Time-resolved Volumetric MRI Blood Flow — A Doppler Ultrasound Perspective —

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ABSTRACT

Hemodynamic information is increasingly inspected to assess cardiovascular disease. Abnormal blood-flow patterns include high-speed jet flow and regurgitant flow. Such pathological blood-flow patterns are nowadays mostly inspected by means of color Doppler ultrasound imaging. To date, Doppler ultrasound has been the prevailing modality for blood-flow analysis, providing non-invasive and cost-effective blood-flow imaging. Since recent years, magnetic resonance imaging (MRI) is increasingly employed to measure time-resolved blood-flow data. Albeit more expensive, MRI enables volumetric velocity encoding, providing true vector-valued data with less noise. Domain experts in the field of ultrasound and MRI have extensive experience in the interpretation of blood-flow information, although they employ different analysis techniques.

We devise a visualization framework that extends on common Doppler ultrasound visualizations, exploiting the added value of MRI velocity data, and aiming for synergy between the domain experts. Our framework enables experts to explore the advantages and disadvantages of the current renditions of their imaging data. Furthermore, it facilitates the transition from conventional Doppler ultrasound images to present-day high-dimensional velocity fields. To this end, we present a virtual probe that enables direct exploration of MRI-acquired blood-flow velocity data using user-friendly interactions. Based on the probe, Doppler ultrasound inspired visualizations convey both in-plane and through-plane blood-flow velocities. In a compound view, these two-dimensional visualizations are linked to state-of-the-art three-dimensional blood-flow visualizations. Additionally, we introduce a novel volume rendering of the blood-flow velocity data that emphasizes anomalous blood-flow patterns. The visualization framework was evaluated by domain experts, and we present their feedback.

Keywords: MRI, Doppler ultrasound, cardiovascular, blood flow, visualization and interaction

1. INTRODUCTION

Cardiovascular disease (CVD) comprises a group of conditions with a prevalence of over thirty percent of the American population, and is currently the leading cause of death worldwide.[1] This group of conditions is currently mostly assessed based on the morphology of the cardiovascular system. However, the blood-flow dynamics strongly influence the cardiovascular biology, and hence pathogenesis. A better understanding of the blood-flow dynamics therefore potentially leads to better diagnosis and prognosis of CVD.

Various imaging modalities enable acquisition of blood-flow data. The prevailing modality is Doppler ultrasound (US), which employs frequency changes due to the Doppler effect. US provides an appealing spatiotemporal resolution at a low cost. However, the field-of-view is limited, and the imaging quality depends on operator skills. Doppler US does not allow for full volumetric flow imaging. Alternatively, tomographic imaging modalities enable acquisition of time-resolved volumetric data. We focus on non-invasive magnetic resonance imaging (MRI). In particular, phase-contrast MRI (PC-MRI) enables acquisition of quantitative time-resolved volumetric velocity fields, also referred to as 4D PC-MRI data. For the cardiac case, these data typically span the human thorax,

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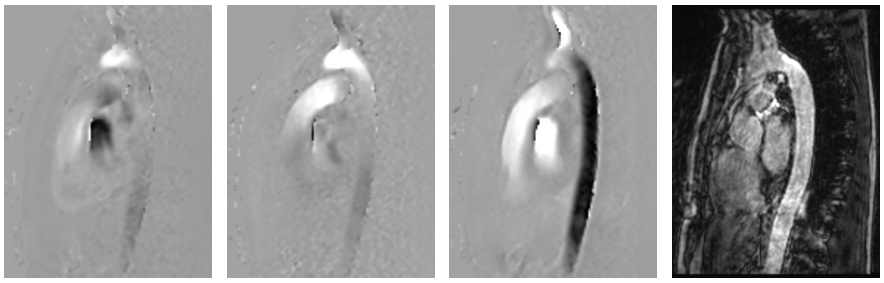


(a) (b) (c) (d)

Figure 1: Typical 4D PC-MRI blood-flow data consists of 20 to 25 time points during the heartbeat. Each time point comprises a volumetric velocity field of about 150×150×50 voxels, sized 2.0×2.0×2.5 mm. Velocity data (a) right to left (b) front to back (c) head to feet, and (d) anatomical scan.

and represent one heartbeat (Fig 1). In contrast to US, MRI provides a lower spatiotemporal resolution, and is more expensive. However, MRI is less prone to noise, and allows for larger fields of view. PC-MRI blood-flow measurements are typically performed for complex pathologies.

Domain experts in the field of ultrasound and MRI have experience in the interpretation of blood-flow information. However, both fields employ different techniques for their visual analysis. In this work, we present a visualization framework that extends on conventional color Doppler ultrasound renditions, while exploiting the added value of the true volumetric MRI velocity data. To this end, we mimic Doppler US images using a virtual probe to inspect 4D PC-MRI data. We link the Doppler US inspired renditions to state-of-the-art geometry-based blood-flow visualizations of the 4D MRI blood-flow data, as well as a novel velocity-field volume rendering. This enables both US and PC-MRI experts to relate their familiar visualization to other renditions, and to explore the advantages and disadvantages of the different visualization techniques for current US and MRI flow imaging. Our approach potentially supports the transition from ultrasound inspection to the state-of-the-art visual analysis of 4D PC-MRI for suitable cases.

In summary, we introduce a real-time visualization framework for 4D PC-MRI blood-flow data, comprising:

- an interaction scheme to operate a virtual probe, facilitating exploration of the volumetric blood-flow data,
- a compound view with interactive Doppler-US inspired renditions, geometry-based blood-flow visualization, and a novel blood-flow velocity field volume rendering that conveys the dynamics in three dimensions.

2. RELATED WORK

Ultrasound has become the de facto standard for acquisition of blood-flow information, and has yielded application-specific knowledge, relating flow characteristics to the progression of various conditions.[2] Alternatively, MRI acquisition provides volumetric data of the cardiovascular anatomy and blood flow. The imaging process is less operator-dependent, and provides better signal-to-noise ratios.

In previous work, various cross-field approaches have been studied. This includes research that addresses physical simulation of US, which is mainly used for educational purposes.[3–5] Limited work has been carried out to simulate Doppler US, typically based on computational fluid dynamics (CFD) models.[6]

Instead of a physical simulation of Doppler US, we aim for a recognizable visualization system that exploits benefits from US and MRI blood-flow data. Visualization was readily recognized as a valuable tool to convey simulation results.[7] The value of mimicking Doppler US was previously presented by Nayak et al.[8] for MRI fluoroscopy. We take a more elaborate approach for 4D PC-MRI, introducing a virtual probe to interactively explore the volumetric 4D PC-MRI blood-flow velocity data. We introduce several interaction techniques that allow movement of the probe in the full six degrees of freedom, comprising 3D translation and rotation, using elementary two-dimensional interactions. The interaction techniques differ from previous work presented by the authors.[9]

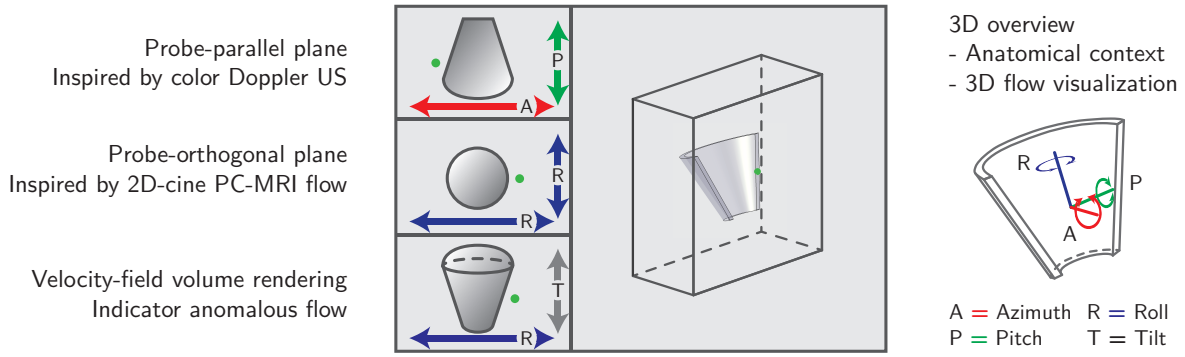


Figure 2: A compound view presents blood-flow information, based on a virtual probe. This includes Doppler US and 2D-cine PC-MRI inspired planes, a velocity-field volume rendering, and a 3D overview. Navigation is based on 2D interactions, enabling translations and rotations.

3. ULTRASOUND-INSPIRED VIRTUAL PROBE

3.1 Appearance

To mimic Doppler US, a virtual probe is employed to navigate through the volumetric blood-flow field. The virtual probe consists of a graphics primitive in the shape of a configurable truncated cone that is halfway intersected along its long axis, also called a hemi-frustum. The probe is equipped with two oblique planes to represent information around the probe. Furthermore, there is a rotation handle, rendered as a green sphere on the right-hand side. The handle is also used as an orientation marker, which visually unites the different viewports. The green sphere indicates the orientation of the different visualizations with respect to the coordinate frame spanned by the virtual probe (Fig. 2).

3.2 Interaction

As opposed to a tangible US probe, the virtual probe is embedded inside the volume. The initial positioning requires a three-point selection, based on conventional orthogonal planes. The first two points determine the probe long axis, while the third point secures the binormal of the probe.

After positioning, the user can interact with the probe to explore the data. Similar to a hardware US probe, six degrees-of-freedom are provided. Interaction with the virtual probe is performed with a computer mouse, using elementary two-dimensional interactions, comprising translation and rotation. These interactions can be performed in the various viewports of the compound view (Fig. 2). The viewports are fully linked, and hence interactions that affect the virtual probe are directly updated in all other viewports.

Translation is performed in the three-dimensional overview, moving the probe in its parallel plane. This restriction omits complex three-dimensional displacements. Intuitive rotation in three dimensions is more challenging. For the probe, three axes of rotation are distinguished: azimuth, roll and pitch. These interactions are performed by means of horizontal and vertical dragging mouse movements, or gestures, in the two-dimensional viewports. The direction of these gestures intuitively correspond to the rotation of the virtual probe.

To inspect the three-dimensional nature of the velocity-field volume rendering, an additional tilt interaction is introduced. In contrast to the aforementioned interactions, the location of the virtual probe is not affected. Instead, a vertical gesture tilts the camera position in the volume rendering viewport, facilitating inspection of the three-dimensional projection. This stands in contrast to the main three-dimensional viewport, which provides a trackball-style camera interaction.

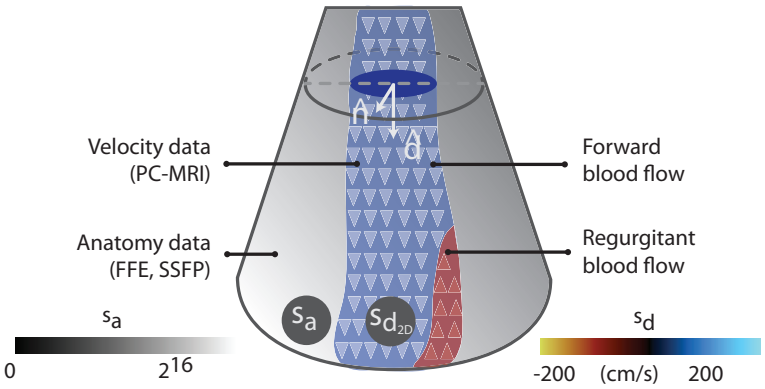


Figure 3: The probe-parallel plane shows both anatomical (s_a) and blood-flow ($s_{d_{2D}}$) information. A speed threshold distinguishes the blood-flow regions, conveying in-plane velocities inspired by Doppler US. The inspection direction $\hat{\mathbf{d}}$ is determined by the long axis of the probe, and $\hat{\mathbf{n}}$ defines the plane normal.

4. ULTRASOUND-INSPIRED VISUALIZATION

4.1 Mimicking ultrasound renditions

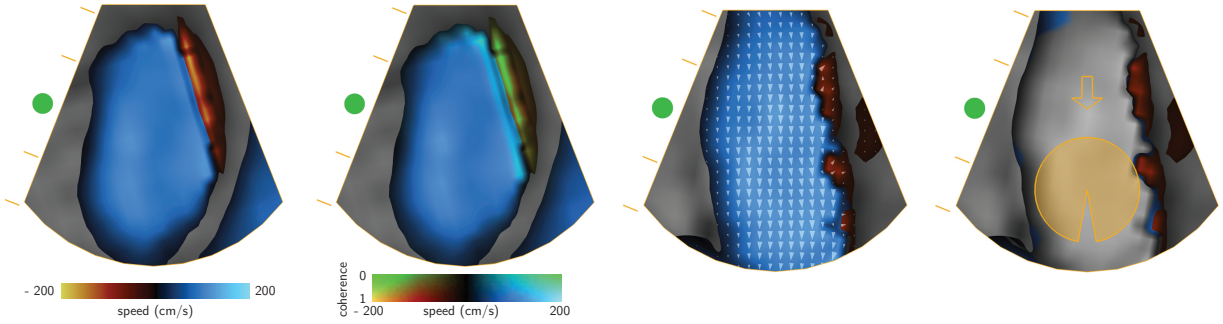
The long axis of the probe, from base to top, represents the inspection direction analogous to the direction of the ultrasound beam. A plane is defined parallel to the long axis to mimic a color Doppler visualization (Fig. 4). Since the plane is connected to the position and orientation of the probe, the visualization will be updated when the probe is repositioned. The plane is shown in the top-left view (Fig. 2), and conveys both anatomy and blood-flow velocities.

A user-defined threshold on the blood-flow speed distinguishes between flow regions and stationary regions (Fig. 3). Stationary tissue is depicted by anatomical data. This is typically the fast-field echo (FFE) data obtained with the flow acquisition. Alternatively, separate high-contrast data can be used, e.g., using steady state free precession (SSFP) acquisition. On the US-inspired plane, the scalar values that represent anatomy s_a are equal to the values of the anatomical data, mapped by a gray-scale transfer function.

To mimic color Doppler US, the three-directional velocities $\vec{\mathbf{v}}$ are projected onto the plane using the plane normal $\hat{\mathbf{n}}$. Next, the sign of the angle ϕ between the normalized inspection direction $\hat{\mathbf{d}}$ and the projected velocity vectors $\vec{\mathbf{v}}_p$ is computed. The sign determines if the probe is aligned parallel of anti-parallel with respect to the local velocity data. According to the Doppler US convention, flow that moves away from the virtual probe is mapped to blue, while flow moving towards the probe is mapped to red. The scalar values that represent the Doppler US $s_{d_{2D}}$ are mapped by a red-blue transfer function (Fig. 4a), and are defined at positions $\mathbf{x}$ as:

$$\vec{\mathbf{v}}_p(\mathbf{x}) = \vec{\mathbf{v}}(\mathbf{x}) - (\vec{\mathbf{v}}(\mathbf{x}) \bullet \hat{\mathbf{n}}) \cdot \hat{\mathbf{n}},$$
$$\phi(\mathbf{x}) = \frac{\vec{\mathbf{v}}_p(\mathbf{x})}{||\vec{\mathbf{v}}_p(\mathbf{x})||} \bullet \hat{\mathbf{d}},$$
$$s_{d_{2D}}(\mathbf{x}) = \mathrm{sgn}(\phi(\mathbf{x})) \cdot ||\vec{\mathbf{v}}_p(\mathbf{x})||.$$

Clinical US imaging apparatus often provide a green emphasis to indicate high-speed or turbulent flow. We incorporate this into our visualization. For turbulence, Doppler US relies on the temporal variance, emphasizing rapidly changing flow regions.[10] However, due to the inferior temporal resolution of PC-MRI blood-flow imaging, we provide a green highlight based on spatial information to indicate anomalous regions. Low coherence indicates potential anomalous flow behavior, which is emphasized in green using a two-dimensional transfer function (Fig. 4b). To this end, we adopt the local phase coherence (LPC) measure,[11] indicating the coherence between the normalized flow directions $\hat{\mathbf{v}}$ of M neighbors surrounding position $\mathbf{x} =< x, y, z >$:



(a) (b) (c) (d)

Figure 4: Doppler US inspired planes, based on the probe-parallel plane. (a) A red-blue color map encodes anterograde and retrograde flow within a speed threshold. (b) Incoherent flow areas are emphasized by a green color, using a 2D transfer function, (c) and arrowheads are used to show in-plane directions. (d) A widget enables inspection within a user-defined angle.

$$\mathrm{lpc}(\mathbf{x}) = \frac{1}{M} \sum_{i=-1}^{1} \sum_{j=-1}^{1} \sum_{k=-1}^{1} \hat{\mathbf{v}}(\mathbf{x}) \bullet \hat{\mathbf{v}}(x+i, y+j, x+k)$$

The US-inspired plane communicates the flow direction in relation to the probe long axis, providing limited directional information. Therefore, we have extended the visualization with an arrowhead overlay, representing in-plane projections of the three-directional flow vectors. The semi-transparent white arrowheads are scaled with the in-plane speed, and cause minimal interference with the underlying visualization (Fig. 4c).

Furthermore, we propose an addition to Doppler US imaging to emphasize regurgitant flow. The conventional color mapping depends on the orientation of the probe long axis. To clarify this dependency, we introduce a widget that enables inspection within a certain angle. Whenever the mouse cursor hovers over the plane, a widget appears (Fig. 4d). Using the scroll wheel of the mouse, an angle can be set interactively, depicted by a cut-out that is similar to a pie-chart division. The regions where the angle between the projected velocities and the inspection direction $\hat{\mathbf{d}}$ is smaller than the defined angle are omitted from the visualization. Areas that deviate from the forward direction by more than the set angle are emphasized.

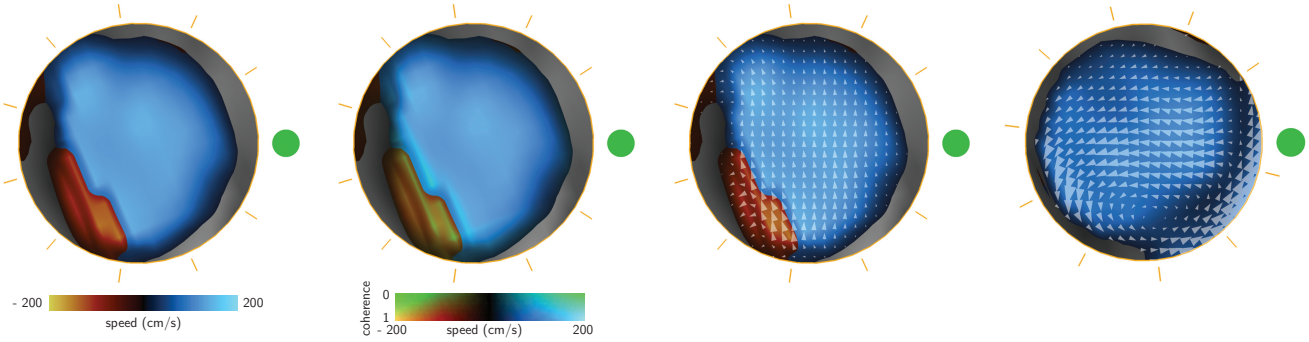
4.2 Enhancing ultrasound renditions

Besides mimicking Doppler US renditions, we furthermore provide enhanced representations of the 4D PC-MRI data. Inspired by two-dimensional cine PC-MRI blood-flow imaging, we introduce a planar reformat that shows the through-plane velocities, which requires a plane perpendicular to the vessel centerline. Since the probe long axis is set parallel to the blood-flow direction to mimic US inspection, we use a plane orthogonal to the long axis to obtain the through-plane velocities. Using the previously introduced speed threshold, the through-plane velocities s_t are computed by projecting the three-dimensional velocity data $\vec{\mathbf{v}}$ to the normalized Doppler inspection direction $\hat{\mathbf{d}}$ (Fig. 3):

$$s_t(\mathbf{x}) = \vec{\mathbf{v}}(\mathbf{x}) \bullet \hat{\mathbf{d}}.$$

These values are mapped by a transfer function (Fig. 5a and 5b). Arrowhead overlays convey the in-plane blood-flow directions. The arrowheads show the in-plane blood-flow directions (Fig. 5c), including a regurgitant region. Furthermore, the directions may reveal rotations in a vessel, such as a projection of a right-handed helix in the ascending aorta (Fig. 5d).

Moreover, we introduce a novel velocity-field volume rendering (VFVR), inspired by three-dimensional US visualizations. We use the shape of the virtual probe as the bounding geometry for the volume rendering,



(a) (b) (c) (d)

Figure 5: Through-plane velocities on the probe-orthogonal plane mimic 2D-cine PC-MRI flow. (a) The velocities are mapped by a red-blue color map. (b) Incoherent areas are emphasized with a green color. (c) Arrowhead overlays are used to emphasize direction. (d) The arrowheads reveal rotations, e.g., a projection of the right-handed helix in the ascending aorta, as the flow moves away from the probe, and hence towards the viewer.

which is based on a raycasting approach.[12] Instead of conventional volume rendering, based on scalar-valued volume data, we aim for a holistic view of the vector-valued velocity data.[13] Therefore, the probe long axis is again employed as the inspection direction $\hat{\mathbf{d}}$. For each sample along the viewing ray, the angle ψ between the inspection direction and velocity field is computed. Similar to the US inspired planar reformat, the sign of the angle ψ is extracted to distinguish if the flow is forward or backward, relative to the inspection direction. In detail, the scalar values $s_{d_{3D}}$ used for the volume rendering are defined as:

$$\psi(\mathbf{x}) = \frac{\vec{\mathbf{v}}(\mathbf{x})}{||\vec{\mathbf{v}}(\mathbf{x})||} \bullet \hat{\mathbf{d}}$$
$$s_{d_{3D}}(\mathbf{x}) = \mathrm{sgn}(\psi(\mathbf{x})) \cdot ||\vec{\mathbf{v}}(\mathbf{x})||$$

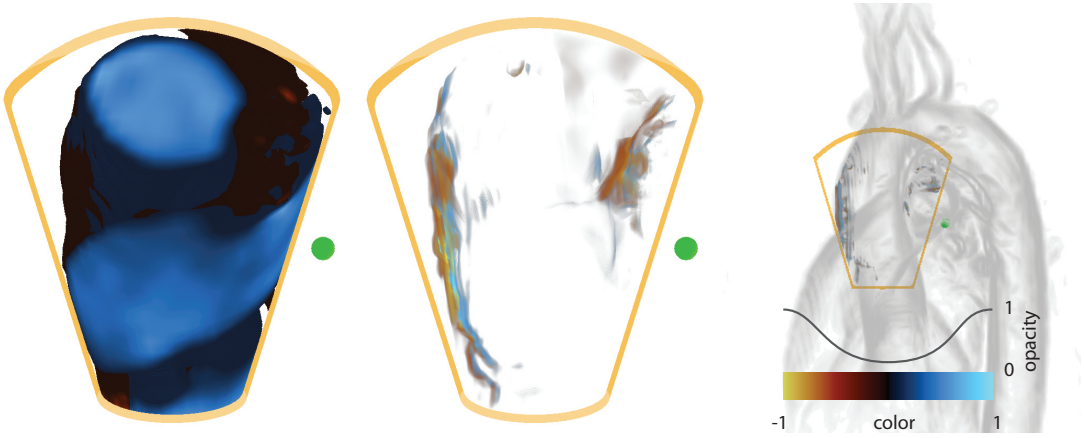
The values within the speed threshold are composited front-to-back, and colors are mapped after data interpolation, using a red-blue transfer function. When interacting with the probe, the volume rendering is updated in real-time. The resulting renditions provide a dense representation (Fig.6a).

To reveal anomalies within the blood flow, different aspects of the field can be inspected. Excessive variations in the flow direction potentially indicate aberrant flow regions. The variation between the angles ψ in a local neighborhood can be expressed by using the local phase coherence measure.[11] We incorporate this coherence measure into the VFVR raycasting, and apply transparency to hide the coherent regions, emphasizing anomalous regions. For instance, Fig. 6b shows imaging artifacts near the vessel wall. Due to the emphasis on anomalous flow regions, anatomical context information may be lost. Therefore, we add a translucent overlay that depicts the anatomy for reference (Fig. 6c).

The compound view, depicted in Figure 7, furthermore contains geometry-based flow visualizations, exploiting the volumetric nature of the PC-MRI data. Pathlines and particle trace are adopted for this purpose, including a anatomical context through gradient-based volume rendering of the blood-flow lumen.[9]

5. RESULTS

All the described elements, including the Doppler US and 2D cine PC-MRI inspired planes, as well as the VFVR are combined with contemporary geometry-based blood-flow visualization techniques, including integral lines and particle traces.[9] The different visualizations are presented in a compound view, which is divided into four viewports (Fig. 7). Each of these viewports can be enlarged to a single full-size viewport. All views are interactively linked, enabling the physician to observe the blood flow from different angles during exploration.



(a) (b) (c)

Figure 6: Velocity-field volume rendering. (a) Without specific opacity modulation, VFVR leads to a dense visualization. (b) Alternatively, abnormal flow can be emphasized by the variation of angles between the inspection direction and the blood-flow directions, using an opacity modulation (see d). The abnormalities can also be highlighted using the local phase coherence.[11] (d) The sparse representation in figure b lacks anatomical context, which is provided by a gradient-magnitude projection of the blood-flow lumen.

The combination of all renditions affects the performance. The performance bottleneck is found in different volume projections, such as the VFVR and the volume rendering of the anatomical context, for which the framerate depends on the viewport size. Nevertheless, the compound view generally achieves interactive frame rates of about 15 frames per second or more.

Performance tests were carried out using a conventional computer system with a dual-core processor, 6 GB internal memory and an NVidia GeForce 570GTX graphics card. The Doppler US inspired planar reformat and the 2D-cine MRI flow inspired planar reformat both render at approximately 58 frames per second, with a viewport size of 512x512 pixels. The VFVR performs at 29 frames per second without an overlayed anatomical context. With this overlay, the VFVR performs at a mere 8 frames per second. However, the VFVR is commonly active in a much smaller viewport, as part of the compound view. In this case, the overall interactivity of the system is not affected. The performance of the geometry-based flow visualizations in the 3D overview varies, depending on the used technique. On average, these flow visualization techniques render at about 30 frames per second, and interactivity is maintained when combined with a volume rendering of the anatomical context.

6. EVALUATION

The resulting compound view emerged from a close collaboration with the domain experts. To evaluation the visualization framework, we have obtained feedback from two expert physicians using a questionnaire. Both physicians indicate that visual inspection is key to get a better understanding of the intricate blood-flow velocity data. They emphasize that the presented virtual probe interactions provide a significant step in the right direction. However, they also point out that it might require some level of experience and training to get used to fully control the motion.

The combination of views with the ability to visualize blood flow similar to color Doppler ultrasound imaging was considered between effective and very effective. The arrowhead overlay was marked as indecisive by one of the physicians that finds it difficult to evaluate its potential without further analysis. A repeated request by one of the physicians was the addition of quantitative information in the visualizations, e.g., in the widget to set an angle between the inspection direction and the flow field. The velocity volume rendering and the compound view were also evaluated as very effective. However, it was also remarked that to make strong statements about their potential, further evaluation would be necessary on a larger set of patient data.

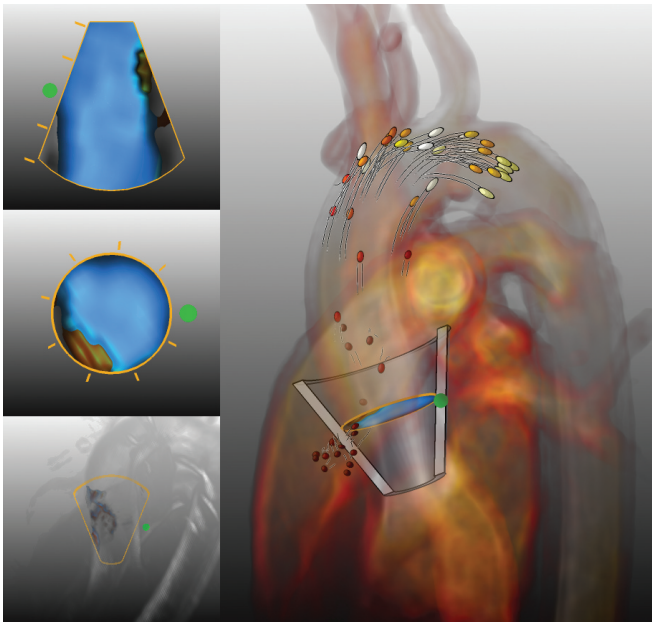


Figure 7: Video 1: All elements are included in the compound view. The probe serves as a basis for 3D geometry-based flow visualizations. The associated planes are updated when the probe is repositioned. They convey the blood-flow velocities inspired by Doppler US and 2D cine PC-MRI. Furthermore, the VFVR approach provides a holistic view of anomalous regions in the blood-flow field. http://dx.doi.org/doi.number.goes.here

According to the interviewed physicians, the main disadvantages of the tool are that there might be the need of a training period to use the tool, and the lack of attached quantitative information in the visualization. The potential was summarized in three points. First, the tool can be used to show the potential of MRI to measure flow, and demonstrate the findings in ultrasound meetings. It can also stimulate more research towards quantitative analysis of blood flow. Finally, it will enable research especially for the study of turbulence, allowing the visualization of, e.g., valve lesions beyond the field of Doppler ultrasound.

7. CONCLUSIONS AND FUTURE WORK

In conclusion, we present a visualization framework with a compound view based on volumetric PC-MRI blood-flow data. All views are linked interactively. The combined visualization renders at interactive framerates, and offers smooth animation of the hemodynamics.

Besides geometry-based three-dimensional blood-flow visualizations, we introduce two planar reformats, based on the position and orientation of a virtual probe. The probe-parallel plane constitutes the basis of an US-inspired visualization, simulating velocities along a Doppler US beam. Additionally, the probe-orthogonal plane is used to mimic two-dimensional through-plane PC-MRI velocities. Velocities on both planes are color mapped using a red-blue transfer function.

For both planes, enhancements were proposed to the familiar visualization techniques. For the probe-parallel plane, we have presented an angle widget, enabling an interactive definition of the angle range to be inspected. Consequently, the predominant laminar flows can be omitted from the visualization. Furthermore, both planes were equipped with arrowhead overlays, enhancing the perception of the projected blood-flow directions.

We have introduced a novel velocity-field volume rendering, using the shape of the virtual probe as a bounding geometry. The VFVR employs the local phase coherence, which is independent of the inspection direction. Large angle variations, or low coherence, indicate flow regions that are worthwhile to inspect.

Physicians in the field underpin the value of the presented visualization framework, and the potential for multidisciplinary clinical research. The interactivity of the approach is deemed essential. The compound view with the Doppler US inspired visualizations are considered intuitive, and valuable for the qualitative analysis.

In the future, an improvement of the interaction could be achieved by attaching a physical device that facilitates the 3D interaction. Furthermore, the visualization approach will be employed more extensively and validated for qualitative inspection of blood-flow behavior in patients suffering from valvular heart disease. This process will potentially lead to further improvements of the visualization techniques in the context of the valvular application. Domain experts envision similar visualization and interaction techniques to be incorporated into the acquisition process. This would enable the rapid detection of blood-flow jets in the three-dimensional domain. Subsequently, an accurate quantitative analysis could be performed along the blood-flow jets, providing valuable insight into the condition of the valve.

ACKNOWLEDGMENTS

We gratefully thank dr. Valentina Puntmann, MD. at King's College London for sharing her domain expertise, and for her valuable support in image acquisition and interpretation.

REFERENCES

[1] World Heart Organization, "Fact sheet CVD." http://www.who.int/mediacentre/factsheets/fs317/ (last visited 11/12/2013) (2013).

[2] Hatle, L. and Angelsen, B., [*Doppler ultrasound in cardiology : physical principles and clinical applications*], Philadelphia: Lea & Febiger (1985).

[3] Kutter, O., Shams, R., and Navab, N., "Visualization and GPU-accelerated simulation of medical ultrasound from CT images," *Computer Methods and Programs in Biomedicine* **94**, 250–266 (June 2009).

[4] Reichl, T., Passenger, J., Acosta, O., and Salvado, O., "Ultrasound goes GPU: real-time simulation using CUDA," in [*Society of Photo-Optical Instrumentation Engineers (SPIE)*], **7261**, 7261E1–7261E10 (February 2009).

[5] Shams, R., Hartley, R., and Navab, N., "Real-time simulation of medical ultrasound from CT images," in [*Medical Image Computing and Computer-Assisted Intervention (MICCAI)*], *Lecture Notes in Computer Science* **5242**, 734–741 (2008).

[6] Swillens, A., Lovstakken, L., Kips, J., Torp, H., and Segers, P., "Ultrasound simulation of complex flow velocity fields based on computational fluid dynamics," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* **56**, 546 –556 (March 2009).

[7] Burns, M., Haidacher, M., Wein, W., Viola, I., and Gröller, M. E., "Feature emphasis and contextual cutaways for multimodal medical visualization," in [*EuroVis*], 275–282 (June 2007).

[8] Nayak, K. S., Pauly, J. M., Kerr, A. B., Hu, B. S., and Nishimura, D. G., "Real-time color flow MRI," *Magnetic Resonance in Medical Sciences* **43**(2), 251–258 (2000).

[9] Van Pelt, R. F. P., Oliván Bescós, J., Breeuwer, M., Clough, R. E., Gröller, M. E., ter Haar Romeny, B. M., and Vilanova, A., "Interactive virtual probing of 4D MRI blood flow," *IEEE Transactions on Visualization and Computer Graphics* **17**(12), 2153–2162 (2011).

[10] Kasai, C., Namekawa, K., Koyano, A., and Omoto, R., "Real-time two-dimensional blood flow imaging using an autocorrelation technique," *IEEE Transactions on Sonics and Ultrasonics* **32**(3), 458–464 (1985).

[11] Chung, A. C. S., Noble, J. A., and Summers, P., "Vascular segmentation of phase-contrast magnetic resonance angiograms based on statistical mixture modeling and local phase coherence," *IEEE Transactions on Medical Imaging* **23**(12), 1490–1507 (2004).

[12] Scharsach, H., "Advanced GPU raycasting," in [*Central European Seminar on Computer Graphics*], 69–76 (2005).

[13] Frühauf, T., "Raycasting vector fields," in [*IEEE Visualization*], 115–123 (1996).