Understanding Blood-Flow Dynamics: New Challenges for Visualization

Roy van Pelt, *Eindhoven University of Technology, The Netherlands*
Anna Vilanova, *Delft University of Technology, The Netherlands*

Modern simulation and imaging techniques are providing intricate blood-flow velocity data, the analysis of which can lead to new insights into how blood flow relates to the development of cardiovascular disease. Rapidly interpreting this complex data requires novel comprehensive visual representations.

Traditional diagnosis and risk assessment of cardiovascular disease rely on the morphological information found in anatomical data from ultrasound, computed tomography, or magnetic resonance imaging (MRI). Blood-flow data also contains information that can aid in assessing cardiovascular disease—now the leading cause of mortality worldwide, with more than a third of the deaths in the US alone.[1] However, as the "Complexity of Multidimensional Blood-Flow Data" sidebar describes, blood-flow velocity data has complex behavior patterns that make it difficult to harness valuable information. Comprehensive visualization techniques promise to unlock the understanding of this data and enable important insights about these hemodynamics.

Modern computer simulations and novel flow-imaging techniques, such as color Doppler ultrasound and flow-encoded MRI, provide time-varying blood-flow velocity fields of unprecedented quality. Analysts can now obtain greater amounts of multidimensional blood-flow velocity data more frequently, empowering them to derive valuable quantitative information such as flow rates and pressure, and to evaluate the complex behavior of blood-flow patterns such as vortices and helices. Computational fluid dynamics (CFD) models and phase-contrast MRI (PC-MRI) measurements, in particular, provide volumetric velocity data throughout a heartbeat for both cardiac and cerebral applications.

Although this contemporary data clearly harbors valuable information that will help explain how hemodynamics relate to the development of cardiovascular disease, most physicians are unfamiliar with velocity data and are therefore unsure what blood-flow patterns to expect in a pathological case or how to interpret them.

We believe the solution lies in visualization research, which deals with the effective visual communication and interpretation of complex data. For medical applications such as blood-flow behavior analysis, visualizations must be highly efficient because physicians typically have little time to analyze patient-specific data. Unfortunately, direct representations of large volumetric blood-flow fields lead to visual clutter and occlusion, which limits understanding.

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Paradoxically, more visual information diminishes comprehension.

We have identified several open challenges in the visualization of time-varying volumetric blood-flow data, also called 4D blood-flow data, and evaluated this data in the context of state-of-the-art visualization research. In most areas, blood-flow analysis can gain considerable momentum from these visualization advances.

CLINICAL RELEVANCE

A large body of clinical research indicates that atypical blood flow directly relates to medical conditions.[2,3] Anomalous blood flow may influence the morphology of surrounding tissue, and even small morphological changes can considerably influence the bloodstream. This dependence reinforces the detrimental effects of cardiovascular disease. Thus, understanding blood-flow behavior can aid the diagnosis and prognosis of pathology as well as the assessment of treatment risk and follow-up findings.

Figure 1 shows that analysis of blood-flow information can play a vital role in the diagnosis of many cardiovascular diseases.[1] Reduced blood supply typifies ischemic heart disease, the largest diagnostic

Complexity of Multidimensional Blood-Flow Data

Traditionally, the diagnosis and risk assessment of cardiovascular diseases, such as congenital defects and arterial anomalies, rely on anatomical imaging data. This data can consist of 2D slices that provide different views of the cardiovascular system and that often vary over time. Three-dimensional anatomical data is also common and occasionally acquired as a time series. Physicians typically analyze this volumetric data slice by slice, which, as Figure A shows, requires a mental reconstruction of the cardiovascular morphology.

Blood-flow velocity data is typically vector-valued and varies over time. Current clinical practice is to use 2D slices with blood-flow information, but clinical research is increasingly turning to 3D data. Time-varying 3D flow data, often referred to as 4D blood-flow data, consists of 3D vector fields that provide quantitative velocity information. This dense and continuous data is obtainable from fluid dynamics simulations or flow-sensitive magnetic resonance imaging (MRI) measurements.

Slice-based inspection of 3D cardiovascular anatomy is already challenging, even for a trained physician. Adding the velocity directions and the time dimension makes traditional slice-based inspection virtually impossible. Moreover, this high-dimensional data is becoming progressively richer, with increasing spatial and temporal resolutions, making it more elaborate to analyze. For simulations, this richness is due to increased computational power, while for measurements it is attributable to more sophisticated acquisition techniques.

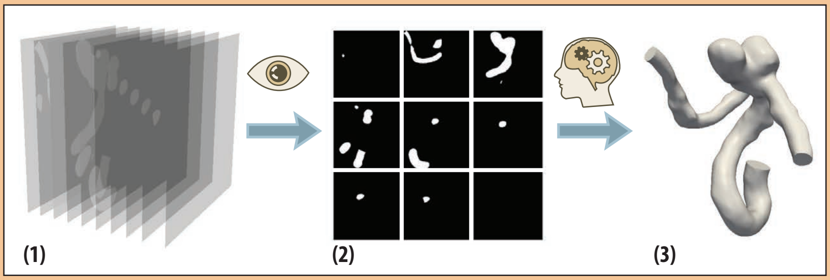

Figure A. Mental reconstruction of 3D data. (1) A 3D dataset contains the anatomical representation of a cerebral aneurysm. (2) Conventionally, physicians inspect this dataset slice by slice, which for simplicity is depicted as a consolidated black-and-white image. (3) On the basis of these slices, trained physicians mentally reconstruct the aneurysm's 3D anatomy.

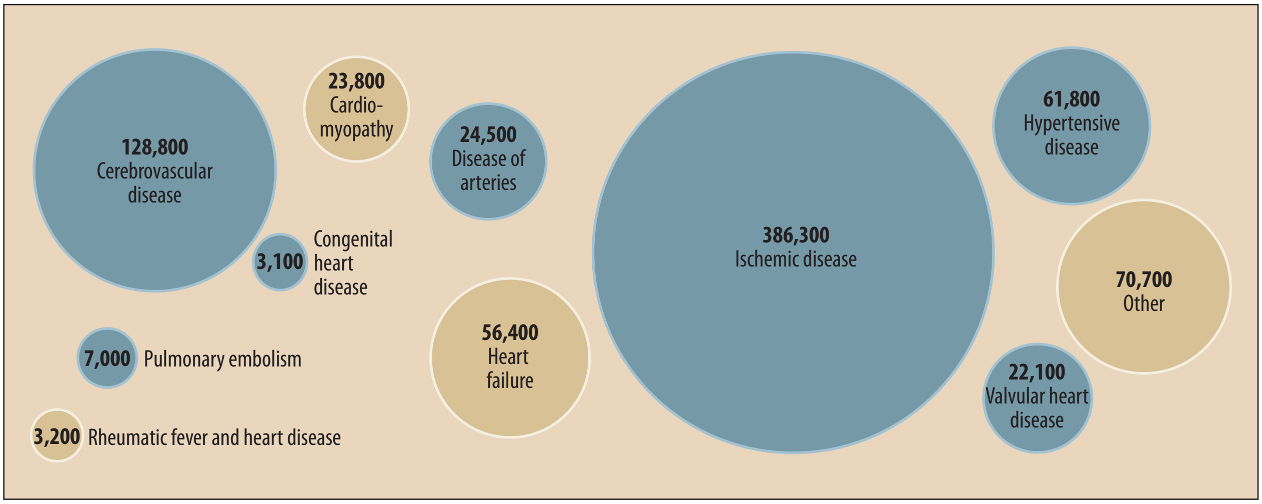

Figure. 1. Overview of cardiovascular disease mortality in the US in 2009. For most cardiovascular diseases, blood-flow analysis can provide valuable diagnostic and prognostic information. Groups with the most potential to benefit from such analysis are in blue. The benefits to other groups, in beige, are currently less clear, but future research could reveal new connections.

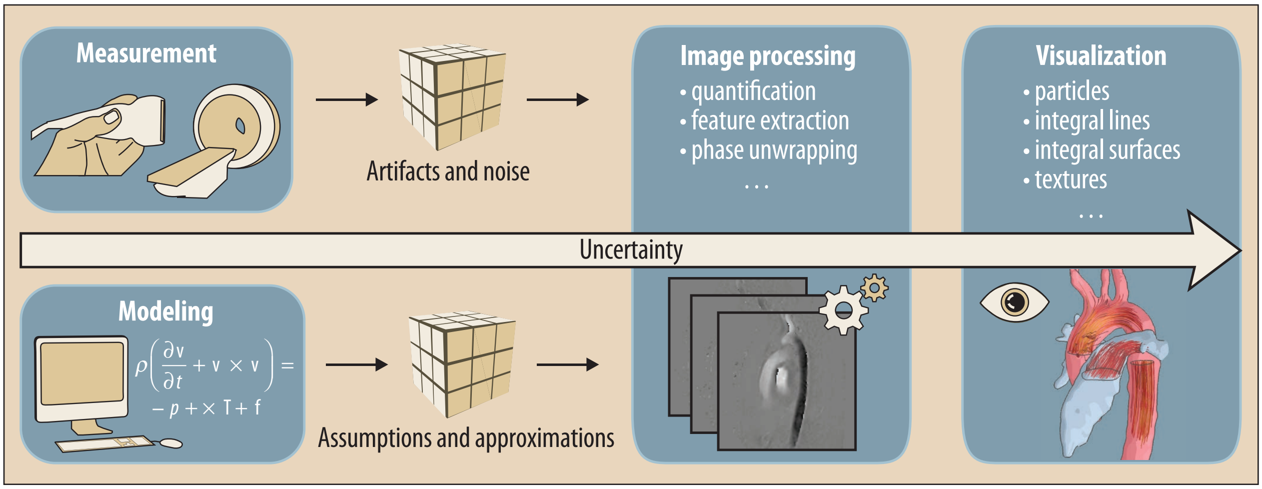

Figure 2. Blood-flow velocity data processing pipeline. The pipeline typically starts by enhancing and quantifying the data acquired through measurement or modeling. The final step is comprehensive data visualization. Every part of the pipeline accumulates error, from acquisition noise to poorly chosen user parameters. This uncertainty propagates through the pipeline and affects the final result.

group. Cerebrovascular diseases form the second largest group; in this context, physicians look at blood flow primarily in aneurysms of the brain vasculature.

Clinical research in blood-flow behavior focuses on anomalies of the large arteries, such as aortic aneurysms or dissections, and disorders of the cerebrovascular system. Cardiac blood-flow investigation is also gaining ground, for example, to assess valvular insufficiencies and the efficacy of implanted valves.

Another application area is congenital heart disease, which arises from abnormal maturation of the heart and blood vessels. The morphological malformations notably change the hemodynamics, which in turn affects the surrounding tissue, thus accelerating disease development.

For example, researchers have used 4D velocity measurements to assess the blood flow of a patient suffering from a congenital defect after treating the single-ventricle physiology with the Fontan procedure, a surgical intervention.[4] Many patients develop late complications from the gradual change inflicted by the interaction between the bloodstream and vessel wall. Because it is impossible to capture this morphologically complex situation in a 2D plane, 4D blood-flow imaging is an exceptionally valuable source of diagnostic information.

Such potentially critical applications are becoming more evident as clinical research continues to reveal new applications that benefit from blood-flow analysis.[2,3]

BLOOD-FLOW ANALYSIS AT A GLANCE

Figure 2 shows the acquisition and processing of blood-flow velocity data, which can come from both CFD modeling and imaging. In CFD modeling, physicians use imaging data to obtain an accurate patient-specific anatomical segmentation and rely on 2D time-varying blood-flow information to identify inflow conditions. Given the segmentation and inflow conditions, as well as the blood flow's physical properties, the modeling software computes blood-flow behavior. The models use fluid and vessel-wall properties and boundary conditions to provide high-resolution and noise-free fields. However, the resulting flow is an approximation based on model assumptions.

Another noninvasive method of measuring blood-flow velocity data is through Doppler ultrasound, which cost-effectively provides high spatiotemporal resolution. However, the acquired data is prone to noise, and velocities are measurable only along the direction of ultrasound wave emission. For this reason, we chose to exclude it from our study of 4D blood-flow data techniques. PC-MRI is more expensive, but yields a better signal-to-noise ratio and measures true volumetric and quantitative velocities.

Regardless of the specific imaging technique, data imperfections are inevitable because of factors related to the hardware, operator, patient, or some combination of these. Any data processing pipeline must include postprocessing to reduce these imperfections and enhance the data for subsequent analysis.

Clinical research currently focuses on quantitative blood-flow analysis, largely neglecting thorough visual inspection. Physicians investigate reproducible measures, such as flow rate, pressure, cardiac output, and wall shear stress. A strong correlation between a measure and disease development makes these measures viable clinical indicators.

Blood-flow patterns are known to play an important role in the development of cardiac disease. These patterns are, however, hard to quantify due to the complexity of their appearance, and the intricate changes they undergo over time. Derived scalar measures, such as helicity and vorticity, can indicate certain patterns as feature intensities, but these measures do not reveal the 3D pattern shape and dynamics. Consequently, comprehensive visualization is essential to analyze blood-flow behavior.

FLOW VISUALIZATION RESEARCH

Visualization research aims to convert nonvisual data into readable and recognizable images. Two decades of research into visualizing flow fields has yielded a wealth of techniques for a range of scientific and engineering applications. These techniques fall into three broad categories:

- *texture-based,* which convey the flow field by applying the directional structure to randomly generated textures;[5]
- *geometry-based,* which use objects such as particles, lines, or surfaces to represent the field structure;[6] and
- *feature-based,* which enable the explicit extraction of meaningful flow characteristics, or features.[7]

In addition, analysts can use mathematical approaches to derive the flow fields' elementary structures, or topology. Fluid problems essentially involve 3D time-varying flow fields. Developments in flow visualization research have enabled effective and efficient representations of 2D and 3D flow fields, and techniques are well established for visualizing 2D time-varying flow fields. However, visualizing 3D flow fields over time remains challenging. Also, relatively few methods address the problems in measured flow data. For example, topology-based techniques often cannot cope with measurement noise.

BLOOD-FLOW VISUALIZATION CHALLENGES

The ultimate goal of quantitatively and qualitatively analyzing patient-specific blood flow is to facilitate the future diagnosis, prognosis, and treatment of cardiovascular disease. This goal gives rise to a range of visualization obstacles—not just those already common in medical visualization research. Because complex flow visualization challenges have been rare in the medical domain, it is important to investigate suitable new ways of visualizing blood-flow dynamics, tailoring them to clinical needs and evaluating their effectiveness. To that end, we have identified established techniques to fuse data sources from different modalities. We have also investigated high-level conceptual visualization approaches, or paradigms, and ways to evaluate the effectiveness of visualization techniques.

Visualization techniques

A large body of research has evolved to analyze, filter, and visualize large amounts of flow data. Blood-flow visualizations can draw on established techniques, while addressing new specific challenges.

Fusing data sources. For some parts of the cardiovascular system, quantification using derived measures, such as flow rates or pressures, might be sufficient. For the vessel network of the entire circulatory system, single-dimension CFD simulations, which exclude volumetric aspects, can provide such measures. However, for various other regions, analysts need to understand volumetric flow patterns to better grasp how blood-flow dynamics influence cardiovascular disease development.

Besides a wealth of clinically relevant derived measures, medical imaging often provides patient-specific information such as the anatomy or luminal morphology. For example, MRI delivers varied acquisition sequences, each of which results in a different imaging contrast; one sequence might emphasize fat-water boundaries, while another targets anomalous tissues. Fusing data sources, possibly from different modalities, is of great importance in quickly understanding a large amount of heterogeneous data.

A promising approach is to supplement the limited spatial and temporal resolution of imaging data with physically based fluid simulations.

Although fusing imaging data and fluid simulations has many potential benefits, it remains a significant technical challenge. In clinical practice, imaging data is the prevailing information source, but measured blood-flow data has limited spatiotemporal resolution and is affected by noise. In contrast, fluid simulations provide noise-free, high-resolution flow fields that physics can substantiate, but they are not yet established in clinical routine. The simulations depend on model assumptions and therefore provide only an approximation of the ground truth.

A promising approach is to supplement the limited spatial and temporal resolution of imaging data with physically based fluid simulations, thus supporting better visualizations and animations. Extending measured data with simulations can also provide insight into the patient's treatment options and prognosis.

For simulation and visual reference, analysts segment anatomical imaging data, extracting the boundaries of the anatomical structures. For a blood-flow application, a time-varying volumetric reference of the cardiovascular anatomy is preferable. To date, however, segmentation provides only a static approximation, since anatomical time-varying image data is not acquired to restrain imaging time. The 4D velocity field lacks morphological information in the diastolic phases, but analysts could use a combination of information to obtain an approximate time-varying anatomy.

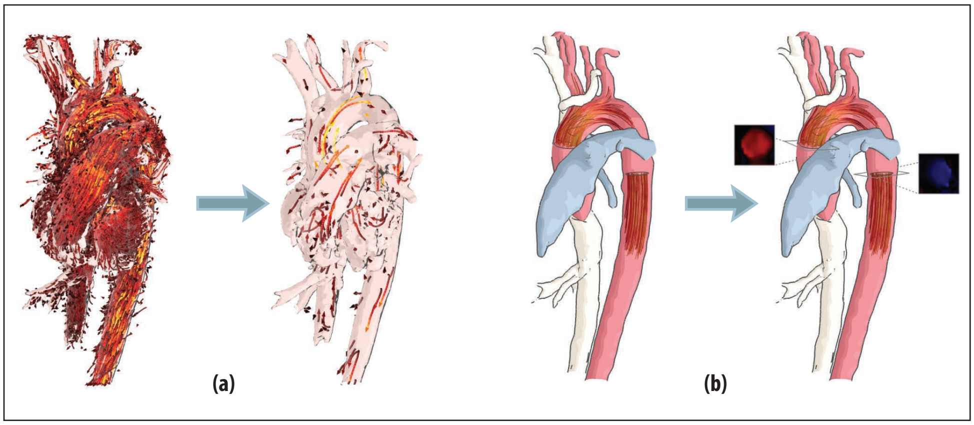

Figure 3. Reducing visual clutter in 4D blood-flow velocity data. (a) Reduction requires filtering dense flow information, which can be achieved through hierarchical clustering. The challenge is to identify a suitable similarity measure and abstraction level. (b) Selecting a region of interest may be used to reduce visual clutter, shown here as two-vessel cross-section, while domain knowledge is included using familiar color coding.

Custom filtering. The clinical domain often requires specific features that differ from the technical features defined for general-purpose flow visualization. While those in the technical domain search for critical points and vortex cores, physicians are more interested in the efficiency of the cardiovascular blood flow, energy dissipation, pressure differences, and cardiac output.

One approach to tailoring visualization and interaction techniques to the needs of clinicians is to custom-filter blood-flow data using domain-specific flow features to select key information.[7] Extracting such features remains an open problem, however, particularly taking into account their temporal evolution. Furthermore, feature extraction is extremely difficult for noise-prone measured blood-flow data.

Partitioning can reduce data domain complexity by selectively eliminating irrelevant information, as in Figure 3a. The partitioning composes clusters using similarity measures that rely on velocity data. Such measures should incorporate domain expertise, which is challenging because it requires deriving and visualizing a variety of indicators.

A formidable obstacle to clustering is that such processes typically have a high computational cost, which scales poorly with added dimensions. For blood-flow data analysis, partitioning results in 4D clusters, which are inherently difficult to visualize and interpret.

Tailored mapping and rendering. Like custom filtering, tailored mappings and renderings are promising in that different views of intricate data could lead to new insights. For example, so-called smart visibility techniques can uncover essential information by deforming the data domain or geometric representations.

However, tailoring is technically challenging—problems that perception theory might help solve because of its mature research in methods of interpreting image content. Animation, for example, might be the logical choice in visualizing time-varying data, but perceptually it poses a high cognitive load and thus might not be suitable for extensive visual analysis.

Furthermore, the visualization of rich quantitative information remains problematic. An ignorant color coding choice, for example, could lead to an erroneous perception of values. Figure 4 shows the difference between rainbow color coding, which is prevalent in a clinical setting, and black-body radiation coding. Rainbow color coding has serious perception drawbacks, such as a lack of perceptual ordering and apparent sharp gradients that are not actual data features,[8] which makes other choices, such as black-body radiation coding, better for new visualizations.

Interactive parameterization and inspection. A visualization's effectiveness depends on many user parameters, and the process of setting these parameters is more laborious for the visualization of blood flow than for most conventional medical visualizations. In clinical practice, little time is available to set parameters manually, so informed presets are frequently necessary. For example, the manual placement of 3D seed positions for geometry-based flow visualizations is user-biased and remains tedious.

Interactive parameterization and inspection are essential to visual exploration of the fused data sources needed to unlock the information in 4D blood-flow data. Physicians must analyze their data rapidly. Real-time interaction engages them and enables the fast analysis of spatial relations and temporal variations.

New visualizations can also profit from current visual representations used in clinical routines. In Figure 3b, for example, red-blue pseudocoloring similar to Doppler ultrasound depicts MRI blood-flow information on the planes. New approaches should combine existing hemodynamics knowledge with expertise in and emerging technologies from medical imaging, fluid physics, fluid simulations, and data analysis. To make future blood-flow analysis easier, visualization research must bring to bear expertise from a variety of domains to create a visual synergy, aiming for new understanding and the improvement of diagnosis and treatment.[9]

Visualization paradigms

The increased understanding of hemodynamics is driving the need for different visual analysis paradigms. These paradigms rely on various visualization techniques, which create unique challenges for blood-flow dynamics applications.

Exploratory. At present, blood-flow research aims for new insights. From a clinical perspective, few clear tasks or questions have yet emerged, so any exploratory visualization paradigm must include a variety of tailored flow visualization techniques. This typically involves global-to-local inspection, which aims to accelerate analysis by enabling details on demand and intuitive interaction. Probing techniques, for example, fit the exploratory paradigm.[7] Ultimately, any such paradigm should seek to provide the user with an extensive set of fast and intuitive visual inspection tools that enable varied data analysis aimed at obtaining new understanding.

Task-driven. Exploration of blood-flow data can lead to indicators for use in task-driven visualization analysis. The goal is to achieve effective and efficient results, providing only the essential visualization and interaction options. Because physicians must investigate established parameters on large sets of patient data, the task-driven paradigm is central to clinical trials and diagnosis.

Education-driven. The exploratory and task-driven paradigms are directly related to clinical practices, so their value is obvious. The education-driven paradigm is more tangential, but it is equally valuable. Similar to an atlas of human physiology, a clear reference of complex hemodynamics is important for research and even more so for education. However, the lack of a ground truth complicates the construction of a blood-flow atlas, both for healthy and pathological blood flow.

Visualization evaluation

Physicians should be involved not only in the conception of new visualization approaches, but also in the evaluation of resulting techniques. Physicians are currently exploring complex blood-flow data because to date there is no ground truth for hemodynamics—a reality that is slowing the clinical acceptance of blood-flow information. Although this complication is significant, it is not insurmountable. Other medical applications have been adopted in clinical routine from extensive clinical trials that underpin the correlation between observations and disease. Furthermore, research analysts could generate a statistical atlas from a range of datasets. With confidence in the acquisition, such an atlas can provide a viable ground truth substitute.

Even so, visualization research should account for this lack of a ground truth, particularly in validating explicit feature-extraction techniques. Visualization evaluation also raises many questions about visual communication, interaction, and insights gained relative to other techniques. At present, only a limited number of physicians are involved in the emerging field of blood-flow analysis, which narrows the evaluation scale. Perceptual evaluations could provide some information, since they generally do not require domain knowledge and thus could be based on feedback from the general public.

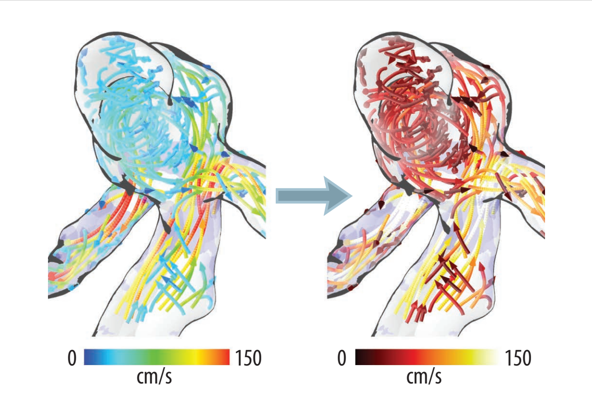

Figure 4. Perception theory prescribes approaches for effective visual communication, which blood-flow visualization could incorporate. For example, the black-body radiation map (right), which has a logical ordering and intuitively relates high-speed blood flow to brighter colors, might be a more suitable color coding choice to communicate blood-flow velocities than the currently prevalent rainbow color map (left).

The evaluation of blood-flow visualization techniques should occur at different levels. Current evaluation studies are more concerned with the quantitative aspect of results, assessing the required time and value of the findings. In the near future, evaluations should also consider the technique's visual effectiveness and practical application in diagnosis and treatment.

PROGRESS TO DATE

Much work has already been done to address the obstacles and opportunities we have described. With few exceptions, blood-flow visualizations use geometry, such as particles or lines, traced through the velocity field. To reduce visual clutter, visualization can selectively depict these objects at user-defined locations. The selection of these locations is increasingly interactive, and several approaches combine this selection with real-time blood-flow visualizations.[6,10]

Recent blood-flow visualization research is addressing explicit feature extraction. Some approaches tailor features to medical applications[11] while also using generic features, such as flow rates and vortices. By combining extracted features with the properties of lines traced through the blood-flow field, the visualization can filter line bundles.[12]

Some researchers are addressing the challenges in partitioning the data domain. Most techniques cluster 2D or 3D flow fields, but some recent pioneering work is attempting 4D hierarchical clustering.[13] The resulting hierarchy helps determine the visualization density.

To aid mapping and rendering, some researchers have applied visual deformations to facilitate the interpretation of complex blood-flow behavior. One approach draws on smart visibility to straighten the aorta, making interactive visual comparison much easier.[14]

For certain aspects of blood-flow visualization, a consensus of good practice is evolving. The custom is to show an anatomical context, often based on a segmentation of the acquired velocity data. To make sure that anatomical context is not overly prominent in the visualization, researchers are investigating visual styles, from contour lines to semitransparent surfaces.[11]

Most visualizations suggest certainty, but errors and approximations accumulate throughout the blood-flow data processing pipeline, so the lines, or other geometric primitives, that represent blood flow do not always represent data correctly. Because the measurements from which lines were derived have errors, line traces can only approximate actual lines. Recent work has attempted to visualize the uncertainty involved with tracing lines in measured blood-flow data, showing bundles of the many viable lines in the uncertain data.[15]

Despite these advances, several visualization problems remain open. To the best of our knowledge, the large parameter space (line length, color choice, and so on) involved with blood-flow visualization is mostly unexplored, and few approaches combine measurement and simulation. Hopefully, in the near future, findings from clinical research will enable task-driven approaches.

There is also a need for comprehensive evaluation studies to complement the ongoing evaluation of clinical applicability. The literature often includes expert feedback, but future visualizations will require more thorough evaluation when used for clinical trials or even in daily practice. Also, perceptual studies of flow data are required.

New findings about blood flow will contribute to the already substantial hemodynamics knowledge that cardiologists and hematologists need to diagnose and assess the risk of cardiovascular disease. Visualization will enable both the depth and breadth of future knowledge gains. Modern flow visualization techniques are increasingly conveying blood-flow velocity fields effectively, which will deepen the understanding of blood-flow dynamics. However, to achieve breadth, visualization must be tailored to meet clinical needs. Blood-flow visualization becomes more difficult when including derived measures, other patient-specific data, and uncertainty information. Physicians are not trained to handle visualization techniques other than conventional approaches, such as angiography and Doppler ultrasound, so new visualizations must exploit representations that are already part of clinical routines.

Comprehensive visualization techniques will require fusing information sources and combining measurements with fluid simulations. Including domain and perceptual knowledge has the potential to produce new visualization techniques, but interdisciplinary communication complicates this evolution. Clinical research is already analyzing blood-flow data, so it is essential to bridge the gap between the experts involved. Indeed, the key to future blood-flow visualization research is the ability to integrate many areas of expertise in medical imaging, fluid simulations, and data analysis.

In a few years, the knowledge gained through exploration can be translated to task-driven paradigms, enabling clinical trials to evaluate diagnosis and treatment solutions. The development of task-driven techniques, including quantitative analysis, requires a strong collaboration among visualization researchers, physicians, and a range of other functions within the healthcare industry. With such collaboration, approaches will become mature enough to enable standardization for clinical practice.

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***Roy van Pelt** is a postdoctoral researcher in the Department of Biomedical Image Analysis at Eindhoven University of Technology, The Netherlands. His research interests include medical visualization, medical image analysis, and parallel computing. Van Pelt received a PhD in biomedical engineering from Eindhoven University of Technology. Contact him at r.f.p.v.pelt@tue.nl.*

***Anna Vilanova** is an associate professor in the Computer Graphics and Visualization group at Delft University of Technology, The Netherlands. Her research interests include medical visualization and image analysis of multivalued data, such as diffusion-weighted imaging and 4D blood flow. Vilanova received a PhD in computer science from the Vienna University of Technology, Austria. She is an associate editor of* Computers & Graphics. *Contact her at avilanova@tudelft.nl.*