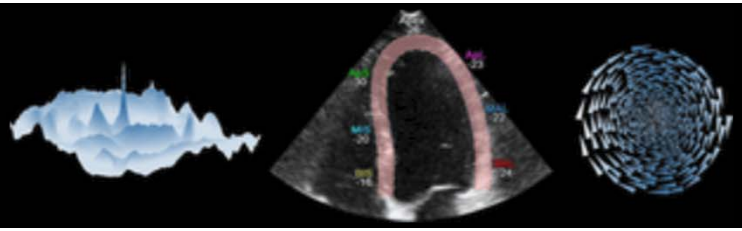
UFFC2019 US school

Ultrasound motion imaging & Experimentations



Day 3 – Part 1

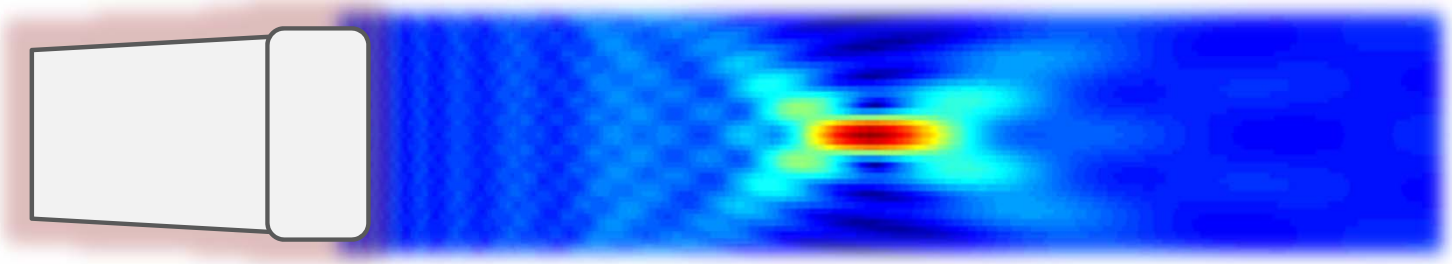
Flow Phantom Design

Alfred C. H. Yu, PhD

Professor, University of Waterloo

LITMUS

LABORATORY ON INNOVATIVE TECH IN MEDICAL ULTRASOUND



Wall-Less Flow Phantoms

For Investigation of Flow Mapping Techniques

Flow Phantom: The Basics

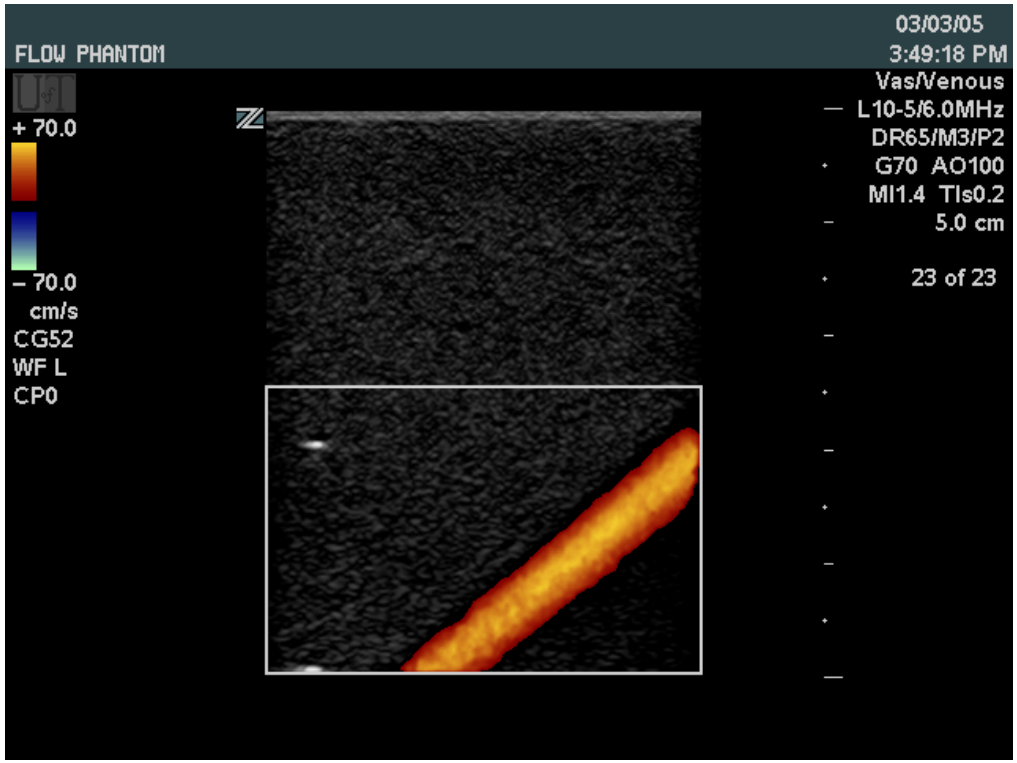
A model representation of human vasculature

- ↳ Should have well-characterized flow characteristics
- ↳ Ideally phantom properties should be controllable

Example: Gammex-RMI 1425 commercial phantom



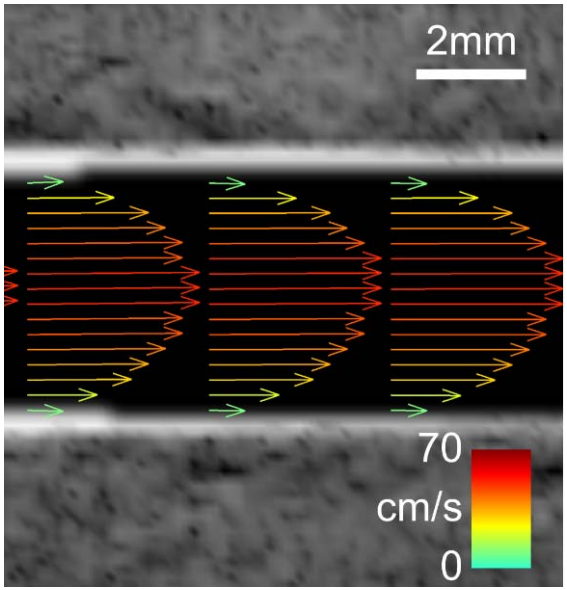
Source: Sun Nuclear Corporation

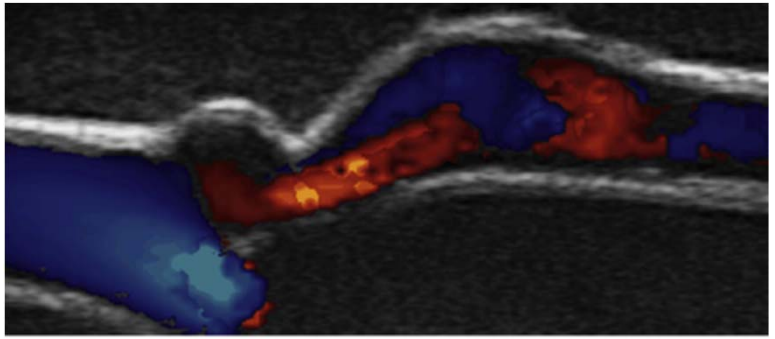


Alfred's first color Doppler image formed using Matrix Pencil method

Flow Phantom: Three Major Roles







Calibration device: For quality assurance of clinical Doppler scanner

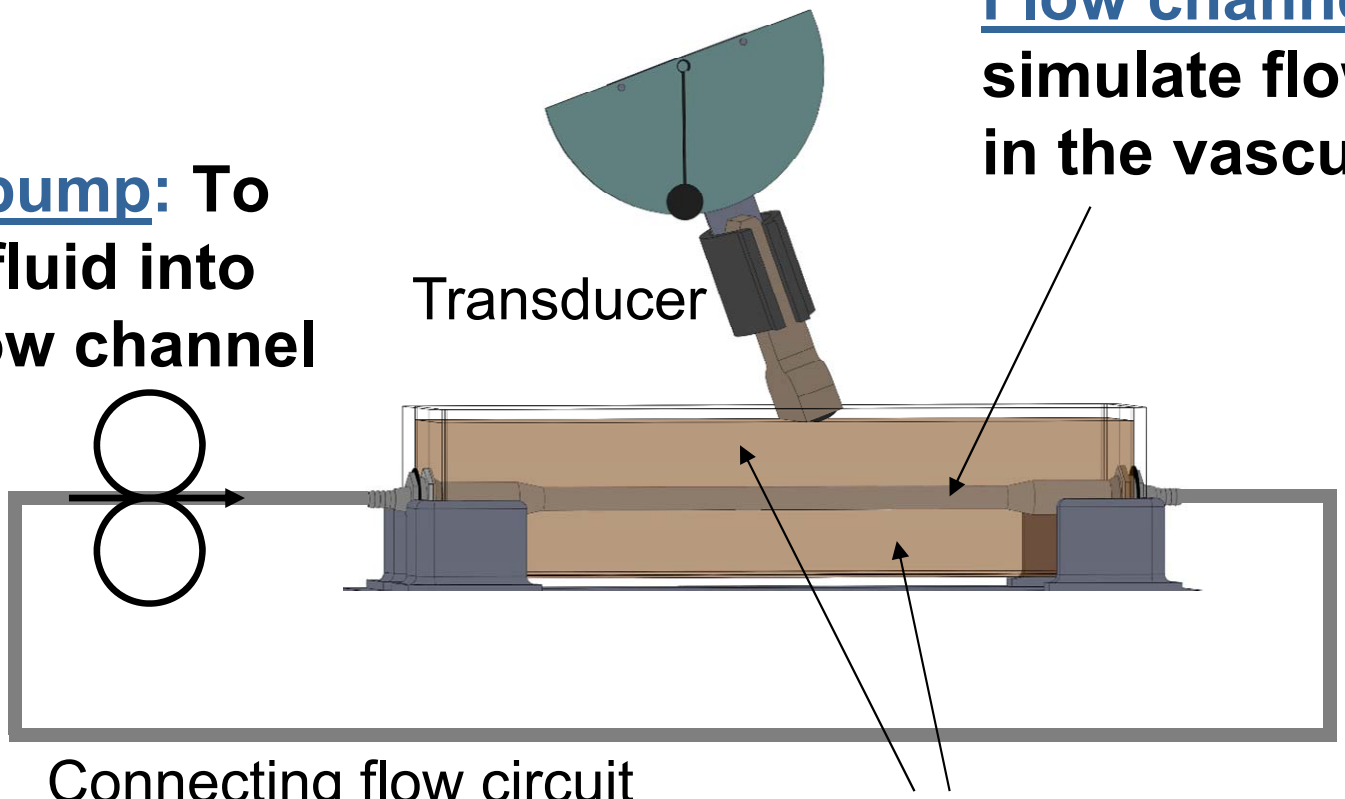
Performance analysis / demo: For development of new flow signal processing and imaging techniques

Investigative tool: For derivation of hemodynamic insight into complex vasculature

Major Components of a Flow Phantom

Flow channel: To simulate flow dynamics in the vasculature

Flow pump: To drive fluid into the flow channel



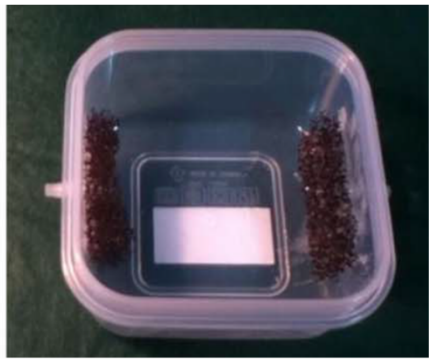
Tissue mimicking slab: To simulate tissue surrounding a vascular segment

Straight-Tube Model: The Simplest Wall-Less Phantom

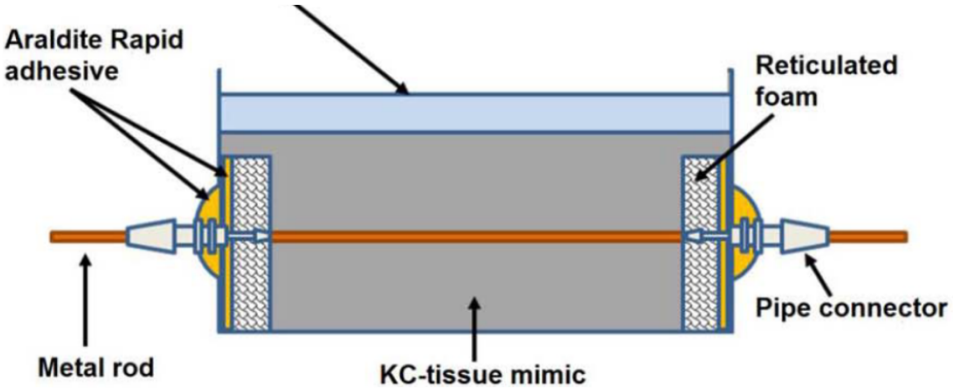
General fabrication approach: Lost-core casting

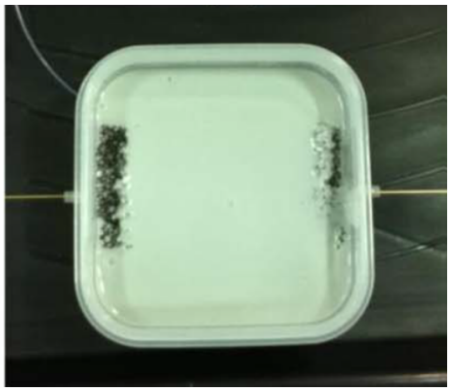
- ↳ Mount a rod within an empty box
- ↳ Cast a tissue mimicking slab around the rod
- ↳ Withdraw the rod to form a tubular lumen





Zhou et al., *IEEE T-UFFC*, 64(1), 53-65, 2017





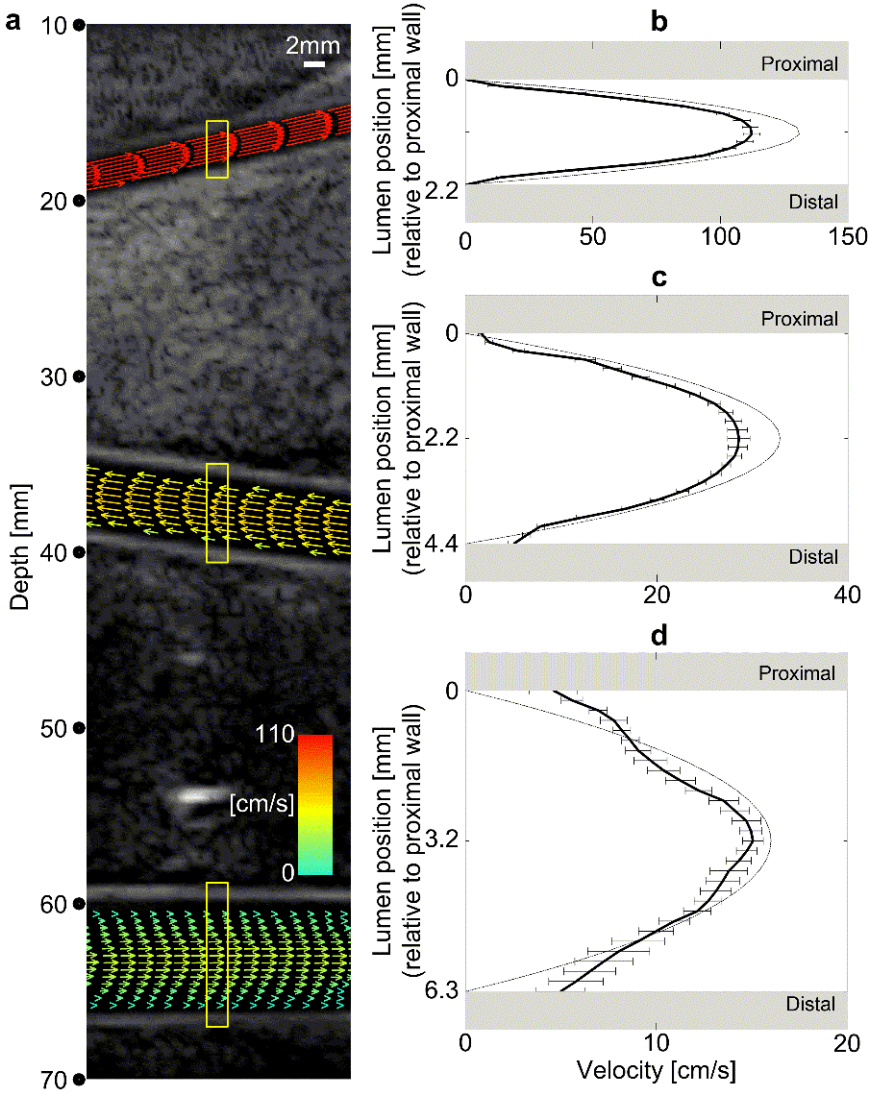
Straight-Tube Phantom: Further Remarks

<u>Advantage</u>: Flow profile is known to be parabolic if phantom operates in steady flow condition

- ↳ Useful for performance evaluation of flow estimators

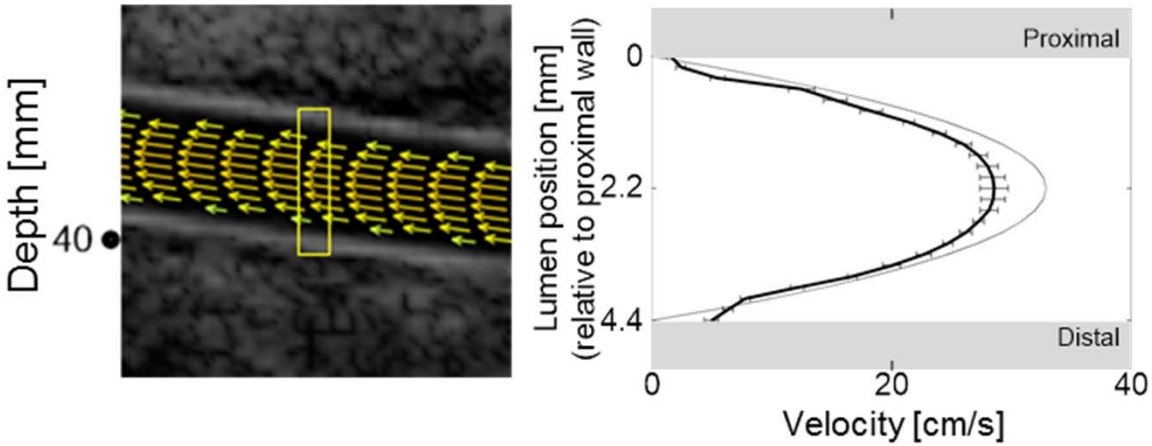
Multiple flow channels may be casted within the same tissue mimicking slab

- ↳ Channel diameter and alignment angle may vary



Yiu et al., *UMB*, 40(9), 2295-2309, 2014

Straight-Tube Phantom: Further Remarks

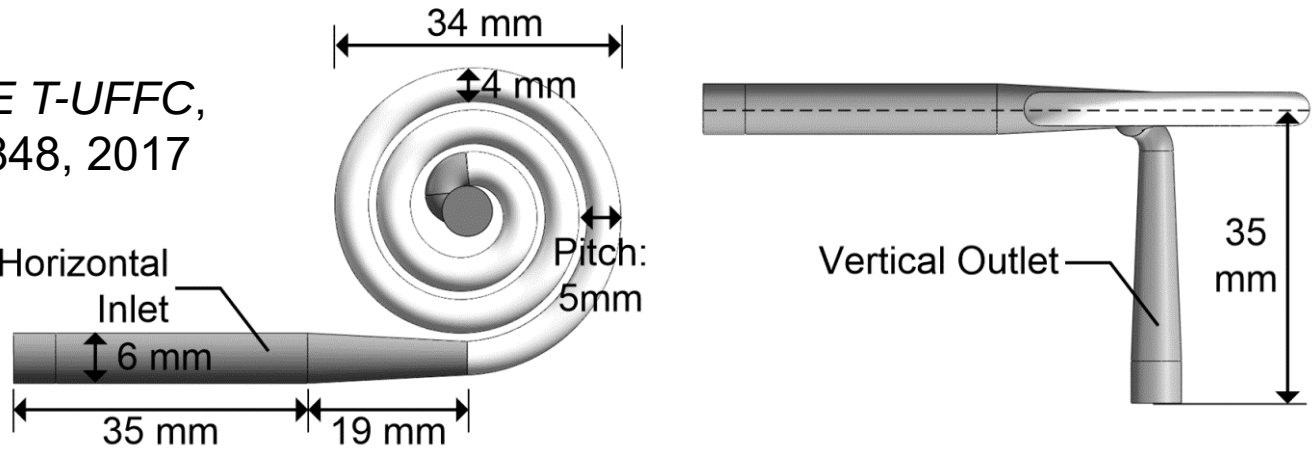


Limitation: Flow channel geometry is overly idealized

- ↳ Does not generate multi-directional flow (known to be present in human vasculature)
- ↳ Hard to test the estimation performance of flow vector estimators at different flow angles
  - Require manual repeat of data acquisition at different transducer-flow angles

Spiral Phantom: Towards the Design of a Multi-Directional Flow Model

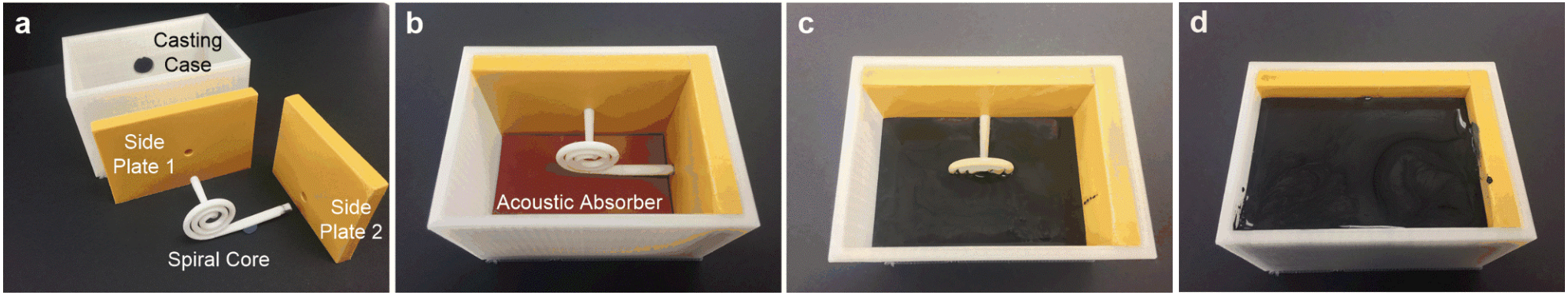
Yiu and Yu, *IEEE T-UFFC*, 64(12), 1840-1848, 2017



Key feature: Multi-loop spiral lumen geometry

- ↳ Curvy lumen geometry naturally gives rise to flow patterns that cover all possible flow angles
- ↳ Dimensions can be controllably defined to fit multiple spiral loops within the transducer aperture width

Spiral Flow Phantom: Fabrication Protocol

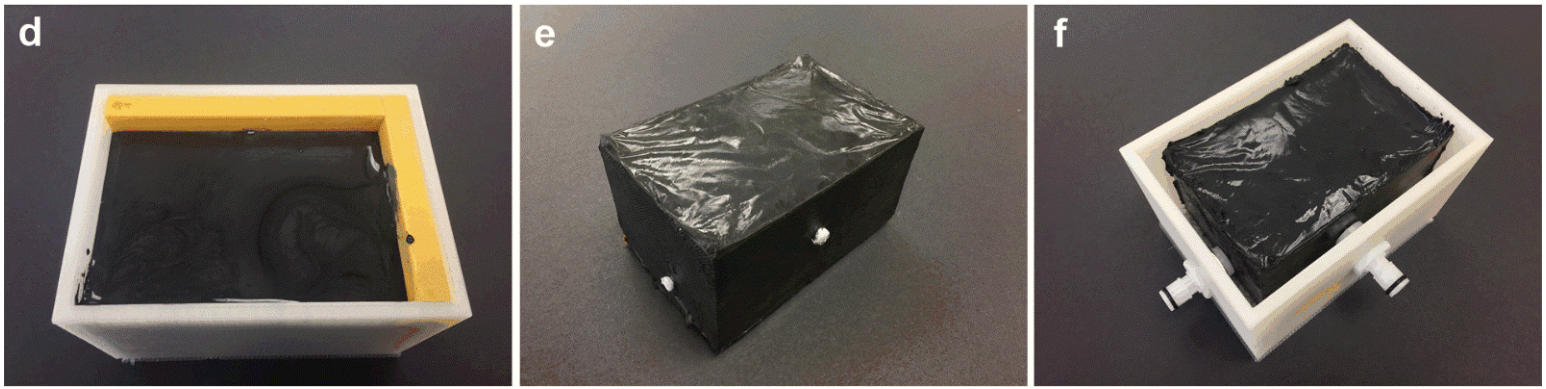


Yiu and Yu, *IEEE T-UFFC*, 64(12), 1840-1848, 2017

Involves computer-aided design and 3-D printing

- ↳ Use SolidWorks to draft casting parts and spiral core
- ↳ Build casting parts using a fused deposition modeling (FDM) system
- ↳ Use polylactic acid (PLA) as the 3-D printing material (soluble in chlorinated solvents)
- ↳ Cast tissue mimicking solution around the spiral core

Spiral Flow Phantom: Fabrication Protocol



Yiu and Yu, *IEEE T-UFFC*, 64(12), 1840-1848, 2017

Steps to complete the fabrication process

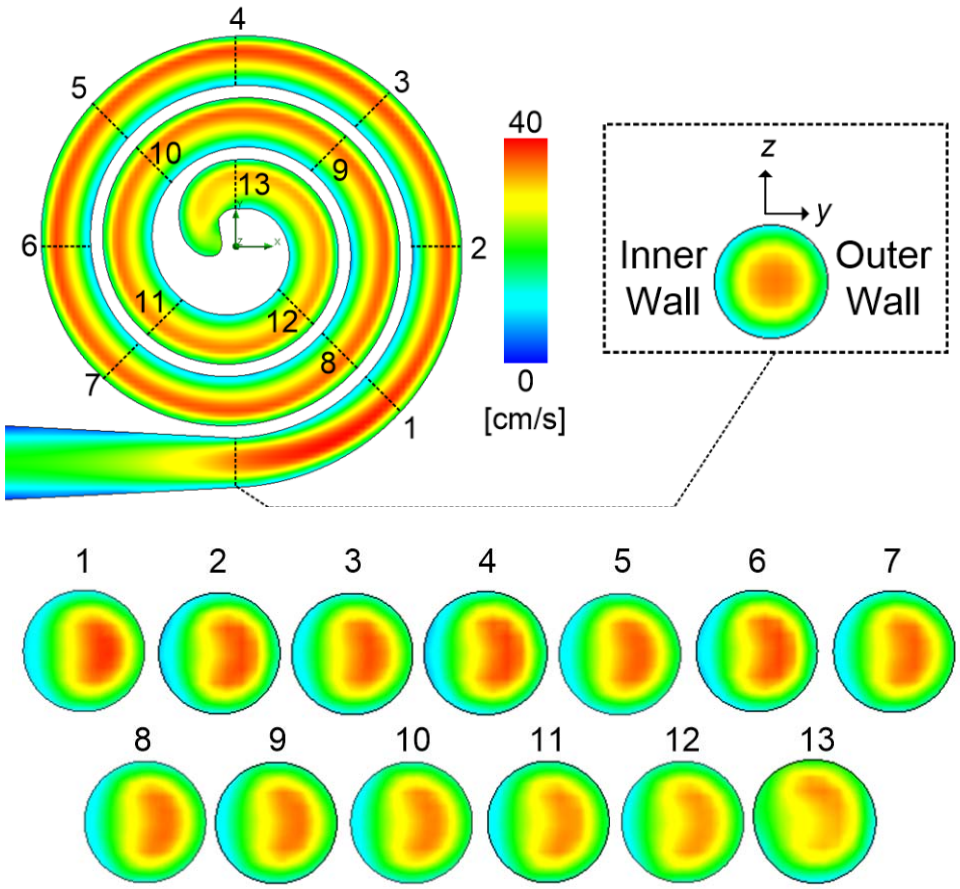
- ↳ Immerse the casted tissue slab in chloroform for 24 h
  - PLA (spiral core) dissolves in chloroform without affecting the tissue slab (polyvinyl alcohol based)
- ↳ Add flow connectors to the phantom box
- ↳ Remount the coreless tissue slab onto the box for use

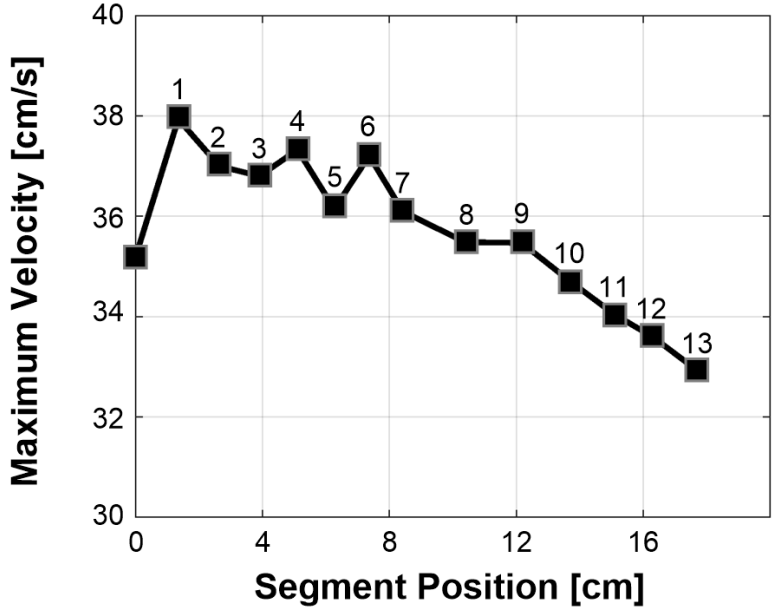
Flow Profile within Spiral Lumen: A Computational Fluid Dynamics Analysis

Software: Solidworks Flow Simulation

Inlet Flow Rate: 3 mL/s Outlet Pressure: Atmospheric Pressure (101 kPa)

** Note: Fluid properties set to match those of blood **





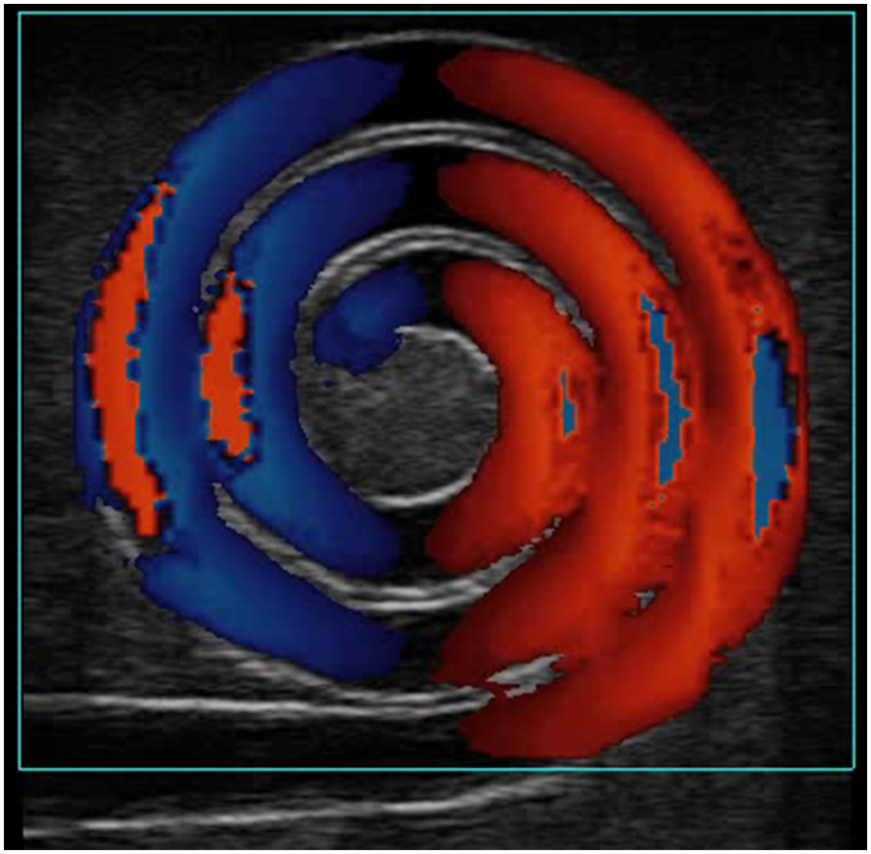
Observations

- Centrifugal flow velocity profile
- Slight decrease in peak velocity

Spiral Flow Phantom in Action: Color Flow Imaging & Vector Flow Imaging

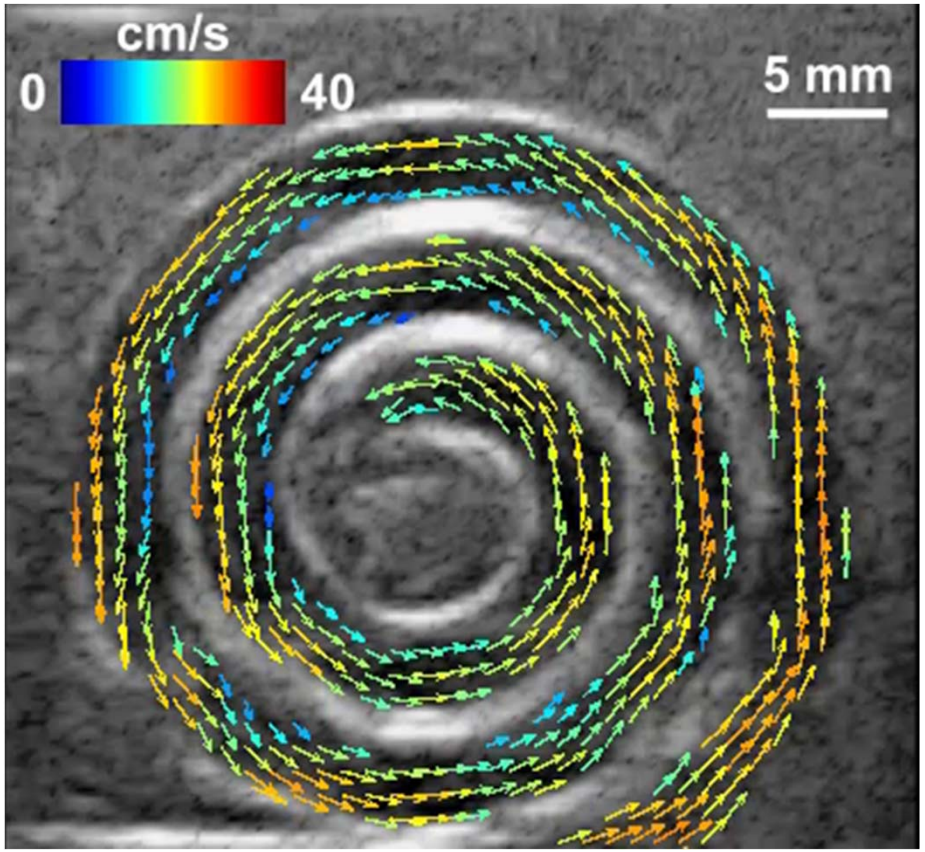
Color Flow Imaging Cineloop (SonixTouch)

Freq.: 5 MHz PRF: 3.3 kHz Frame rate: 10 fps



Channel-Domain Research Platform

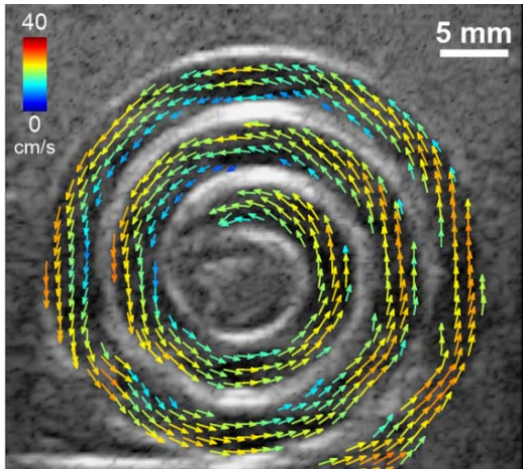
Freq.: 5 MHz PRF: 10 kHz Frame rate: 800 fps

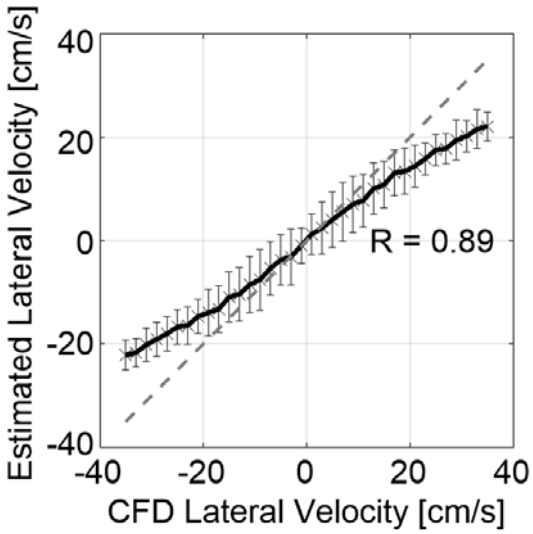


Key Observation: Spurious coloring artifacts in CFI are avoided by vector flow imaging

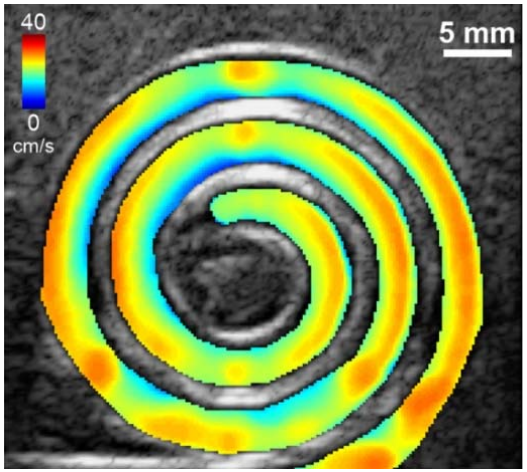
Comparison of Flow Vector Estimates to CFD Values

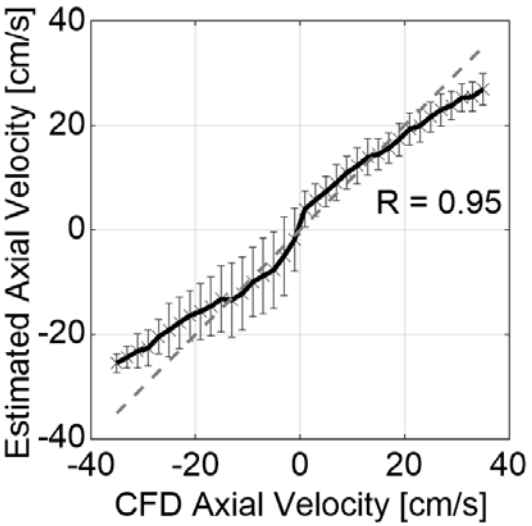
Flow Vector Map



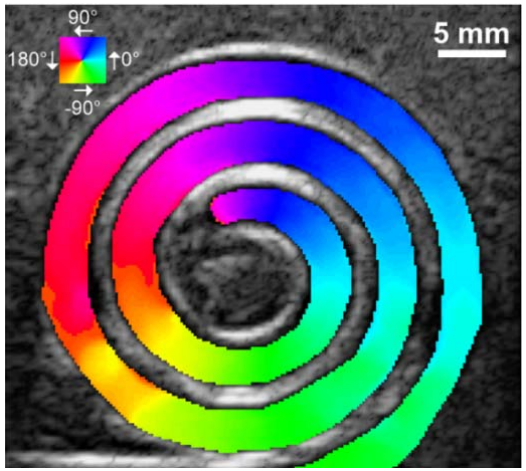


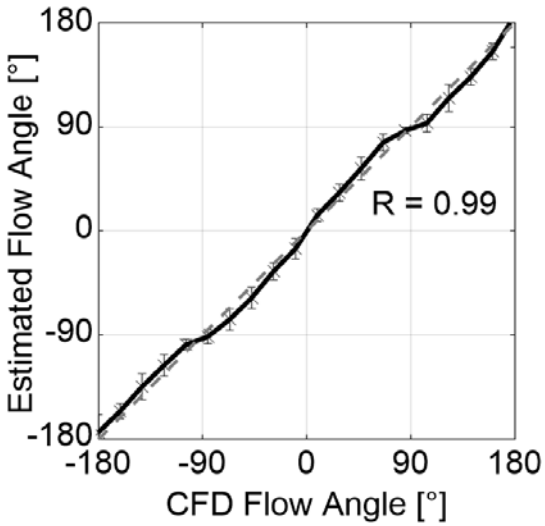
Flow Magnitude





Flow Angle





Key finding: Estimated flow angle consistent with expected value

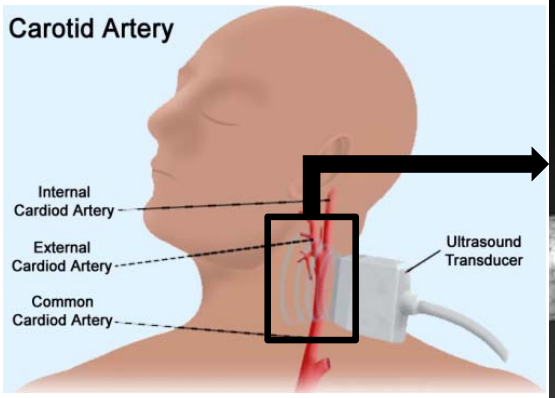
Towards the Design of Anatomically Realistic Flow Phantoms

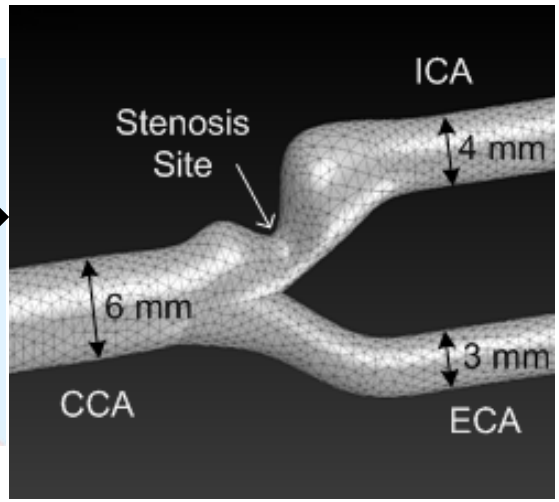
Motivation #1: Flow maps derived from anthropomorphic phantoms can serve well as showcase demos

- ↳ Issue with spiral flow phantoms: Useful test platform for flow estimator performance analysis, but not designed to model real human vasculature

Motivation #2: Help assess whether a flow mapping technique can depict pathological flow features

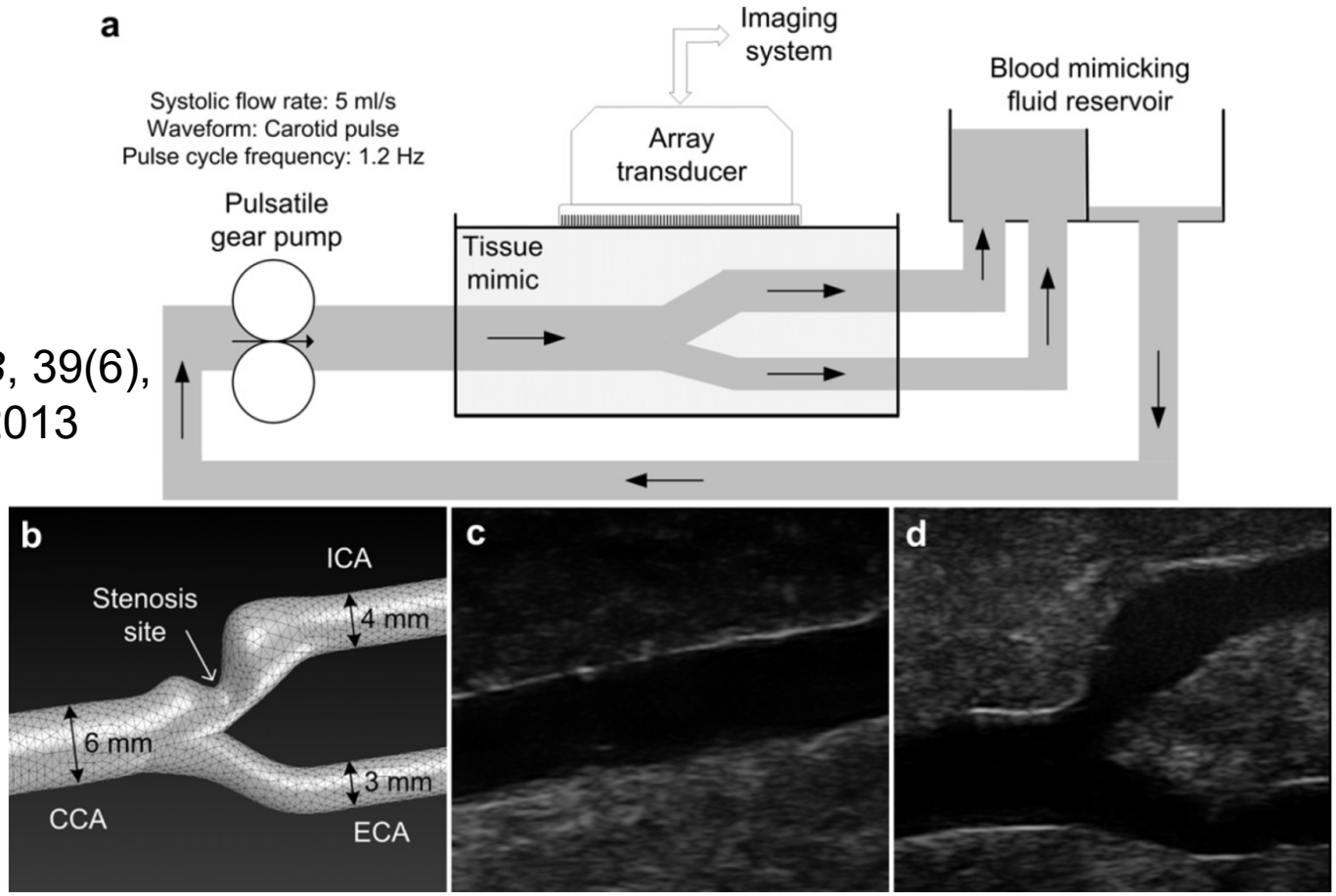
- ↳ Example: Complex flow in a stenosed carotid artery





Carotid Bifurcation Phantom Design: General Overview

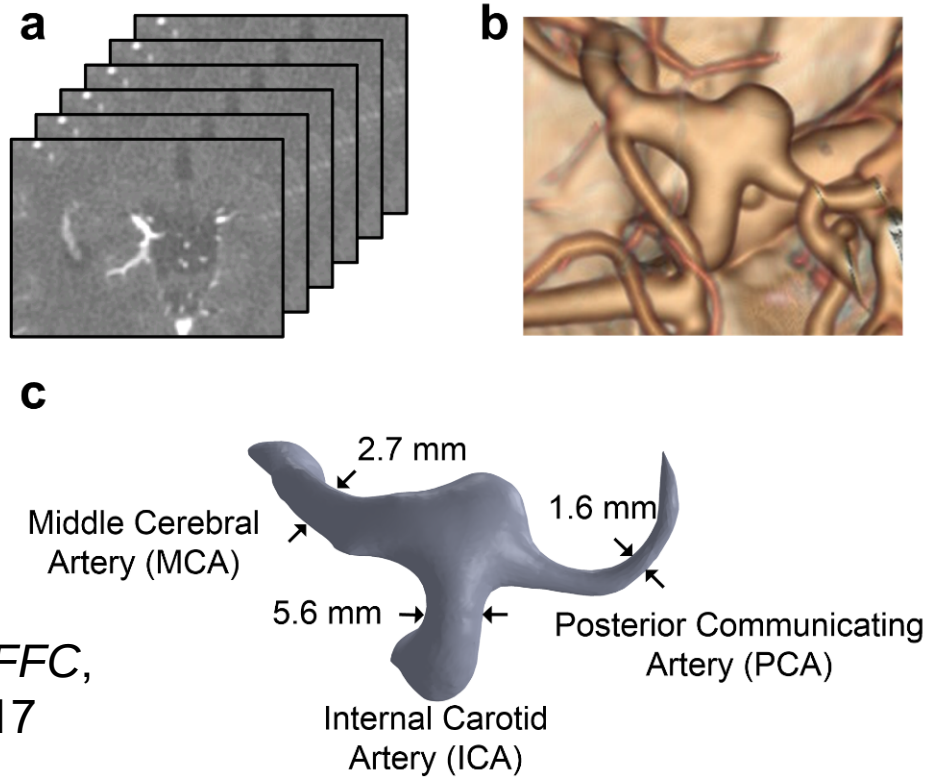
Yiu and Yu, *UMB*, 39(6), 1015-1025, 2013



Based on the same lost-core casting protocol described earlier

↳ Draft carotid CAD model and build 3-D printed cores

A More Advanced Example: Patient-Specific Phantom Design



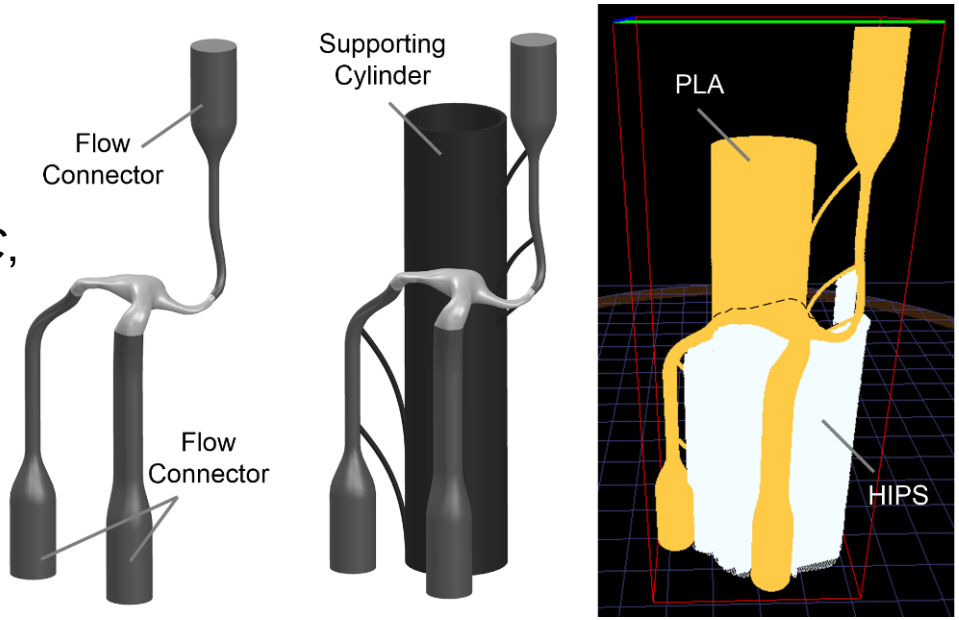
Ho et al., *IEEE T-UFFC*, 64(1), 25-38, 2017

Intracranial aneurysm geometry of a 60-yr old patient

- ↳ Data source: CT angiography (with data stored as DICOM)
- ↳ CAD model derived using Mimics software

Patient-Specific Aneurysm Phantom: Fabrication Protocol

Ho et al., *IEEE T-UFFC*, 64(1), 25-38, 2017



CAD model further refined in SolidWorks

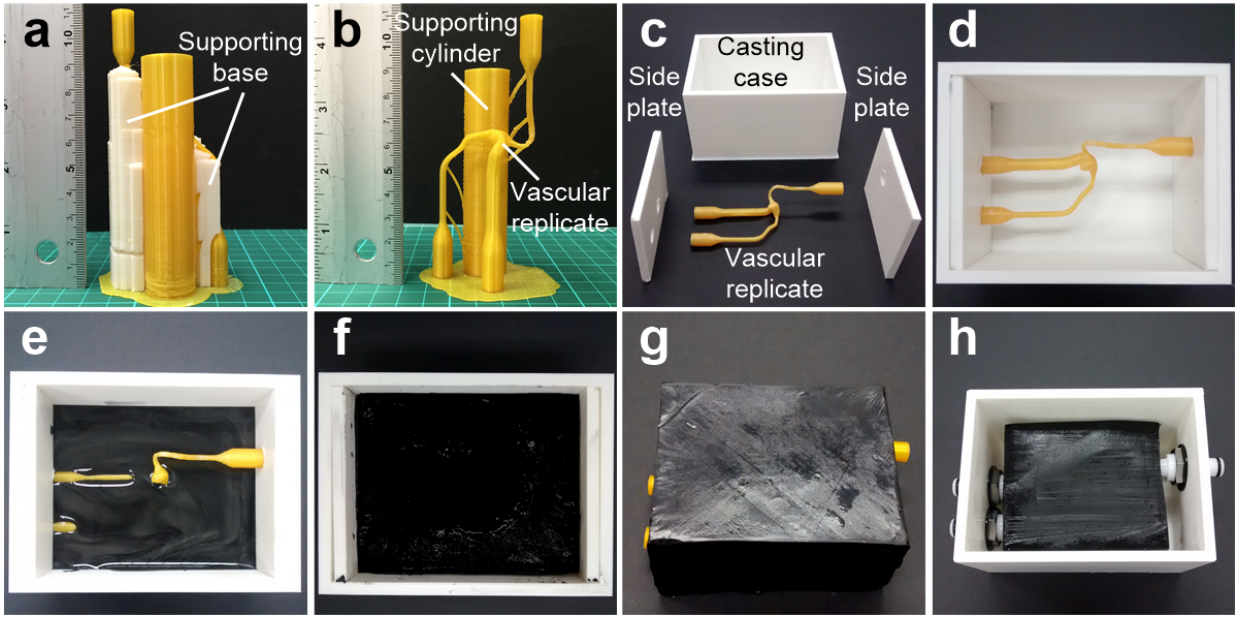
- ↳ Other features relevant to phantom construction were added: 1) flow connectors, 2) supporting cylinder

The use of a supporting base is critical during 3-D printing

- ↳ PLA as the vessel core material, and HIPS (high-impact polystyrene) as the supporting material

Patient-Specific Aneurysm Phantom: Fabrication Protocol

Ho et al., *IEEE T-UFFC*, 64(1), 25-38, 2017

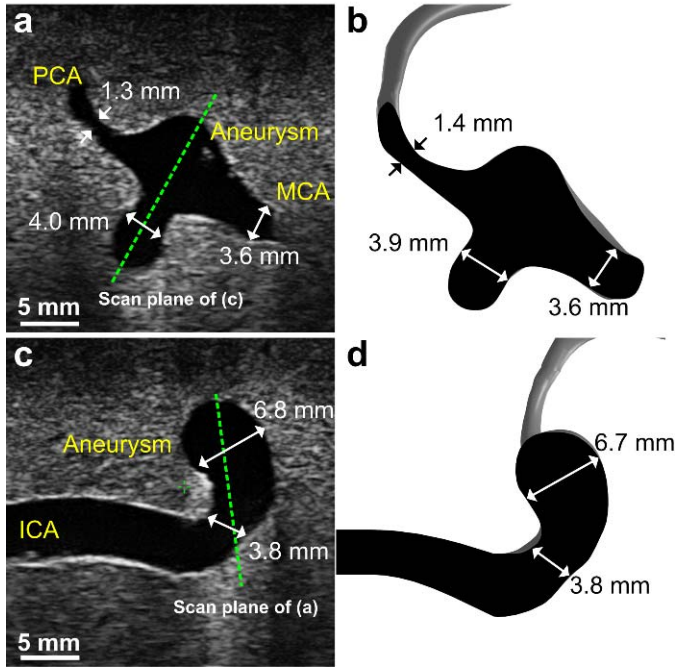


Vascular replicate retrieved using a two-step procedure

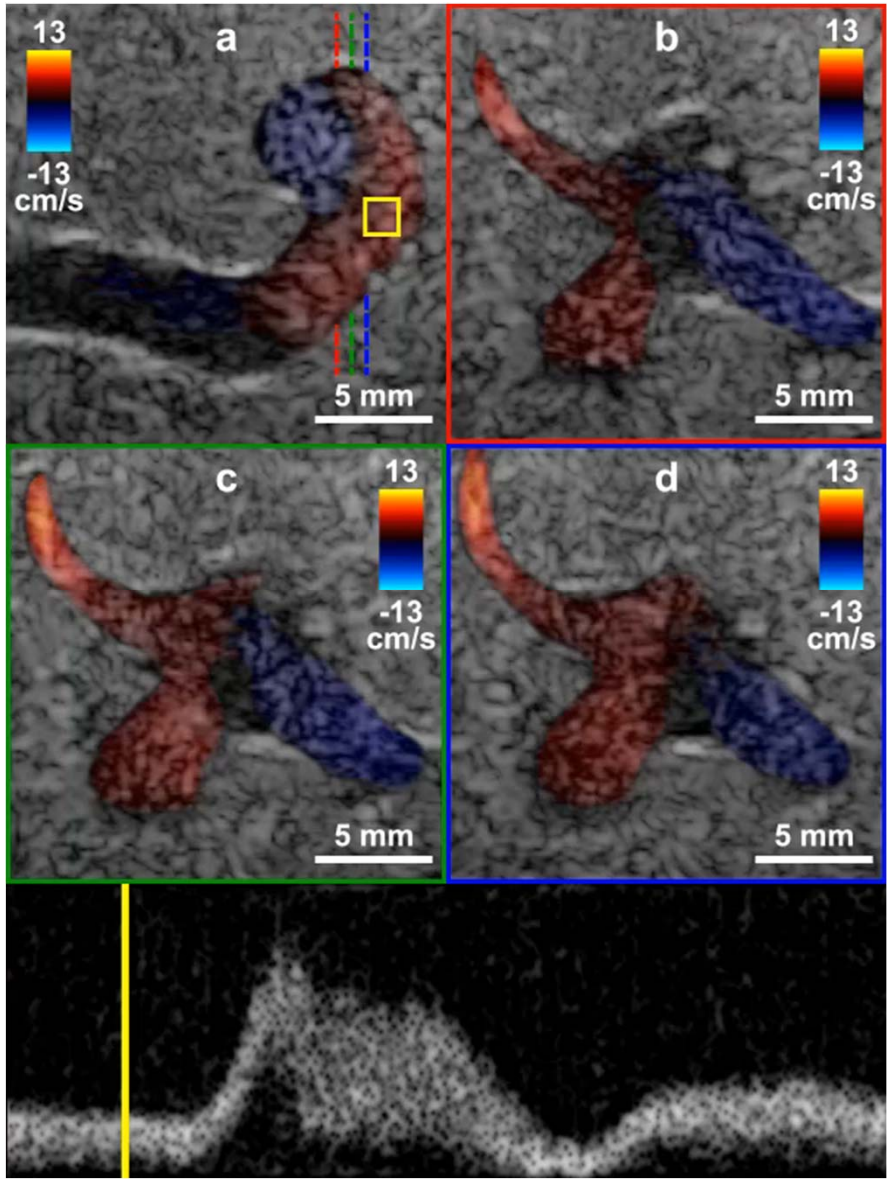
- ↳ Use limonene to dissolve HIPS supporting base
- ↳ Cut the connecting branches between vessel and supporting cylinder (and smoothen cut points with sandpaper)

Lost-core casting was then performed as similar to that described earlier

Aneurysm Phantom in Action: Demonstration of 3D Flow Patterns



Ho et al., *IEEE T-UFFC*, 64(1), 25-38, 2017



Multi-planar flow rendering with color-encoded speckle imaging

Technique to be discussed further after coffee break

Other Considerations for Flow Phantom Design

Beyond the Vessel Model

Flow Pump: An Essential Component of a Flow Phantom

Different flow profiles may be needed

- ↳ Steady flow for calibration phantoms (e.g. straight tube)
- ↳ Pulsatile flow (e.g. carotid pulse) for anthropomorphic phantoms

Various types of flow pumps are available, but not all are relevant to flow phantom development

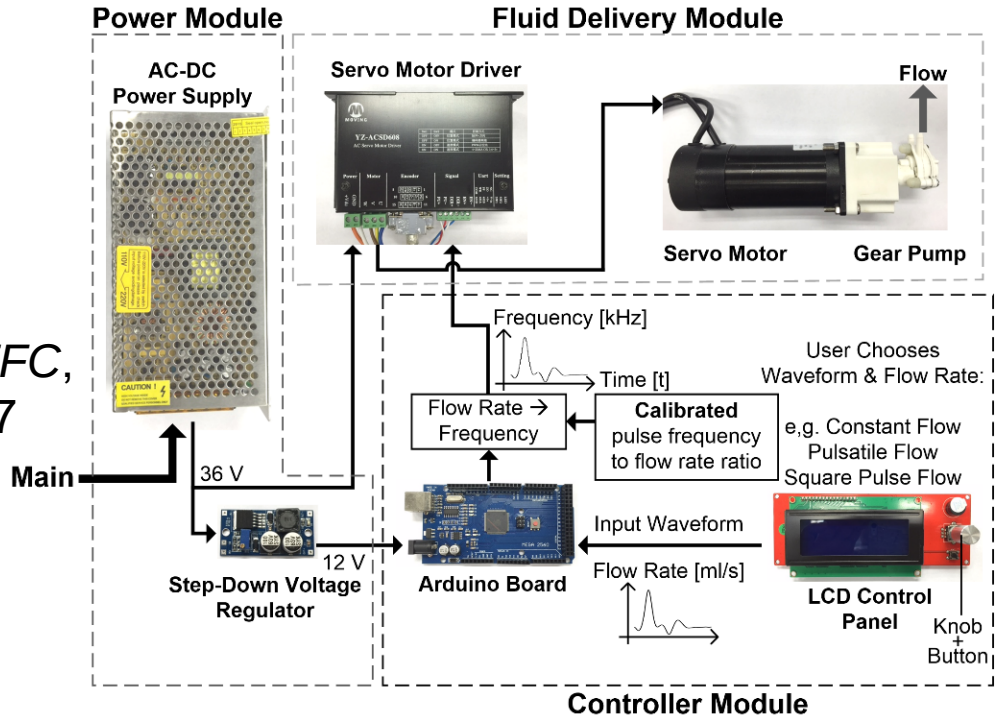
- ↳ Relevant ones: Gear pump, piston pump (good for pulsatile flow control)
- ↳ Occasionally useful: roller pump (for constant flow), syringe pump (for microflow models)
- ↳ Try to avoid: Peristaltic pump (hard to control flow profile)

Commercial pre-programmed flow pumps exist

- ↳ Example: AccuFlow-Q (Shelley Medical)

Customized Flow Pump Development: Not a Difficult Task

Ho et al., *IEEE T-UFFC*, 64(1), 25-38, 2017



Cost-effective and allows comprehensive control of operations

- ↳ Parts required: gear pump, servo motor, motor driver, power module, Arduino board, user control panel
- ↳ Arduino board programmed to control the operation of the flow pump's servo motor driver

Blood Mimicking Fluid: Another Key Component

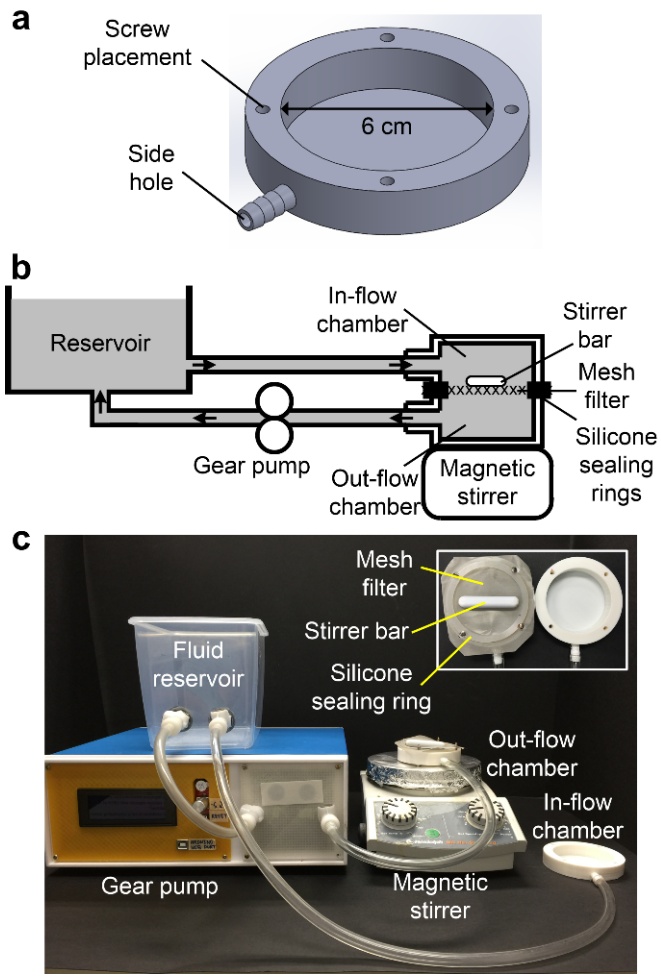


Source: CIRS Inc.

Fluid properties should match the viscosity and acoustic properties of human blood

- ↳ Standardized formula available [Ramnarine et al, UMB, 24(3), 451-459, 1998]
- ↳ Key constituents of the formula:
  - Dextran (for viscosity matching)
  - Glycerol (for acoustic speed and density matching)
  - 5 μm Orgasol particles (for acoustic scattering matching)

Making Your Own Blood Mimicking Fluid: Not a Difficult Task



Ho et al., *IEEE T-UFFC*, 64(1), 25-38, 2017

Mix ingredients in the formula as required

- Use of a flow circuit can facilitate circulatory flow (more preferred than vortex mixing)

Important: Devise an effective mesh filter for use during mixing

- Needed to prevent large particle aggregates from forming
- Recommended mesh: stainless steel mesh with 33 μm pore size (316L, TWP Inc.)
- Use magnetic stirrer to avoid particles from accumulating on the filter mesh itself

Tissue Mimicking Slab: Overview of Material Types Available

General fabrication goal: Form a tissue layer with acoustic properties matched to human tissue

- ↳ Key factors: acoustic speed, attenuation coefficient
- ↳ Mechanical properties matching preferred but not essential

Different tissue mimicking materials have been reported

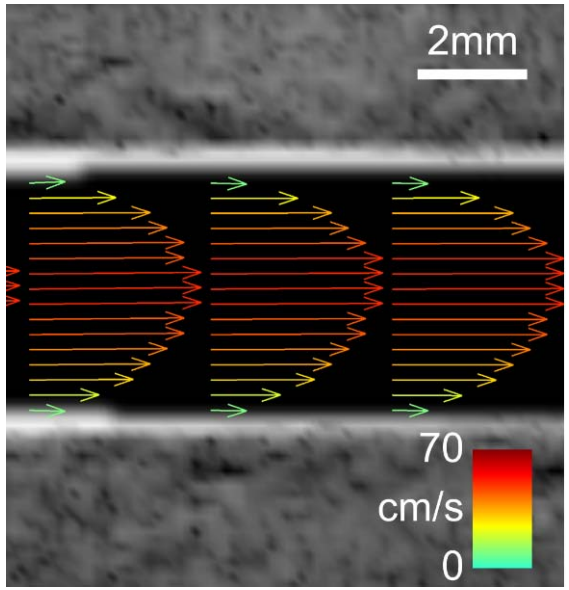
- ↳ Agar-gelatin mixture: Strong acoustic matching, and draw a balance between agar's brittleness and gelatin's softness
- ↳ Konjac and carrageenan: Mechanically tough and more resilient against cracking than agar-gelatin
- ↳ Polyvinyl alcohol (PVA) cryogel: Mechanical properties can be tuned through manipulating the freeze-thaw cycle

Walled Flow Phantoms

For Evaluation of Vascular Wall Imaging Techniques

Walled Flow Phantom: The Basics

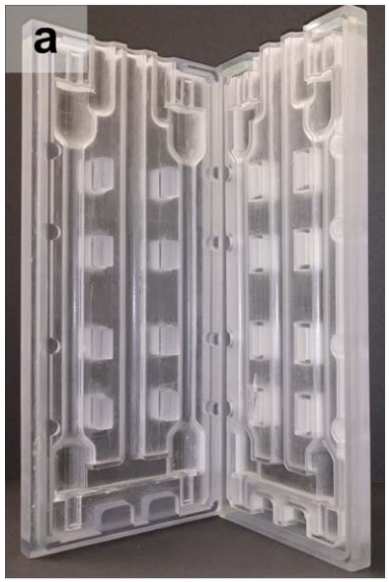
Easy to see if a phantom is wall-less from B-mode image (with only one bright line at lumen wall)

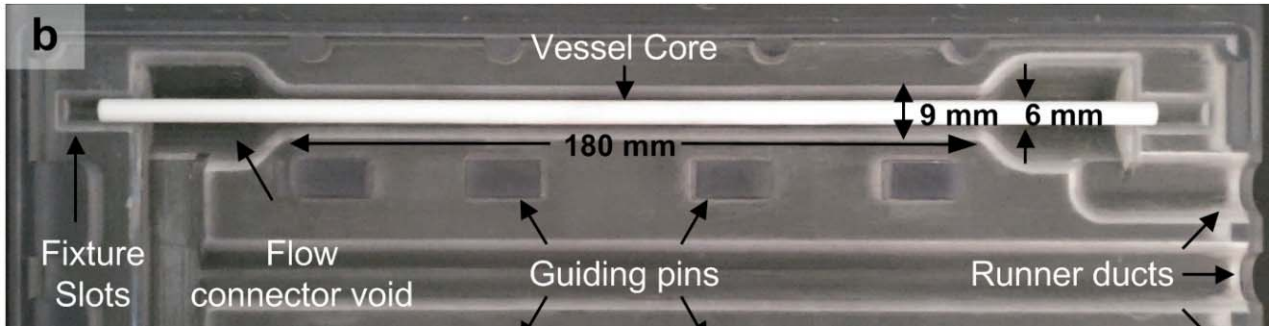


Motivation: Wall-less phantoms have systemic limitations

- ↳ Tissue mimicking slab does not accurately model arterial wall tissue (Young's moduli of artery and soft tissue are quite different)
- ↳ Wall-less phantoms are designed as experimental tools for flow mapping analysis, but they are not intended to model vascular wall dynamics

Straight-Tube Walled Phantom: Fabrication Protocol





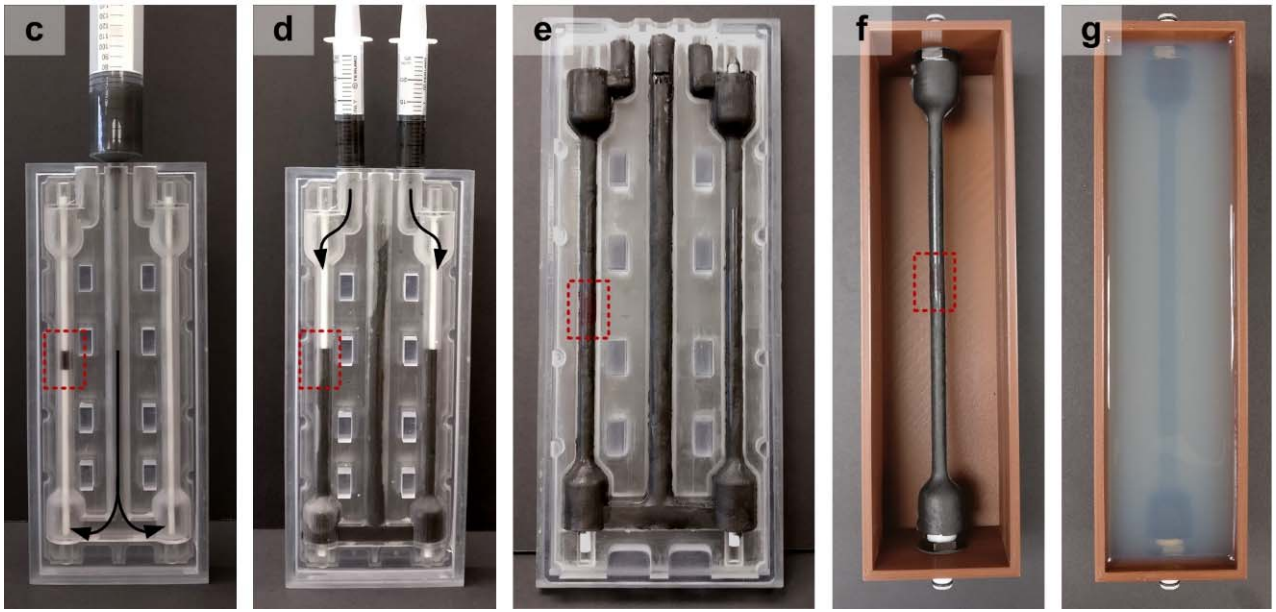
Chee et al., *UMB*, 44(4), 872-883, 2018

General approach: Injection molding

- ↳ Design an outer negative mold with expanded luminal void dimensions
- ↳ Mount an inner core within the outer mold's luminal void
- ↳ Fill the gap between inner core and outer wall with the vessel mimicking material (PVA)

Straight-Tube Walled Phantom: Fabrication Protocol

Chee et al., *UMB*, 44(4), 872-883, 2018

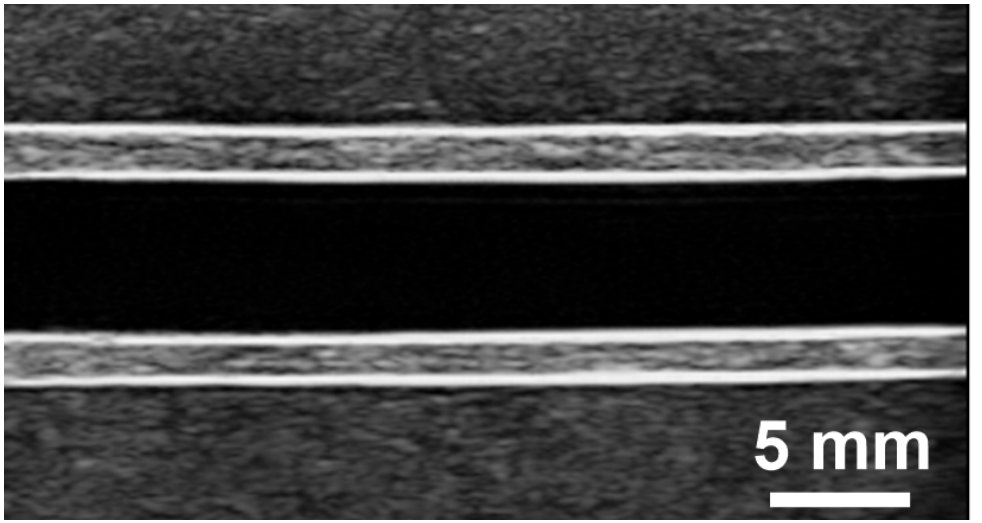


Steps to form vessel tubes and form a walled phantom

- Slowly inject PVA vessel mimicking solution through the runner duct of the sandwiched mold
- Put the entire loaded mold through freeze-thaw cycle
- Cut off the PVA strips in the runner ducts to retrieve the vessel tube, and mount them onto a box with tissue slab

Straight-Tube Walled Flow Phantom: Further Remarks

Clear echo signature difference of wall region (with two bright lines at the two edges of lumen wall)

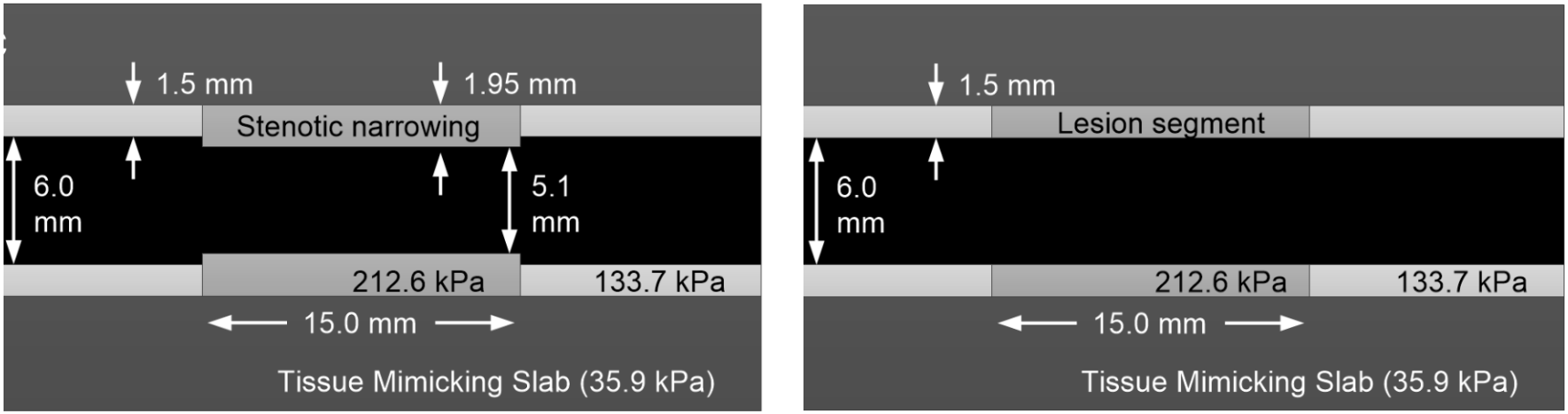


Chee et al., *UMB*, 44(4), 872-883, 2018

PVA-based wall material's elasticity can be tuned

- More freeze-thaw cycles ➔ More PVA crosslinking to lead to greater wall stiffness
- Young's elastic modulus may be estimated through tensile testing to derive stress-strain curves

Extension of Straight-Tube Phantoms: Multi-Segment Models



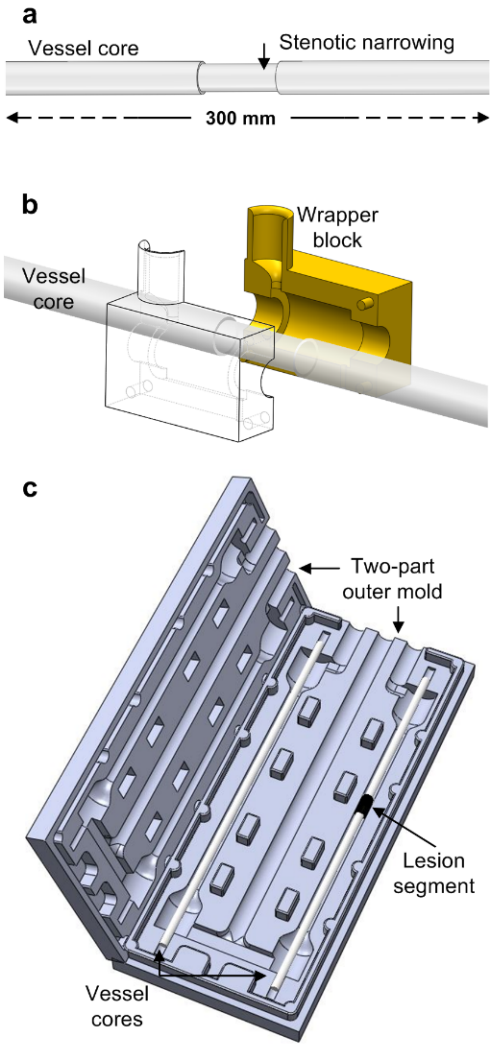
Chee et al., *UMB*, 44(4), 872-883, 2018

Possible to generate a lesion segment with properties different from other parts of the artery segment

- ↳ Both geometric and mechanical differences can be created for the lesion segment

General fabrication solution: Multi-part injection molding

Multi-Segment Walled Phantoms: Fabrication Protocol



<u>Key step #1</u>: Manipulate the vessel core geometry to induce geometric differences for the lesion segment

- ↳ E.g. create a stenotic narrowing region on the vessel core

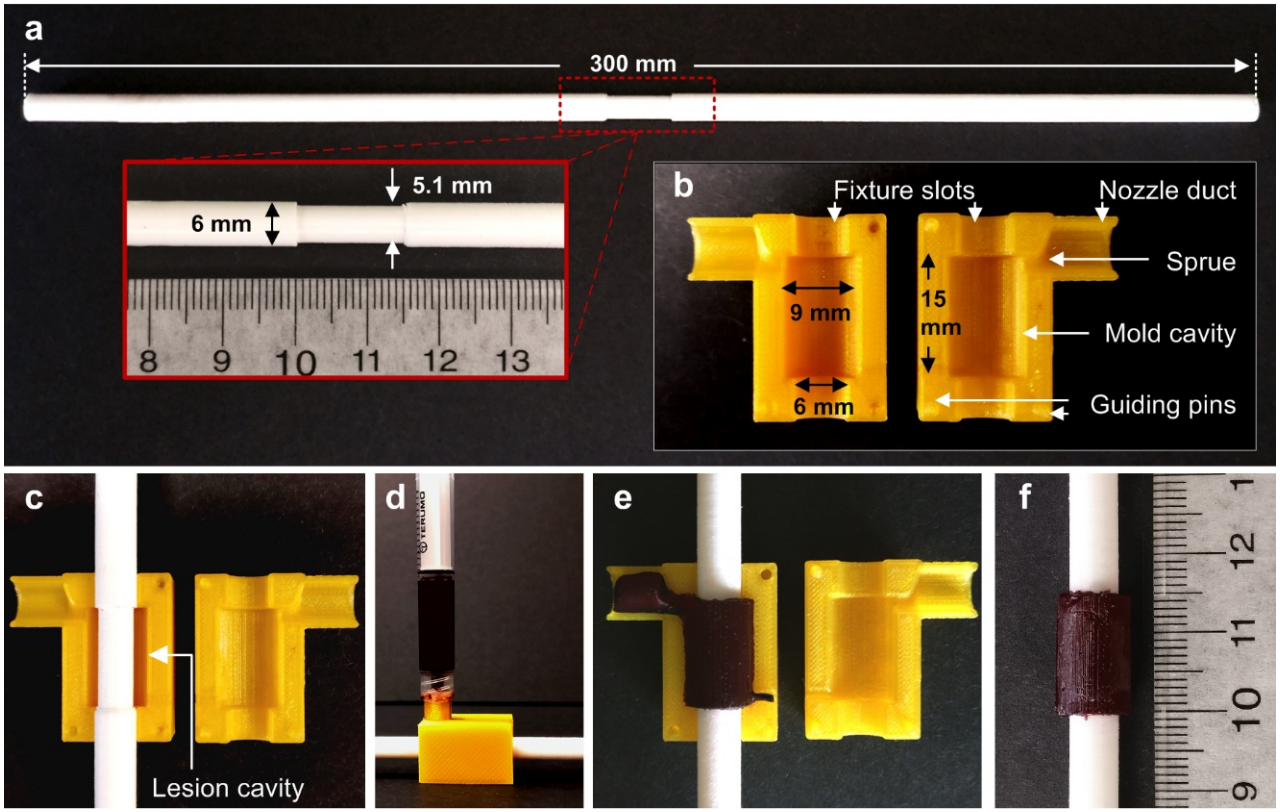
<u>Key step #2</u>: Design a wrapper block to cast the lesion segment separately so that its elasticity can be different

- ↳ E.g. create a lesion segment that is stiffer than elsewhere

Chee et al., *UMB*, 44(4), 872-883, 2018

Multi-Segment Walled Phantoms: Fabrication Protocol

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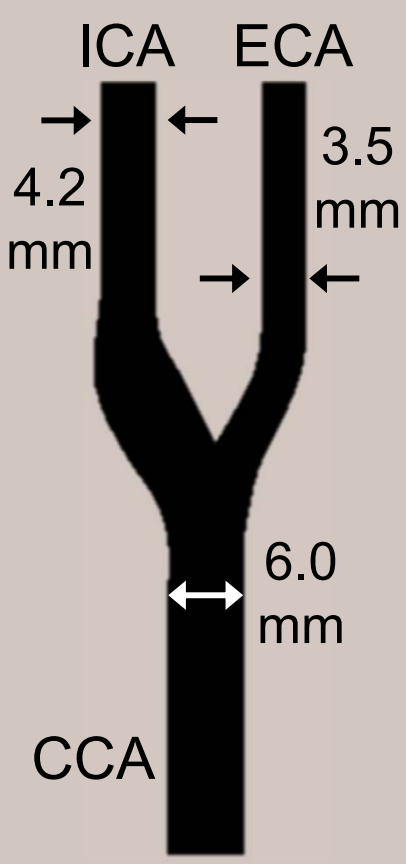
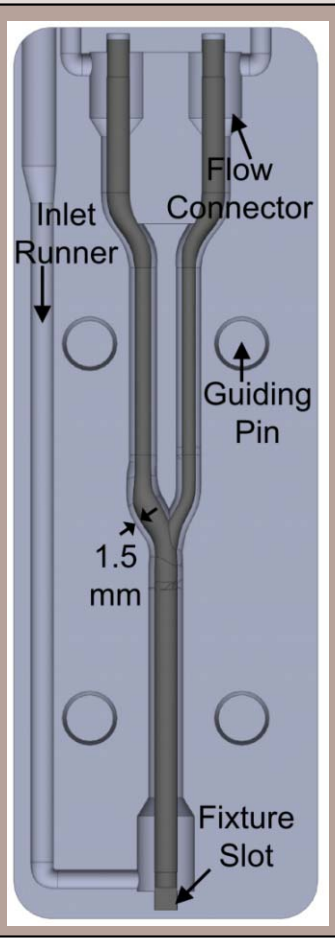
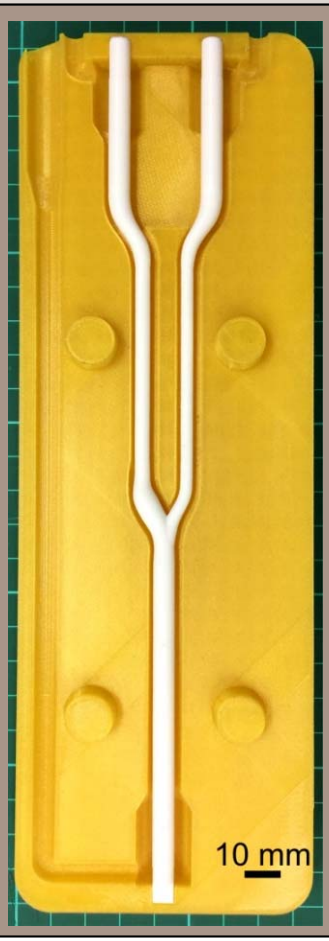
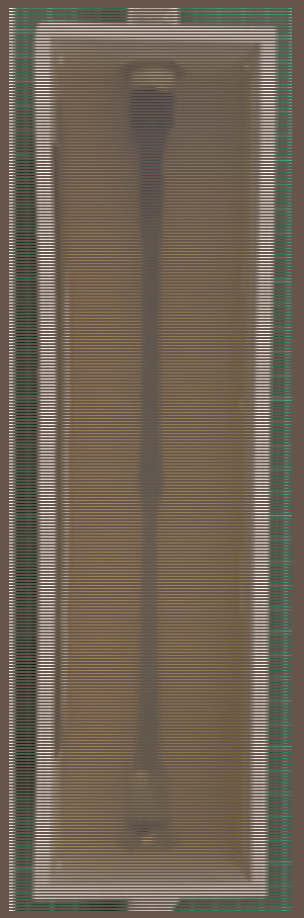
Injection molding done locally on the lesion cavity first

↳ Create a vessel core with a lesion segment mounted on it

Proceed with straight-tube injection molding afterward

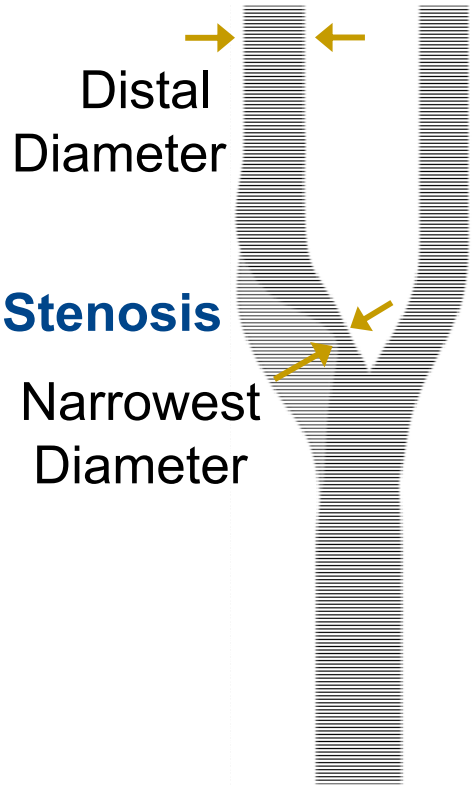
Anatomically Realistic Walled Phantoms Can Be Fabricated Too

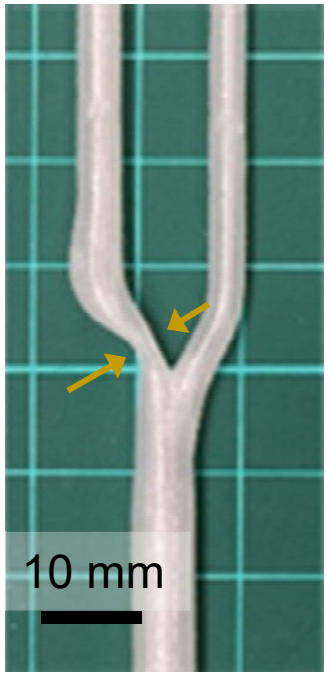
Chee et al., *IEEE T-UFFC*, 63(11), 1852-1864, 2016

Conceptualize Model	CAD Drafting	Direct 3D-Printing	Vessel Wall Casting	Phantom Assembly
				

Possible to Build a Phantom Library for Atherosclerosis Studies

Approach: Include stenosis when building vessel core

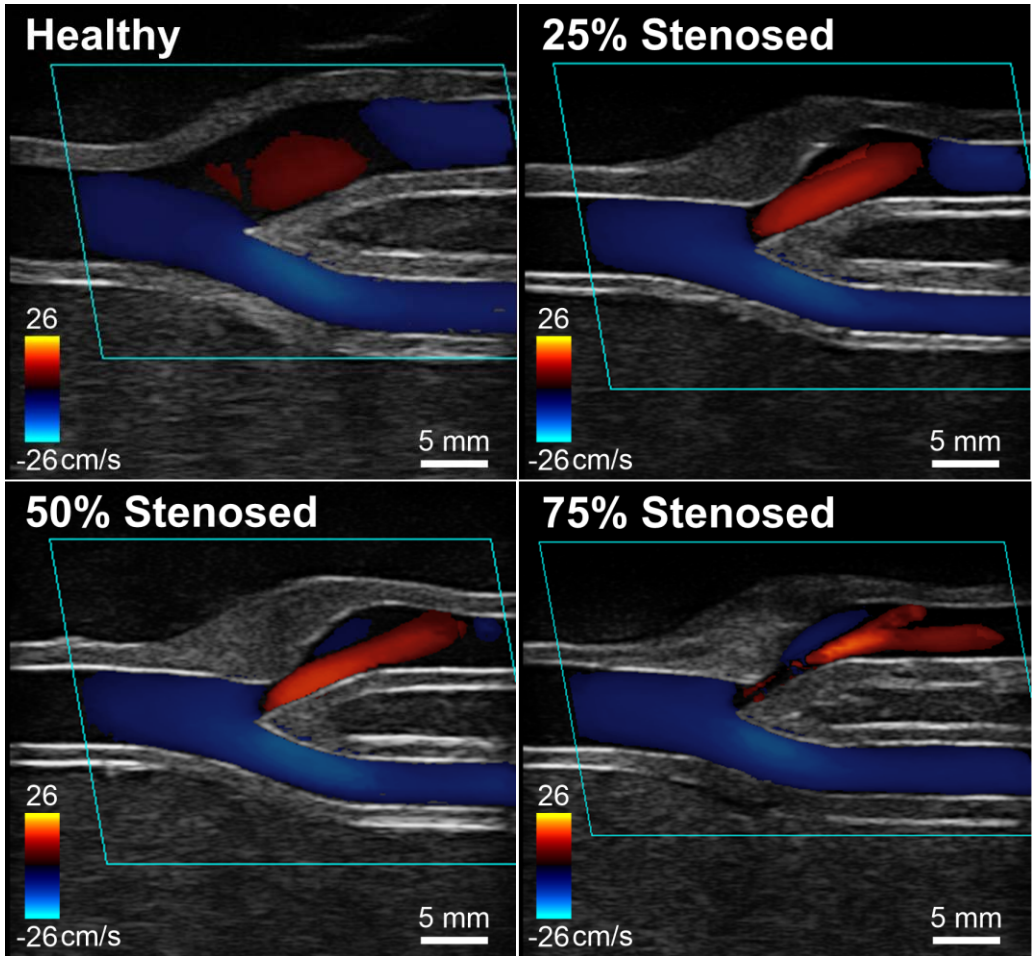




50% Stenosed

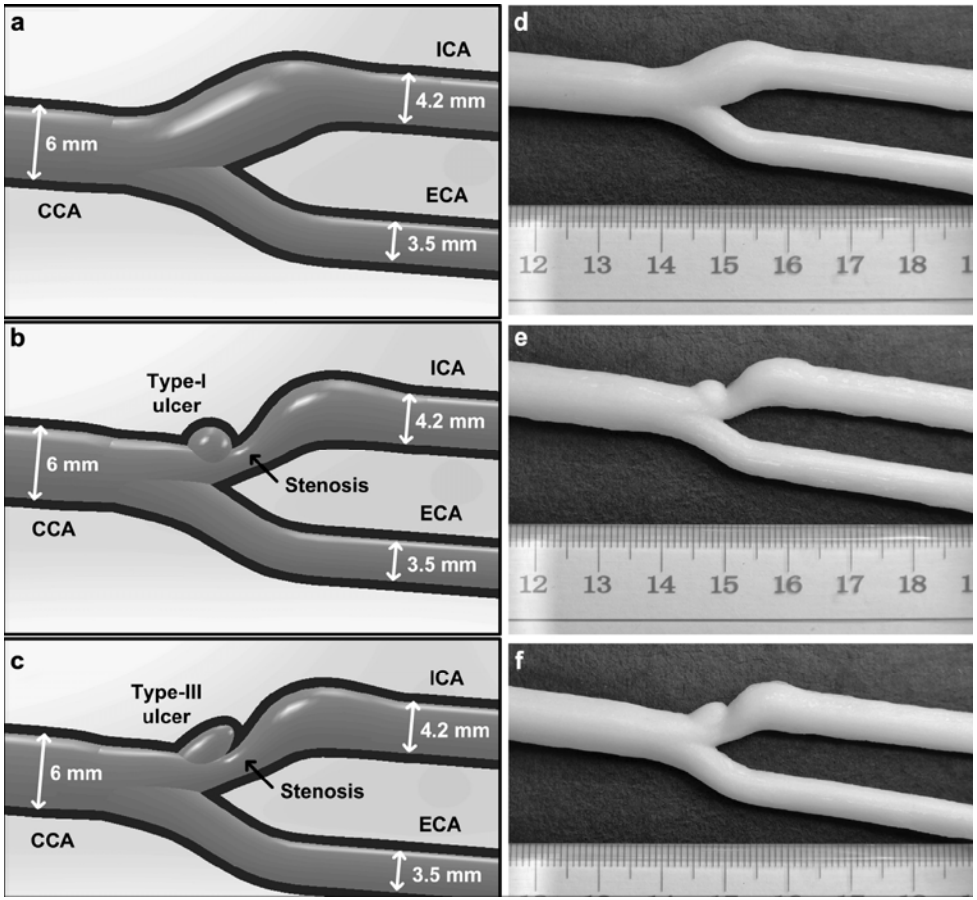
$$(1 - \frac{\text{Narrowest ICA Diameter}}{\text{ICA Distal Diameter}}) \times 100\%$$

Demo: Flow images for phantoms of different stenosis



Chee et al., *IEEE T-UFFC*, 63(11), 1852-1864, 2016

Alternative Fabrication Approach: Direct Rapid Prototyping



Lai et al., *UMB*, 39(9), 1654-1664, 2013.

Useful for beginners if budget permits

- ↳ Prerequisite: Needs access to a stereolithography machine capable of making physical builds with compliant photopolymers

Limitation: Photopolymer material has poor acoustic properties

- ↳ Rubber-like properties ➔ Strong attenuation

Another issue: Elasticity cannot be tuned

Final Words

Summary: Recap of Concepts

Wall-less flow phantoms: Useful for flow experiments

- ↳ Different geometries besides simple straight-tube model are available: e.g. spiral, carotid, aneurysm
- ↳ Phantoms with anatomically realistic vascular geometries are useful for demos and efficacy testing

Pump, BMF, tissue slab: Other major parts of flow phantom

- ↳ Different design considerations should be taken into account when fabricating them

Walled flow phantoms: Needed for wall dynamics studies

- ↳ Segmented models with tunable stiffness are available
- ↳ Designs can be easily extended to carotid bifurcation geometries

Related Readings

Description of wall-less phantom fabrication

Straight-tube model: IEEE T-UFFC, 64(1), 53-65, 2017.

Spiral flow phantom: IEEE T-UFFC, 64(12), 1840-1848, 2017.

Carotid bifurcation phantom: UMB, 39(6), 1015-1025, 2013.

Aneurysm phantom: IEEE T-UFFC, 64(1), 25-38, 2017.

Walled phantom fabrication

Multi-segment straight-tube phantom: UMB, 44(4), 872-883, 2018.

Carotid models with photopolymer-based wall: UMB, 39(9), 1654-1664, 2013.

Carotid models with PVA-based wall: IEEE T-UFFC, 63(11), 1852-1864, 2016.

Other phantom design specifics

Flow pump and blood mimicking fluid fabrication: IEEE T-UFFC, 64(1), 25-38, 2017.