Visualization of (Cardiac) Bloodflow Data

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Motivation: Medical context

• Cardiovascular Disease
  • Prevalence of over 30% USA
  • Major cause of death worldwide

• Diagnosis and prognosis based on morphology and function

• Hemodynamic (Hemo = blood) behaviour influences pathogenesis. Hardly included in current clinical workflow
  • Lack of insight
  • Lack of indicative parameters
  • Lack of standardization

World Health Organization – Mortality estimates 2004 (http://apps.who.int/ghodata/)
Cardiovascular Pathology Example: Aortic Dissection

- Pathophysiology:
  - Tear in intima layer of the vessel wall
  - Secondary flow system
- Prevalence < 1%
- Mortality rate rupture 80%

http://www.wikipubmed.net
Cardiovascular Pathology Example: Cerebral aneurysm

- Cerebral aneurysm
  - Pathological dilations of the vessel wall
  - Increased risk of rupture (mortality rate up to 52%)

- Risk of rupture depends on vessel morphology and blood flow characteristics

- Flow is spatially embedded in the surrounding vessel surface

*Courtesy of Kai Lawonn et al.*
How do we measure Hemodynamics?

First blood-flow pressure measurement

Stephen Hales
1727
Motivation: Hemodynamic information

Simulation
- Computational Fluid Dynamics

Measurement
- Ultrasound
- CT
- MRI
- Rotational X-ray

Phase Contrast
- Modulus Contrast
- Contrast Enhanced

"Towards modelling thrombus formation in Abdominal Aortic Aneurysms"
- Gunther et al. (2006)
Simulation versus Measurements

- Model assumptions
- Numerical approximations

- Artifacts, noisy
- Limited resolutions
- Limited contrast

Research in FlowVis

Recent Vis Research
Blood-flow measurements: Acquisition

Encoding velocity with MRI

Stationary tissue

Blood flow $v(t)$

Constant magnetic field

Linear field gradient

$\Phi = -\gamma \cdot v \cdot M_1$

$\gamma$ is the gyromagnetic ratio

$v$ is the constant velocity

$M_1$ is the first moment of the gradient

Blood-flow measurements: Characteristics

Acquisition artefacts

• Eddy currents
  • Linear bias field
• Phase-wrap:
  • When the measured velocity is greater than acquisition range
• Subtraction noise:
  • Due to respiratory motion and signal from small vasculature
• Low precision of slow flow
  • Contrast-agent might be beneficial
Blood-flow measurements: Characteristics

- Spatial resolution: 150x150x50 voxels
- Temporal resolution: 25 phases

0.5% of all velocity vectors
Temporal Maximum Intensity Projection (T-MIP)

$$max(||v_{t_i}(\hat{x})||)$$
Direct visualization of the data does not convey flow patterns
Flow Visualization Techniques

Particle tracing techniques:

Simulate the trajectory of a particles released inside the blood flow

CFD simulations [Cebral et al. 2011]

Flow measuring with 4D PC-MRI [Meckel et al. 2008]
Particle Tracing - Streamline

Streamline – steady flow – vector field fixed on time
Numerically solve the following equation:

\[ \vec{v}(\mathbf{x}) = \frac{dp(s)}{ds} \]

\[ p(s) = \int \vec{v}_i(p(s))ds \]

\( p(s) \) trajectory
\( \vec{v}(\mathbf{x}) \) vector field value at position \( \mathbf{x} \)
Particle Tracing - Pathline

Pathline – Unsteady flow – Vector field changes on time
Extension of streamlines for time-varying data

Pathline

Streamlines
Visual analysis based in 3D impeded by visual clutter

over 2,000,000 directions in the vector field

0 \quad \text{speed (cm/s)} \quad 200
Visual Clutter

- Anatomical Context
  - Facilitates exploration and localization of regions-of-interest
  - Improves understanding of spatial relations

- Flow Simplification
  - Interactive Probing
  - Clustering

- Multiple flow features/parameters
  also just on the surface
Anatomical Context

- Given segmentation and surface mesh representation of interesting anatomy
- Usually illustrative depiction

Roy van Pelt et al. TVCG – VisWeek 2010
Anatomical Context + Flow

Semitransparent

[Lawonn et al. VMV 2013 ]
Blood Flow Exploration

View-dependent streamlines

[Lawonn et al. EuroVis – Short Paper 2014]

Courtesy of Kai Lawonn et al.
Vascular Interactive Exploration

- Main reason for acquisition save planning time for 2D flow acquisition

- Provide Interactive exploration tools of the 4D(3D + time) flow information

- Probing using “the ring”
  - Select vessel cross-sections, serving as region of interest
  - Cross-sectional contour oriented parallel to the vessel center-line
Vascular Interactive Exploration

- Flow visualization techniques:
  - Stream- and pathlines
  - Exploded multi-planar reformat
  - Flow-rate arrow trails

Roy van Pelt et al. TVCG – VisWeek 2010
Vascular Interactive Exploration

Drawbacks:

- **Local segmentation limited to vasculature**

- **Anatomical context based on laborious semi-automatic segmentation**

- **Automation challenging for congenital heart disease or abnormal anatomy**

Stream- and pathlines  Exploded multi-planar reformat  Flow-rate arrow trails
Blood-flow probing

Specific aims

- No segmentation
- Interactive exploration using 2D interaction

Roy van Pelt et al. TVCG – VisWeek 2011
Blood-flow probing

- Interactive exploration

Virtual probe

- Inspired by ultrasound probe
- Tapered cylinder to fit both heart chambers and vessels
Blood-flow probing fitting

Interactive exploration

Fitting to reduce the degrees of freedom

- Fit the probe tangential to the velocity field
- Pre-processing: T-MOP
  - Temporal Mean Orientation Projection
  - Average of blood-flow orientations, based on structure tensors

\[
\text{TMOP}(x) = \frac{1}{T} \sum_{t=1}^{T} (\tilde{v}(x, t) \otimes \tilde{v}(x, t))
\]
Visualization: Blood-flow probing

Blood flow visualization – Pathlines
Interactive exploration (GPU implementation)
Visualization

Blood flow visualization – Pathlines

Imposter tuboids with halos

Conveys blood-flow (temporal) structure
Visualization

Illustrative particles

- Capture speed with shape
- Inspired by comics
- Imposter ellipsoids
- Speedlines with halos
- Conveys blood-flow recirculation
Visualization: Blood-flow probing

- Blood flow visualization - Particles
Clustering

Create a **sparse** representation of the **4D** velocity data to obtain valuable insight into the flow patterns.

Roy van Pelt et al. CGF – Eurovis 2012
Overview

- 4D dissimilarity measures
- 4D hierarchical clustering
- Representative Visualization
  - Patharrows
Visualization

User-driven level-of-detail selection using the hierarchy

99.00%  8250 clusters
Visualization

Center point selection – 3D

Dense
No explicit temporal coherence
Real-time short pathlines
Visualization

Center point selection – 4D

Sparse
Temporal coherence
Precomputed long pathlines
Visualization

Patharrows represent the 4D blood flow statically.
Visualization

Patharrows represent the 4D blood flow by animation

0  100
speed (cm/s)
Aortic dissection measurement

Right-handed helix

High-speed inflow

Vorticity
Pathline based clustering

- Methods based on directly clustering the pathlines

- Similar challenges:
  - Distance measure between pathlines
  - Effective visual representation

For example, [Born et al. IEEE TVCG 2013]
Focus-and-Context Visualization of Multiple Hemodynamic Parameters

- Domain experts interested in multiple hemodynamic information

- Multiparameter visualization
  - Side-by-side views
  - Embedded views with/without glyphs

*Courtesy of Rocco Gasteiger*
FlowLens-Concept
[Gasteiger et al. 2011]

- Identification of hemodynamic parameters
- Grouping to focus-context pairs and to spatial scopes
- Visualization templates for each pair and scope
- Picture-in-picture presentation based on magic lenses

*Courtesy of Rocco Gasteiger*
FlowLens-Visualization Template based

Velocity vs. pressure

Wall Shear Stress (WSS) vs. surface pressure
Wall Thickness

[Gläßer et al.; TVCG 2014]

Courtesy of Kai Lawonn et al.
Challenges

Presented an overview of existing challenges and visualization strategies with some examples. However, there are still a lot more... Extract flow features of interest, but ...

- What are features of interest?
  - Wall Shear Stress
  - Residence time
  - Topology features. Is that possible at all? *The terms should be interpretable by the physicians*
  - Others...

- What is normal/pathological behaviour?

- Mixture simulation and measured data
  - Compensate weakness and strengths
  - Predict outcome of operation
Further reading

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Questions?
Motivation: Applications

Cardiovascular

Diagnosis
- Stenoses
- Aneurysms
- Arteriosclerosis
- Dissection
- Congenital heart disease
  - Aortic coarctation
  - Tetralogy of Fallot
  - Septal defects
  - ...

Follow-up
- Stent
- Shunt
- Duct

Medical Art - Rogier Trompert (http://www.medical-art.nl)
Blood-flow measurements: Acquisition

Reconstruct blood-flow velocity field

Phase difference

Complex difference

X right to left

Y anterior to posterior

Z superior to inferior

"Comparison of Phase-Difference and Complex-Difference Processing in Phase-Contrast MR Angiography" – Bernstein and Ikezaki in JMRI 1991
Application: Aortic Dissection
Backup: Vector field raycasting

Raycasting Shader Program

\\ View vector correlated
\\ Widget vector correlated
\\ Prevalent flow correlated

Transfer Function

Interaction Widget
Backup: Illustrative flow rendering

Cross-cut selection

Visualization: blood flow
Streamlines
Pathlines

Visualization: context
Flow rate arrows
Exploded planar reformat

PCA-P phase 1 ... PCA-P phase N
PCA-M phase 1 ... PCA-M phase N
Temporal MIP
Visualization: Retrospective

- Anatomical context
  - Facilitates exploration and localization of regions-of-interest
  - Improves understanding of spatial relations
  - Illustrative depiction
    - Cel shading
    - Occluding contours

Currently based on a manual segmentation.
Visualization: Virtual probing overview

1. View-aligned slice (Or: MIP or DVR)
2. Positioning
3. Update
4. Inject seeds
Visualization: Virtual probing overview

(a) Visualization of virtual probing with segment point samples (sp).

(b) Pipeline diagram showing the seeding, visualization, and geometry stages.

(c) Vertex buffer object - memory layout illustrating segment point (sp) and line strip (Ls) data.

(d) Pathline diagram showing adjacency attributes over time.

- $sp_0$, $sp_n$, $sp_{2n}$: Segment point samples.
- $c$: Segment vertex count.
- $n$: Seed count.
- $VS$: Vertex shader.
- $GS$: Geometry shader.
Visualization: Comic inspiration

![Comic inspiration](https://www.dragoart.com)
### Visualization: Blood-flow probing

- **Evaluation results**

<table>
<thead>
<tr>
<th>virtual probe</th>
<th>positioning</th>
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<th>two-click tool, ortho-plane navigation</th>
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<td>pen-stroke tool</td>
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<td>concept, accuracy and speed</td>
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<td>planar reformat as basis</td>
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<td>MIP or DVR as basis</td>
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<td>cross-strips, only vascular oriented</td>
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<td>probe-based clipping, T-MIP data</td>
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Visualization: Blood-flow probing

Anatomical context

SSFP anatomy data

T-MIP blood-flow data
Visualization: Blood-flow probing

- Anatomical context

  orthogonal planes  
  probe parallel plane
Visualization: Blood-flow probing

- Interactive exploration

1. Positioning
   - View-aligned planar reformat
   - Two clicks to define the probe long-axis
Visualization: Blood-flow probing

- Interactive exploration

2. Fitting
- Limit to two degrees-of-freedom
- Easy interaction: \( \hat{\mathbf{x}} \) and \( \hat{\mathbf{y}} \)
- Challenging interaction: \( \hat{\mathbf{z}} \)
Visualization: Blood-flow probing

- Interactive exploration

2. Fitting

Can we find a combination of points $p$ and $q$, such that the probe long axis aligns with the T-MOP field?
Visualization: Blood-flow probing

- Interactive exploration

2. Fitting
  - Optimization problem

\[
T = \frac{TMOP(x) + (\hat{i} \otimes \hat{i})}{2}
\]

- Perform eigenanalysis on T
- Compute eigenvalue coherence:

\[
EC(T) = \left( \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2} \right)^2
\]
Visualization: Blood-flow probing

• Interactive exploration

3. Refinement
  • Translation
  • Rotation
  • Scaling
Example: Aortic dissection
SC Shading with Animated Blood Flow

[Lawonn et al.; Adaptive Surface Visualization of Vessels with Animated Blood Flow, CGF]
Visualization

- Blood flow visualization – Pathsurfaces

Conveys blood-flow rotation

cross-strip

nested tubes
Wall Thickness and Blood Flow

[Lawonn et al.; SciVis 2015]
Wall Thickness and Blood Flow
Occlusion-free Blood Flow Animation in Cerebral Aneurysm with Wall Thickness Visualization
Suggestive Contour Shading

[Lawonn et al.; VMV 2013 ]

Courtesy of Kai Lawonn et al.