approach, depicted in figure 5a, intuitively relates the flow information to the anatomical context and limits the amount of visual information to the demarcated regions-of-interest. A similar approach was implied by Frydrychowicz et al. [9], presenting flow related parameters as an overlay to the vessel structure.

Unfortunately, the obliquely oriented MPR adversely affects the analysis of the flow data. QFE provides a solution by means of an exploded view technique, regularly used in the field of medical and technical illustrations [5]. This technique, presented in figure 5b, aligns the planes with the current view direction, and depicts them alongside the related vessel cross-sections. The original position of a plane is depicted by an indicative contour, accompanied by dashed connection lines, supporting visual correlation of the view-aligned plane and its original position and orientation.

4.2.2 Line primitives

At present, tracing of line primitives is the prevailing approach to represent flow dynamics. QFE adopts the most commonly applied line primitives, namely streamlines and pathlines.

Seeding

Initiating line traces requires a set of seed positions to be determined within the vessel structure. The selected cross-sections are employed as a seeding plane. Differently distributing the seed positions on this plane leads to varying visual outcomes of the line traces.

In order to inspect the impact on the line traces, QFE adopts several seeding strategies. Figure 6 presents an overview of the range of distributions included in the QFE framework. The top row presents seeding strategies.

The radial, circular and rectilinear seeding strategies yield orderly structured seed distributions, transferring their character to the spatial relations between the line traces. Instead of the flow dynamics, merely the seeding structure is perceived when inspecting the line primitives. For this reason, seed positions are mostly distributed randomly. For

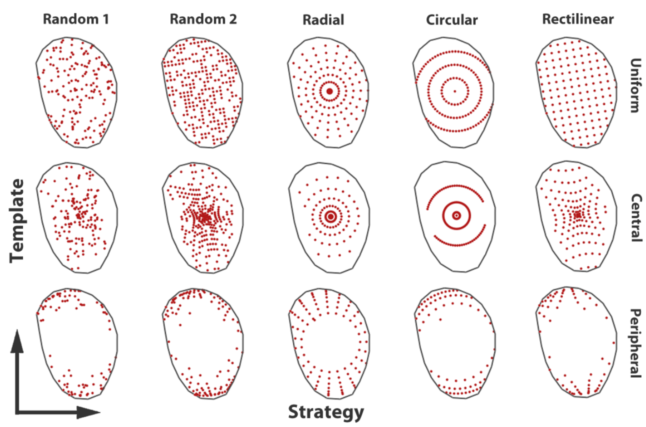


Fig. 6: Seeding approaches impose a structure on the line traces. Different seeding strategies can be inspected and seeding templates can be selected to differentiate seed density with respect to the vessel center.

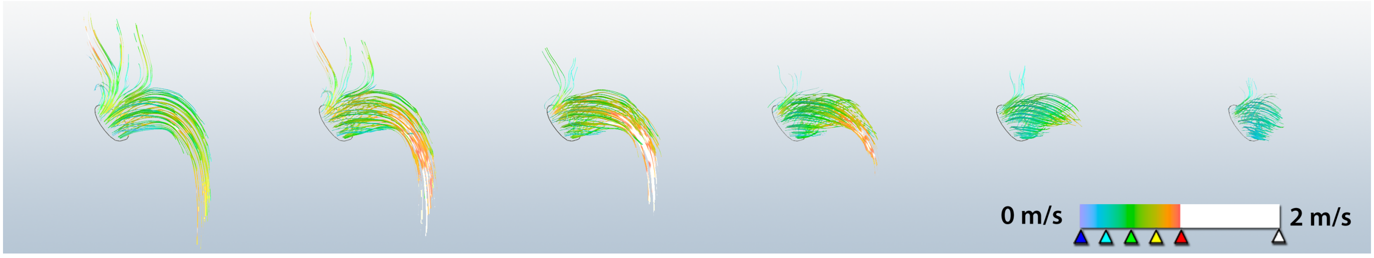


Fig. 7: A sequence of pathlines over time. From left to right, pathlines are traced from a single vessel cross-section for phases number 3 up to 8, capturing a time frame from 165ms up to 440ms within the cardiac cycle.

analyzing the blood-flow velocity field, however, other strategies are valuable to investigate as well.

For instance, the radial seeding strategy provides a denser seeding towards the center of the vessel cross-section. It is worthwhile to emphasize the blood-flow behavior near the vessel center, since the blood-flow velocity profile commonly has a peak velocity near the vessel center. Furthermore, we propose a circular seeding strategy, distributing the seeds according to equally-spaced concentric circles, where the line traces appear as a set of nested tubular surfaces. While the direction of the line traces is severely affected by the seeding structure, the accumulated speed information can be observed from the circular profiles that arise at the endings of the line primitives.

For each of the seeding strategies, a so-called seeding template can be selected, as depicted in figure 6. QFE uses these templates to change the seeding density, focussing on the flow behavior near the vessel center (central) or the vessel wall (peripheral). Conceptually, one may understand these templates to be radial transfer-functions, varying the seeding density based on the distance from the center of the vessel cross-section.

Tracing

Starting from the seed positions, different line primitives are traced using a fourth order Runge-Kutta integration scheme [23]. Line tracing is performed in real-time and can be parameterized interactively.

Streamlines represent the tangent curves of the flow velocity field at an instantaneous point in time. QFE provides functionality to trace and depict these streamlines, as presented in figure 8a. The streamlines are generated in real-time for each phase of the cardiac cycle, allowing the physician to inspect the temporal differences of the instantaneous flow-field structure. In addition, QFE includes the notion of pathlines, as depicted in figure 8b. Pathlines represent the trajectory of a massless particle through the flow-velocity field, enabling a physician to inspect the temporal behavior of the flow field. A thorough theoretical description of these line structures is presented by Weinkauf [31].

As opposed to other systems, we devise an approach that generates restrained pathlines for each phase of the cardiac cycle. Commonly, pathlines are traced through a large extent of the cardiac cycle, accumulating errors due to the numerical integration scheme. This holds in particular for the 4D MRI blood-flow data, with a relatively low temporal resolution of approximately fifty milliseconds, and with peak velocities up to two meters per second. Moreover, long pathlines are sensitive to the initial spatio-temporal seeding position.

Employing the probing approach presented in section 3, multiple cross-sections can be interactively generated at fixed positions. For each cross-section, streamlines or pathlines are traced with a restrained length, respectively integrating the lines in either the spatial or spatio-temporal domain. By placing sufficiently many cross-sections and repeatedly tracing the line primitives for each phase, the total error decreases and the line primitives are generally less sensitive to seed positioning. For the pathlines, this results in a depiction of a set of confined particle trajectories for each phase, instead of a single set of very long trajectories throughout the cardiac cycle. Figure 7 presents a sequence of pathlines over time for a single vessel cross-section, capturing a time frame from 165ms up to 440ms within the cardiac cycle.

Line traces may also be employed to inspect branching behavior of the blood-flow. For that purpose, Frydrychowicz et al. [8] propose a reversed tracing approach, enabling inspection of the particle trajectory that arrives at the seed position under consideration. QFE includes this reversed-tracing approach, as depicted in figure 9.

Visualization

A number of visualization techniques have been applied, to improve the perception of the line primitives, and the flow data they represent. Color is one of the most important visual cues to convey data characteristics. QFE provides a set of pre-defined color maps, together with a transfer-function editor, which allows to interactively change the color

Fig. 8: Randomly seeded line tracing (a) streamlines integration in the spatial domain (b) pathlines integration in the spatio-temporal domain.

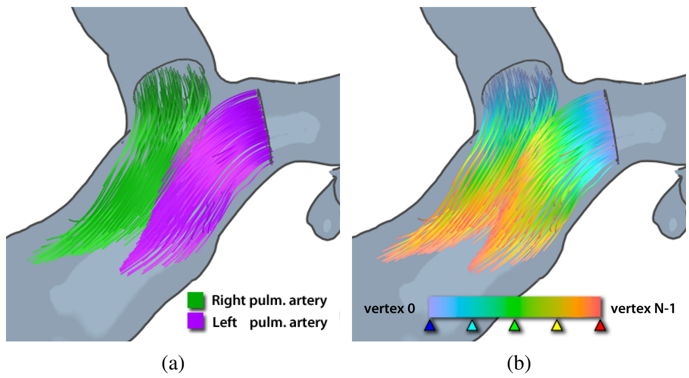


Fig. 9: Reversed pathline tracing (a) color per cross-section (b) color determined by line propagation, linearly mapping colors to the vertices from the seed (0) at the cross-section until the end of the line (N-1).

map. Typical color maps that have been included are the rainbow color map (figure 9b) and a black-body color map (figure 3).

The most often inspected flow characteristic is the blood-flow speed, often depicted by means of pseudocoloring. QFE allows physicians to inspect the blood-flow speed using linearly interpolated color maps, as well as regularly-banded color maps (figure 8). The number of quantization steps can be selected interactively.

The rainbow color map is the de facto standard in current practice, using hue variations to distinguish blood-flow speed variations. This color map is generally applied without correcting for perceptual deficits. The QFE transfer-function editor allows to interpolate color maps in both RGB color-space, as well as the perceptually more uniform CIELuv color-space. Additionally, the editor allows the user to automatically approximate constant lightness in the CIELuv space, while preserving maximal hue for the selected colors.

QFE facilitates the analysis of the blood-flow in different speed ranges, by interactively changing the color map. For example, physicians often inspect the existence of unexpected high-speed fluid streams, known as blood-flow jets. These jets can be easily detected through emphasizing the high speed flows by choosing a salient color with respect to the chosen color map. An example of a color map that uses such a threshold is presented in figure 8. In addition, the transfer-function editor enables step-wise transparency modulation for different speed ranges.

Furthermore, the perception of the line primitives has been improved by super-sampling, anti-aliasing, and local illumination. The Phong reflection model is applied to the lines. The normal vector for each point of the line primitive is selected coplanar to the light direction and the local tangent direction [27].

Lastly, QFE includes an animated highlight, emphasizing the particle trajectory that yields the line primitive under consideration. Using the probed cross-sections, QFE traces the line primitives for each phase of the cardiac cycle, spatially or spatio-temporally integrating flow profiles over time. Because a constant integration time is employed, a decrease of blood-flow speed over time will shorten the line primitives, which could be falsely interpreted as a reversal of the blood-flow direction. Hence, an animated visual cue is introduced to continuously indicate the blood-flow direction, as depicted in figure 10. The highlight is continuously animated, and is therefore not visually ambiguous with the applied static illumination.

Additionally, the animated highlight provides a good indication of the relative blood-flow direction and speed between the line primitives. Assuming a forward tracing of the line primitives, the animated highlight initiates at the seed position in the cross-sectional plane. Subsequently, the highlights advect along the line primitive, fanning out due to mutual differences of the line primitives, which are based on variations in the blood-flow velocity field.

4.2.3 Arrow-trails

In the previous subsections, we have presented techniques that directly depict parts of the unsteady blood-flow velocity field. However, other physically relevant and intuitive parameters can be derived from the blood-flow velocity field.

An important derived parameter is the volumetric flow-rate, defining the volume of blood that passes through a vessel cross-section per phase of the cardiac cycle. This quantity, expressed in m^3/s or ml/s, is of particular interest whenever flow streams bifurcate. The flow-rates after the split should add up to the initial flow-rate value before bifurcation. Hence, this parameter enables the physician to validate the branching of flow streams and to detect possible abnormalities, such as jets and leakages.

QFE includes an arrow visualization, as depicted in figure 11, for which the length of the arrow is determined by the flow-rate at the cross-section. Since flow-rate only has a through-plane component and no direction, we employ the origin and direction of the peak velocity within the cross-sectional area to position an arrow.

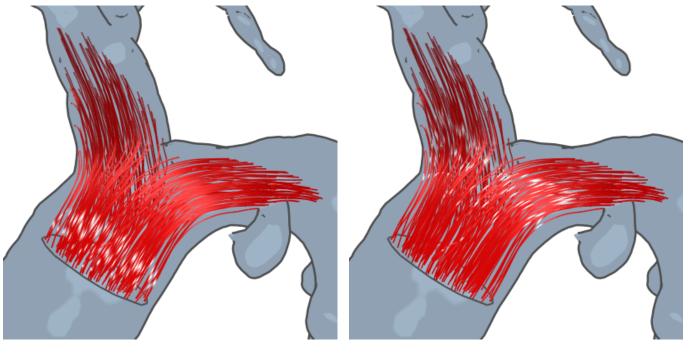
Commonly the volumetric flow-rate is inspected over time. To that end, the flow-rate arrows on each probed cross-section can be animated. A motion trail of the arrows is included, capturing the temporal behavior. A motion-trail consists of a sequence of increasingly faded arrows, which depict flow-rates from the near past. Figure 11a depicts the increase in flow-rate after the contraction of the heart muscle (systole), while figure 11b depicts the decrease of flow-rate when the heart muscle relaxes (diastole). An example of flow-rate arrow-trails depicting branching flow streams is shown on the left-hand side of figure 1.

5 USER EVALUATION

The acquisition of quantitative 4D MRI blood-flow is a relatively young and emerging field of research. Although the blood-flow information is a promising source for diagnosis and risk assessment of cardiovascular diseases, many aspects of the blood-flow are still unknown. Visualization and interaction techniques support the blood-flow data analysis, which will lead to new insights and improve the understanding of the patient-specific hemodynamics.

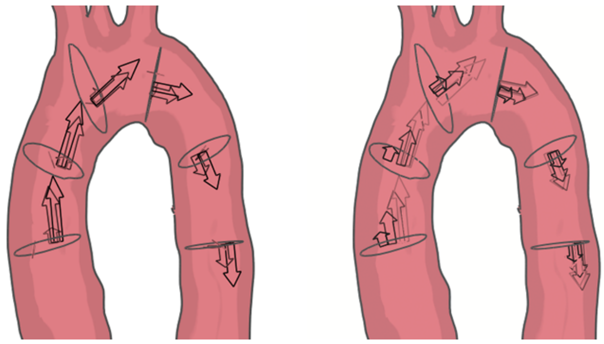
In order to measure the value of the presented visual styles, we have performed an evaluation questionnaire with a group of four physicians that are actively involved with the acquisition of 4D blood-flow data. Given the extent of the research field, this group of cardiologists and research fellows adequately represents the pre-clinical cardiovascular blood-flow research community.

In the first part of the questionnaire, the depiction of the anatomical context is considered, as described in subsection 4.1. While inspecting the morphological structures, it is appreciated that the inside of the vessel wall is depicted view-dependently. While navigating around the vessel structures, three out of four respondents prefer an extensive illumination, currently presented by a diffuse lighting component.



(a) (b)

Fig. 10: Line-trace highlight-animation propagates in the flow direction. (a) early propagation stage (b) late propagation stage.



(a) (b)

Fig. 11: Flow-rate arrow-trails (a) arrows at 140ms after the start of the cardiac cycle (b) arrows at 280ms after the start of the cardiac cycle.

However, when the approximate anatomy is presented in the context of a flow visualization, simplified shading is preferred by all the physicians.

Furthermore, all the respondents agree that the occluding contours greatly improve the perception of the morphological structure. While the occluding contours are considered a necessary feature (figure 4a), most physicians also value the hidden contours (figure 4b). In particular those physicians who study anomalous cardiovascular structures, for instance in the context of congenital heart diseases, noticed an improved depth perception, and generally could grasp the complex anatomies more easily.

In the second part of the questionnaire, the presented interaction and visualization techniques to analyze the blood-flow dynamics are considered. All the respondents agree that the automated cross-section probing, as described in section 3, is very intuitive, and saves valuable time during the data analysis. However, there is a need to interactively modify an automatically positioned cross-section. In particular, it should be possible to move, angulate and scale the cross-section.

Considering the blood-flow visualization aspects, as described in subsection 4.2, the questionnaire started with the planar reformat visualizations. All physicians in our study agree that reformat-based data analysis requires non-angulated and view-aligned cross-sectional planes. Therefore, the exploded planar reformat (figure 5b) is by all means preferred over the integrated planar reformats (figure 5a). In general, the respondents could very well relate the floating plane to the original location, guided by the dashed connection lines. Furthermore, occlusion can be sufficiently avoided, given the typically limited number of inspected planes, and the possibility to hide certain cross-sections. The color Doppler inspired red-and-blue color coding is generally the preferred visualization method, although other representations will also be observed while analyzing the data.

In subsection 4.2.2, we have investigated a variety of seeding approaches, distinguishing between seeding strategies and seeding templates (figure 6). Considering these seeding approaches, the respondents were far from unanimous in many respects. As for the seeding strategies, the physicians indicate that it is worthwhile to investigate the effects, however they prefer not to vary the strategy. A common argument is that they prefer to use a single seeding strategy, for which they know and get accustomed to the impact on the line primitives. In consequence, the physicians should be able to distinguish anomalous flow patterns more easily. Based on the same argument, three out of four respondents prefer the rectilinearly structured seeding over a random seeding, even if they are aware that this imposes a fixed structure on the line primitives.

None of the respondents valued the use of seeding templates. Even though some cardiovascular conditions require inspection of the blood-flow dynamics near the vessel wall or center, still there is a collective conception that changing the seeding template would falsely influence the perception of the resulting line primitives. The templates were intended to focus on the regions-of-interest, avoiding visual clutter and occlusion in the case of densely seeded line primitives. However, it is likely that this approach will not be taken up by the preclinical research community. Providing a proper focus of the blood-flow characteristics within the vascular structure is therefore an interesting topic for further research.

Tracing of line primitives is currently considered to be the most effective visual style to analyze the blood-flow dynamics. For the data analysis, all respondents prefer to trace line primitives from multiple cross-section planes. Even though the appearance of streamlines and pathlines is similar to a large extent for this application (figure 8), all respondents indicate the pathlines as the more intuitive concept.

For both streamlines and pathlines, reversing the trace direction caused considerable doubt. Most physicians indicated that the reversed tracing seemed to be a promising feature, in particular for branching blood-flow streams. However, none of the respondents could indicate a direct application where they would benefit from this feature. Nevertheless, there was common interest to keep this feature available.

In the next part of the questionnaire, the physicians were asked to evaluate the appearance of the line primitives. Color coding of the line primitives can convey many aspects of the data. All physicians in the study agree that from the presented aspects, the blood-flow speed is the most valuable one. However, the possibility to inspect other parameters, such as a color coding of the line propagation, is highly appreciated.

With regards to the color coding, the rainbow color-map was generally valued best to inspect the blood-flow speed. In particular, all respondents preferred the combination with a salient color for a range of high speed flow (figure 8). By qualitative inspection of the data, it was noticed that the salient color directly attracts the attention to high speed flow regions, while for other regions the blood-flow speed could be estimated fairly well. In addition, all participating physicians appreciated the possibility to interactively adjust the color map to inspect the range of blood-flow speeds of their interest.

Illumination of the line primitives was generally accepted positively. Every respondent indicated that the perception of the spatial relations between the line primitives is improved through illumination. With respect to the animated highlight (figure 10), the physicians responded slightly more reserved. It was generally agreed that the highlight provides a profitable visual indicator. Indeed the highlight captures the direction and speed of the particle trajectories that yielded the line primitives. Moreover, relations between the line primitives became more apparent, potentially improving the understanding of complex flow patterns. The visual gain from the highlight was valued best in combination with the circular seeding strategy, which was however considered an improbable strategy choice for current research purposes.

Subsequently, the questionnaire gauges the value of the presented flow-rate arrow trails. The physicians agree that the flow-rate arrow trail provides a clear indication of the temporal behavior of both the flow profile and the flow-rate at the considered cross-section. However, there is also the need for quantitative numbers. The arrow representation is considered a valuable visual indicator that should be accompanied by quantitative flow-rate information.

In the final part of the questionnaire, the physicians were asked to judge the overall performance of the framework. All respondents agreed that real-time parametrization is an important aspect for their data analysis tool, saving them valuable time. Loading the data, typically sized in the range of 150 up to 250 megabytes, takes maximally fifty seconds on a notebook containing a 2.5GHz dual core processor with 3GB of memory. Interaction with the data and parametrization of the visual styles are performed in real-time. Consequently, the performance of our framework was positively valued. In particular, direct modification of the color coding, seeding density and the line-trace length were highly appreciated.

6 Discussion

The QFE system was developed using the C++ programming language, using the OpenGL graphics library, and the visualization toolkit (VTK) in combination with the QT user interface framework. The computational power of modern graphics hardware was utilized for both the visual styles, as well as performance-wise costly algorithms. In particular, tracing of the line primitives is performed in real-time by employing the geometry shader, similar to the approach by Köhn et al. [16]. As a result, the line primitives can be parameterized interactively. The system generally runs at interactive framerates of well over ten frames per second, even when multiple visual styles are combined. In order to achieve these framerates, the graphics hardware needs to implement the unified shading architecture.

The QFE framework was tested on a range of 4D MRI blood-flow data sets. The figures presented throughout the paper were obtained from two volunteer blood-flow data sets. Figures 1, 5, 7, 8, 9 and 10 are based on the first volunteer data set, while figures 2, 3, 4, 6 and 11 depict the second volunteer data set.

In addition, QFE was employed to inspect patient data, examining pathological blood-flow behavior such as depicted in figure 12. The color Doppler inspired red-and-blue color coding on the exploded planar reformat shows the through-plane regurgitant flow. In addition, the pathlines provide insight in the complex turbulent behavior over time. The behavior throughout the cardiac cycle can be inspected by animating the visual styles. The patient study was approved by the local research ethics committee (study no. 08/H0809/49).

7 Conclusions and future work

We have presented the QFE framework, which enables physicians to interactively explore 4D MRI blood-flow data by means of various visualization styles. An illustrative approach was proposed to depict the approximate anatomical context. In addition, we have presented a number of visualization techniques to depict the blood-flow dynamics. All presented techniques rely on the probing method to interactively select vessel cross-sections.

QFE enables direct inspection of the blood-flow data for each of the selected cross-sections by application-specific planar reformats. Furthermore, QFE incorporates both streamlines and pathlines, which are traced for each phase of the cardiac cycle, capturing a vast amount of information on the spatial and temporal blood-flow characteristics. Various seeding strategies were investigated, accompanied by templates to focus the line traces with respect to the vessel center. Properties such as the blood-flow speed can be conveyed by color coding the line primitives, interactively adjusting the color map. Additionally, we propose an animated highlight to continuously indicate the general blood-flow direction. Lastly, QFE includes flow-rate arrow-trails, depicting the flow-rate and peak-flow origin and direction throughout the cardiac cycle.

We have performed an evaluation questionnaire with a group of domain experts, measuring the value of the presented visual styles. All respondents were hesitant about varying the seeding approach. Interactively changing the seed density, however, is a valuable feature in practice. The illuminated line primitives were considered to be the most effective visual style to inspect the blood-flow dynamics, for which the color coding of various parameters was a necessary aspect. The real-time parametrization and interactive color-map adjustments were highly appreciated. Additionally, the animated highlight and reversed tracing feature were considered valuable, even if their direct application in practice was not yet evident. The flow-rate arrow-trails provided a valuable visual indicator when combined with the appropriate quantitative information.

In the future, we see opportunities to include other visual styles that have proven successful to depict line primitives. For example, the line perception could be enhanced by means of shadows [19] or halo effects [7, 18]. Additionally, more elaborate opacity mappings could be applied to the presented line primitives, highlighting only the curves that portray certain properties of interest [25].

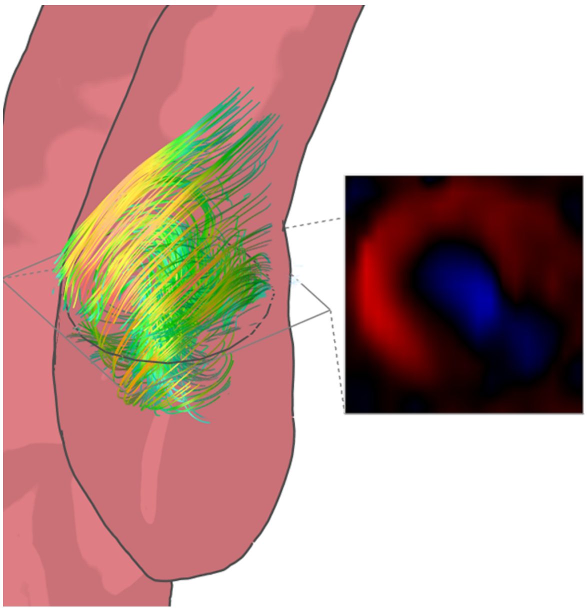


Fig. 12: Exploded planar reformat and pathlines depicting pathological systolic blood-flow in the ascending aorta.

Moreover, the seeding approach will require further research. While the flow visualization literature generally proclaims random seeding strategies, physicians need recognizable patterns to which they get accustomed. In order to fulfill this requirement, it is worthwhile to improve current visualization approaches. For instance, the effect of evenly spaced line primitives, either in object-space or view-space, could be investigated. Similar approaches were presented by Mattausch et al. [18] and Vilanova et al. [30].

Alternatively, the flow field could be clustered, eliminating the dependency on the seeding strategy. This would lead to a more abstract depiction of the blood-flow dynamics, capturing the essential aspects of the entire flow field. In addition, new methods may be incorporated into the presented framework. In particular, it would be worthwhile to include and evaluate integral surfaces and texture based approaches.

Lastly, quantitative numbers and additional knowledge about the unsteady blood-flow data can improve future visual representations. It is important to further investigate the visualization of pathological blood-flow dynamics, constructing novel interaction and depiction techniques for specific cardiovascular conditions.

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References

[1] American Heart Association. Heart disease and stroke statistics, 2010 update at-a-glance. http://www.americanheart.org/statistics/, 2010.

[2] M. A. Bernstein and Y. Ikezaki. Comparison of phase-difference and complex-difference processing in phase-contrast MR angiography. *Magnetic Resonance Imaging*, 1(2):725–729, 1991.

[3] H. G. Bogren and M. H. Buonocore. 4D Magnetic resonance velocity mapping of blood flow patterns in the aorta in young vs. elderly normal subjects. *Magnetic Resonance Imaging*, 10(5):861–869, 1999.

[4] H. Bouma, J. Oliván Bescós, A. Vilanova, and F. A. Gerritsen. Unbiased vessel-diameter quantification based on the FWHM criterion. In *Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, volume 6512, Mar 2007.

[5] S. Bruckner and M. E. Gröller. Exploded views for volume data. *IEEE Transactions on Visualization and Computer Graphics*, 12(5):1077–1084, Sept 2006.

[6] D. DeCarlo and S. Rusinkiewicz. Highlight lines for conveying shape. In *NPAR '07: Proceedings of the 5th international symposium on Non-photorealistic animation and rendering*, pages 63–70, New York, NY, USA, 2007. ACM.

[7] M. H. Everts, H. Bekker, J. B. Roerdink, and T. Isenberg. Depth-dependent halos: illustrative rendering of dense line data. *IEEE Transactions on Visualization and Computer Graphics*, 15:1299–1306, 2009.

[8] A. Frydrychowicz, R. Arnold, A. Harloff, C. Schlensak, J. Hennig, M. Langer, and M. Markl. Images in cardiovascular medicine. In vivo 3-dimensional flow connectivity mapping after extracardiac total cavopulmonary connection. *Circulation*, 118:e16–17, Jul 2008.

[9] A. Frydrychowicz, A. F. Stalder, M. F. Russe, J. Bock, S. Bauer, A. Harloff, A. Berger, M. Langer, J. Hennig, and M. Markl. Three-dimensional analysis of segmental wall shear stress in the aorta by flow-sensitive four-dimensional-MRI. *Magnetic Resonance Imaging*, 30:77–84, 2009.

[10] B. Gooch and A. Gooch. *Non-photorealistic rendering*. A. K. Peters, Ltd., Natick, MA, USA, 2001.

[11] G. Greil, T. Geva, S. E. Maier, and A. J. Powell. Effect of acquisition parameters on the accuracy of velocity encoded cine magnetic reso-

nance imaging blood flow measurements. *Magnetic Resonance Imaging*, 15(1):47–54, 2002.

[12] T. A. Hope, M. Markl, L. Wigström, M. T. Alley, D. C. Miller, and R. J. Herfkens. Comparison of flow patterns in ascending aortic aneurysms and volunteers using four-dimensional magnetic resonance velocity mapping. *Magnetic Resonance Imaging*, 26:1417–1479, 2007.

[13] S. Jin, J. Oshinski, and D. P. Giddens. Entrance flow patterns in the coronary arteries: a computational study. In *ASME Bioengineering*, number 1, pages 2–3, 2003.

[14] D. Kainmüller, R. Unterhinninghofen, S. Ley, and R. Dillmann. Level set segmentation of the heart from 4D phase contrast MRI. In *Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, volume 6914, Apr 2008.

[15] H. Knutsson. Representing local structure using tensors. In *Proceedings of Scandinavian Conference on Image Analysis*, volume 6, pages 244–251, 1989.

[16] A. Köhn, J. Klein, F. Weiler, and H.-O. Peitgen. A GPU-based fiber tracking framework using geometry shaders. In *Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*, volume 7261, pages 72611J–1 – 72611J–10, 2009.

[17] M. Markl, F. P. Chan, M. T. Alley, K. L.Wedding, M. T. Draney, C. J. Elkins, D. W. Parker, C. A. Taylor, R. J. Herfkens, and N. J. Pelc. Time resolved three dimensional phase contrast MRI. *Magnetic Resonance Imaging*, 506:64, 2003.

[18] O. Mattausch, T. Theußl, H. Hauser, and E. Gröller. Strategies for interactive exploration of 3D flow using evenly-spaced illuminated streamlines. In *SCCG '03: Proceedings of the 19th spring conference on Computer graphics*, pages 213–222, New York, NY, USA, 2003. ACM.

[19] T. Peeters, A. Vilanova, G. Strijkers, and B. ter Haar Romeny. Visualization of the fibrous structure of the heart. In *Proceedings of VMV 2006*, pages 309–317, Nov 2006.

[20] N. J. Pelc, R. J. Herfkens, A. Shimakawa, and D. R. Enzmann. Phase contrast cine magnetic resonance imaging. *Magnetic Resonance Quarterly*, 7:229–254, Oct 1991.

[21] M. Persson, J. E. Solem, K. Markenroth, J. Svensson, and A. Heyden. Phase contrast MRI segmentation using velocity and intensity. *Scale Space and PDE Methods in Computer Vision*, 3459:119–130, Mar 2005.

[22] F. H. Post, B. Vrolijk, H. Hauser, R. S. Laramee, and H. Doleisch. The state of the art in flow visualisation: feature extraction and tracking. *Computer Graphics Forum*, 22(4):775–792, 2003.

[23] W. Press, S. Teukolsky, W. Vetterling, and B. Flannery. *Numerical recipes in C*. Cambridge University Press, 2nd edition, 1992.

[24] N. Shahcheraghi, H. A. Dwyer, A. Y. Cheer, A. I. Barakat, and T. Rutaganira. Unsteady and three-dimensional simulation of blood flow in the human aortic arch. *Biomechinical Engineering*, 124:378–387, Aug 2002.

[25] K. Shi, H. Theisel, H. Hauser, T. Weinkauf, K. Matkovic, H.-C. Hege, and H.-P. Seidel. Path line attributes – an information visualization approach to analyzing the dynamic behavior of 3d time-dependent flow fields. In *Topology-Based Methods in Visualization II*, pages 75–88, 2009.

[26] T. S. Sørensen, H. K. Philipp Beerbaum, and E. M. Pedersen. Three-dimensional, isotropic MRI: a unified approach to quantification and visualization in congenital heart disease. *The International Journal of Cardiovascular Imaging*, 21(2):283–292, Apr 2005.

[27] D. Stalling, M. Zöckler, and H.-C. Hege. Fast display of illuminated field lines. *IEEE Transactions on Visualization and Computer Graphics*, 3:118–128, 1997.

[28] R. Unterhinninghofen, S. Ley, J. Ley-Zaporozhan, H. von Tengg-Kobligk, M. Bock, H.-U. Kauczor, G. Szab, and R. Dillmann. Concepts for visualization of multidirectional phase-contrast MRI of the heart and large thoracic vessels. *Academic Radiology*, 15(3):361 – 369, 2008.

[29] S. Uribe, P. Beerbaum, T. S. Sørensen, A. Rasmusson, R. Razavi, and T. Schaeffter. Four-dimensional (4D) flow of the whole heart and great vessels using real-time respiratory self-gating. *Magnetic Resonance in Medicine*, 62(4):984–92, Oct 2009.

[30] A. Vilanova, G. Berenschot, and C. van Pul. DTI visualization with streamsurfaces and evenly-spaced volume seeding. In *Proceedings of VisSym '04*, pages 173–182, 2004.

[31] T. Weinkauf. *Extraction of topological structures in 2D and 3D vector fields*. PhD thesis, University Magdeburg, 2008.

[32] L. Wigström, T. Ebbers, A. Fyrenius, M. Karlsson, J. Engvall, B. Wranne, and A. F. Bolger. Particle trace visualization of intracardiac flow using time-resolved 3D phase contrast MRI. *Magnetic Resonance in Medicine*, 41:793–799, Apr 1999.

[33] P. A. Yushkevich, J. Piven, C. Hazlett, H. Smith, G. Smith, R. Ho, S. Ho, J. C. Gee, and G. Gerig. User-guided 3D active contour segmentation of anatomical structures: significantly improved efficiency and reliability. *Neuroimage*, 31(3):1116–1128, 2006.