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Exploration of 4D MRI Blood-Flow Using Stylistic Visualization

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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 reformat, 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].

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

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

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.

Locating the area to be inspected and probing the vessel cross-

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 × 144 × 144 voxels of 2.0 × 2.0 × 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.
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.

The 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 $v_i(\vec{x})$. For $N$ cardiac phases, this is defined as:

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

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...
the vessel cross-section locations, which are positioned by the physi-
can be inspected. Various visualization styles depict the flow field at
With the anatomical context in place, the quantitative blood-flow field
impede the resulting flow visualization. However, they do not
may be occluded by the blood-flow depictions. However, they do not
released, leaving an uncluttered representation of the anatomical con-
sight into the spatial relations of the structures. In order to facilitate
plifies the representation, reducing depth perception and increasing in-
side 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.
also be omitted without losing the necessary morpho-
logical 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 silhou-
ettes [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 in-
side 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 con-
tour lines. In the past, extensive research has been conducted, inves-
tigating 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 perpendicu-
lar to the view direction. Complementary contour lines, such as suggest-
ive contours, are deliberately omitted for the representa-
tion 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 simpli-
fies the representation, reducing depth perception and increasing in-
sight 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 oc-
cclusion 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 con-
text. 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 physi-
cian using the probing technique presented in section 3. This subsec-
tion describes the blood-flow visualization techniques, incorporated in
the QFE framework. The techniques are interactively parameterizable and
and can be combined without notable loss of performance.

4.2.1 Planar reformat
The first technique is based on the customary MPR, depicting separa-
tate 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 reformatting 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 ex-
ploded view technique, regularly used in the field of medical and tech-
nical 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 vessel cross-sections are em-
yoiled as a seeding plane. Differently distributing the seed positions
within the vessel structure. The selected vessel cross-sections are em-
ymoiled as a seeding plane. Differently distributing the seed positions
within the vessel structure. The selected vessel cross-sections are em-

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.
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 structure 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
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 m³/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.
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 reformat (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 on the exploded planes is preferred over the integrated planar reformats (figure 5d).

In general, 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 preferred over the integrated planar reformats (figure 5d). In general, the respondents agreed that 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 respondents 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 Kohn et al. [16]. As a result, the line primitives can be parameterized interactively. The system generally runs at interactive frame rates of well over ten frames per second, even when multiple visual styles are combined. In order to achieve these frame rates, 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 four 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 reformat. 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 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].

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 Matschus 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


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


