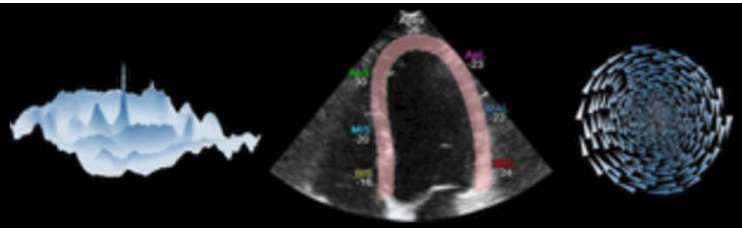
UFFC2019 US school

Ultrasound motion imaging & Experimentations



Day 3 – Part 2

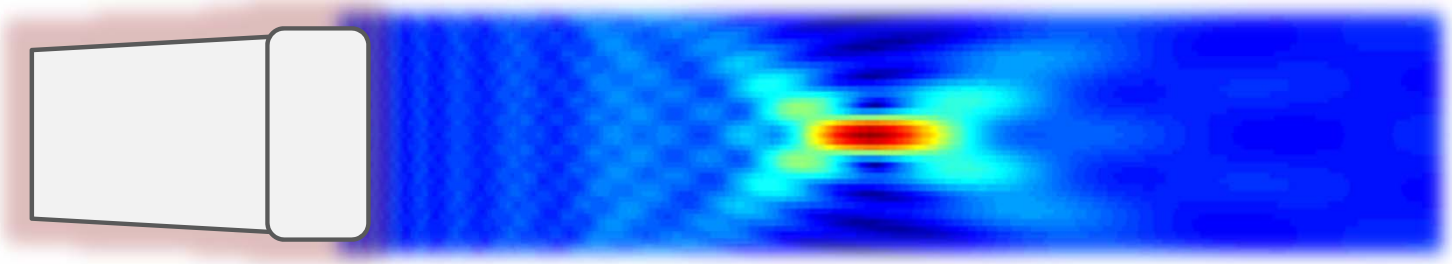
Ultrasound Flow Imaging Innovations

Alfred C. H. Yu, PhD

Professor, University of Waterloo

LITMUS

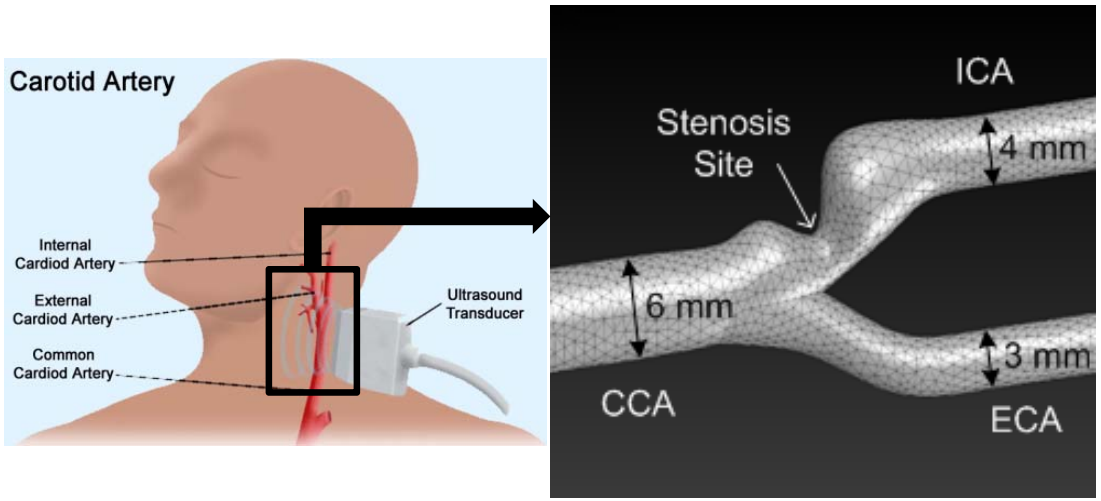
LABORATORY ON INNOVATIVE TECH IN MEDICAL ULTRASOUND



Current Doppler Ultrasound Technology: Is There Enough Time Resolution?

Example

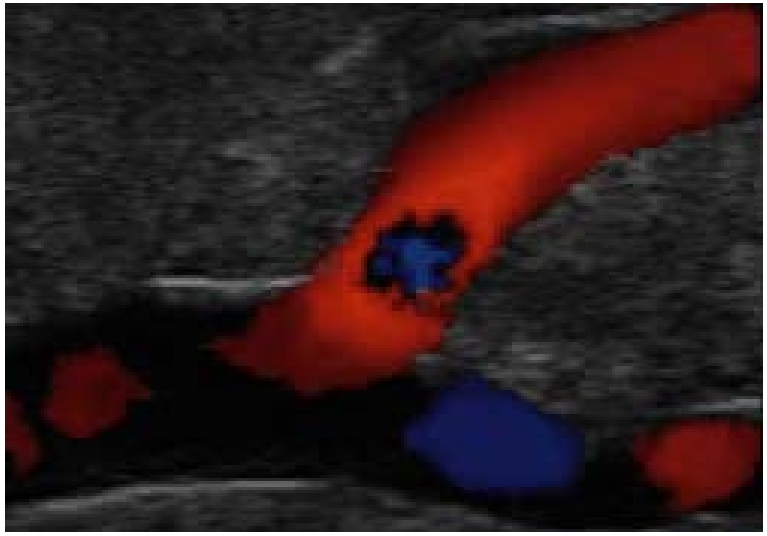
Carotid Bifurcation Model



Color Flow Cineloop

Freq.: 6.6 MHz PRF: 2 kHz

Frame rate: 17 fps (SonixTouch)



Frame rate: Inadequate to resolve pulse-cycle details

Another issue: Bicolor rendering cannot show flow trajectories

High-Frame-Rate Imaging is Critical!

Time resolution: Most important design consideration

Govern whether a dynamic event can be tracked

Real-world example: Wave propagation in two coils

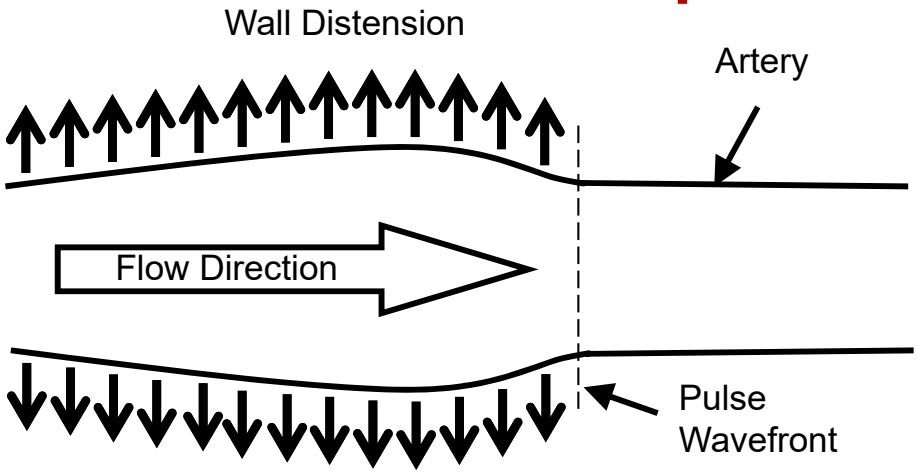


240 fps camera rate **24 fps playback rate**

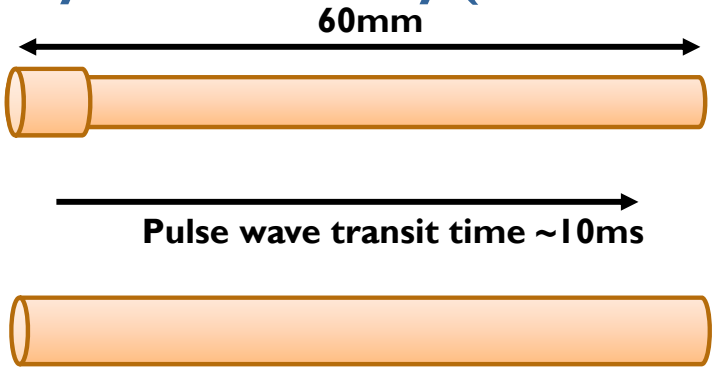
High frame rate beyond video display range is critical to observe dynamical details

Another Example: Tracking Pulse Wave Propagation on Arterial Wall

Transit time of arterial pulse wave is in the order of milliseconds

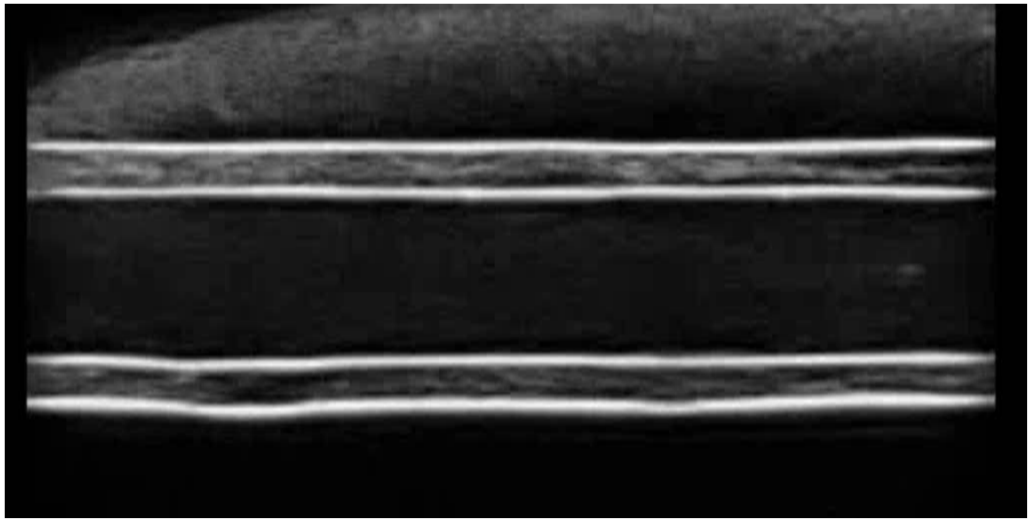


Healthy carotid artery (PWV > 5m/s)



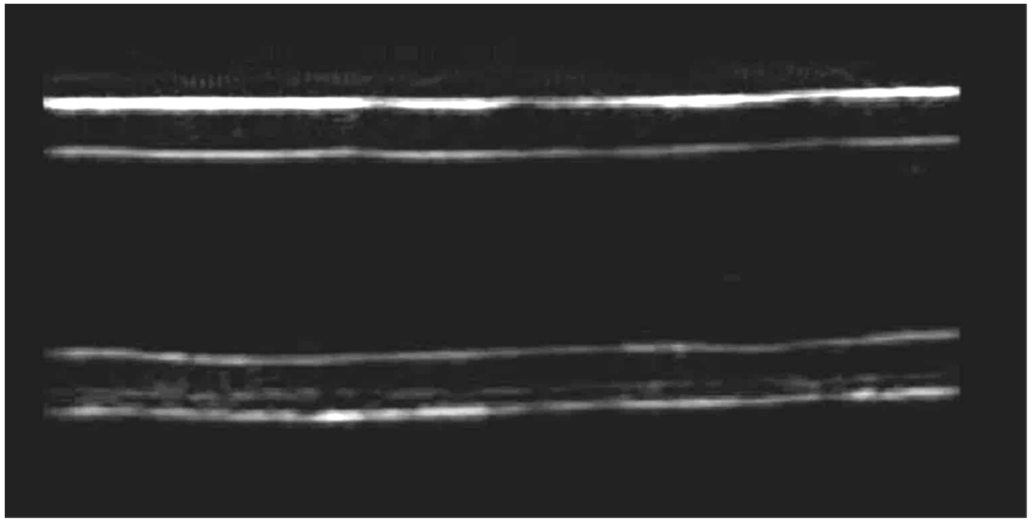
Conventional B-Mode Imaging

25 fps imaging rate **6.25 fps playback rate**



High-Frame-Rate Ultrasound

5000 fps imaging rate **60 fps playback rate**

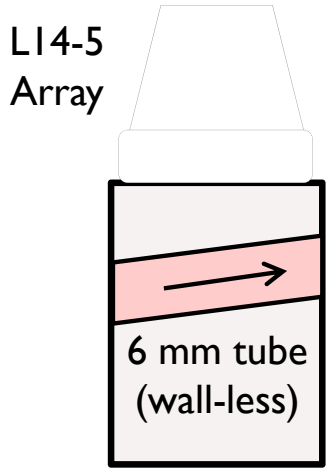


A First Attempt at Achieving Intuitive Flow Visualization: Color Encoded Speckle Imaging

High-frame-rate duplex rendering of flow dynamics

Flow trajectory: Depicted by flow speckle motion

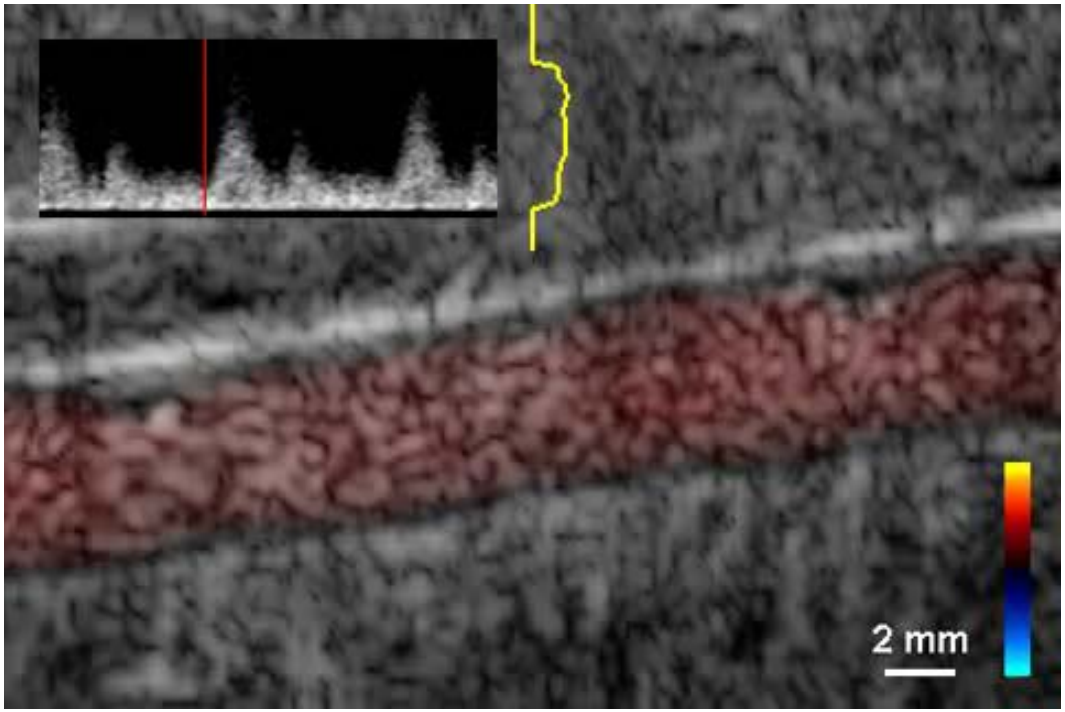
Flow speed: Highlighted by Doppler-based velocity color codes



Doppler angle: 75°

***Max velocity*: 35 cm/s**

***Profile*: Carotid Pulse**



"Color encoded flow speckle imaging" *Ultrasound Med. Biol.*, June 2013

DAQ Parameters

U/S Freq: 7 MHz

Firing method:
Plane wave compounding

compound angles: 5
(-10°, -5°, 0°, +5°, +10°)

DAQ frame rate:
2,000 fps

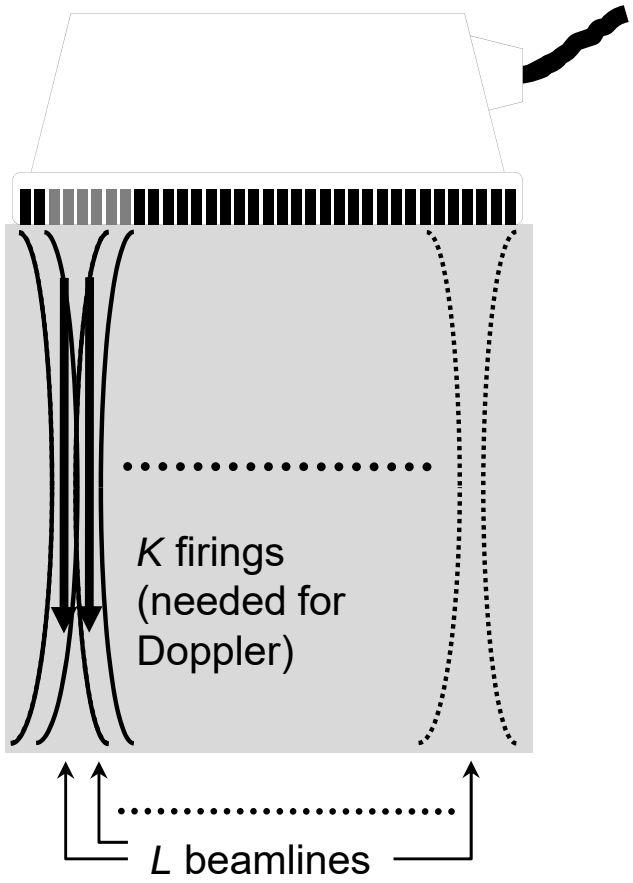
Playback @ 60 fps

High-Frame-Rate Flow Imaging: How?

Strategy: Reduce num. firings needed for each image frame

Conventional Approach

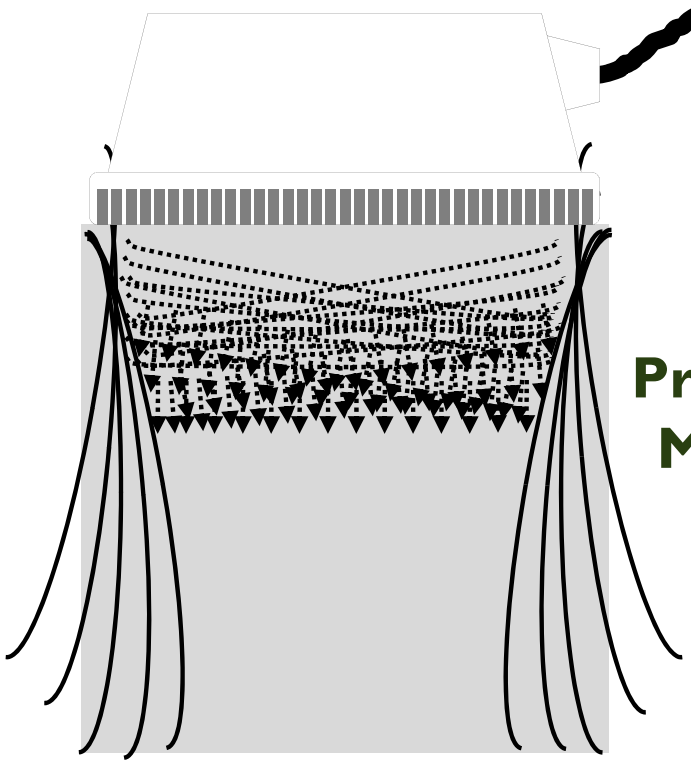
Line-Based Pulse-Echo Imaging



K×L firings per frame

Broad-View Imaging: Potential Solution

e.g. Plane Wave Compounding



Preferred Method

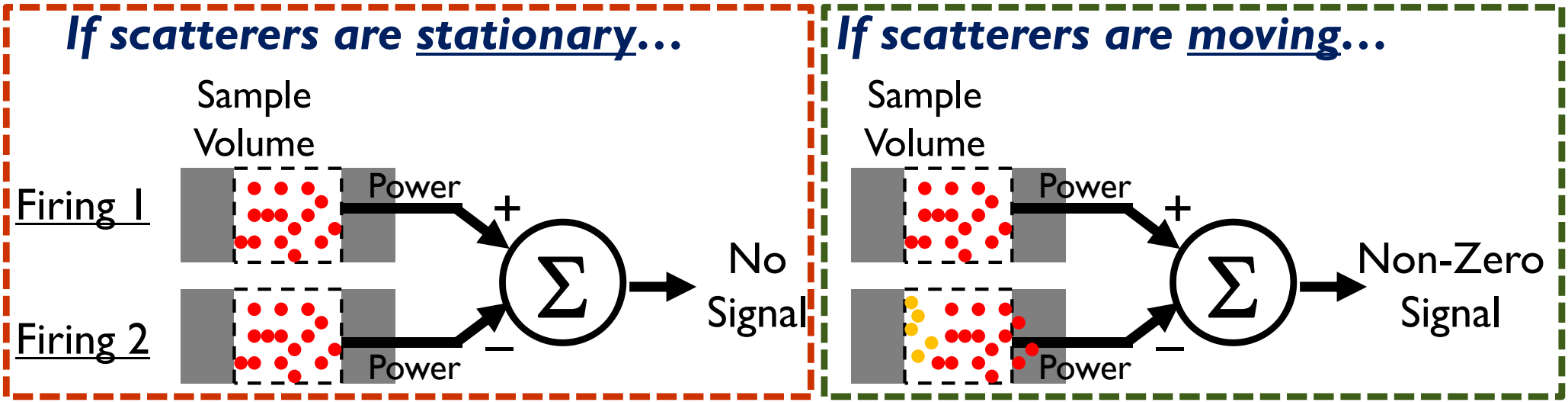
Frame rate = PRF / N_{angle}

** >1,000 fps readily achievable **

Visualizing Flow Trajectories: How?

Strategy: Extract blood speckles from acquired signal

Leverage on blood signal decorrelation at same position between firings

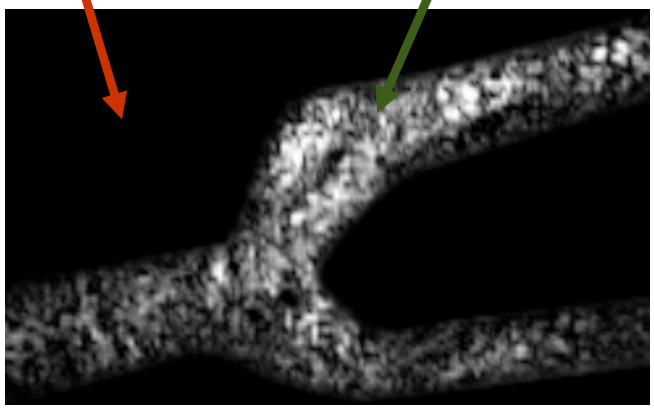


Example

Carotid bifurcation

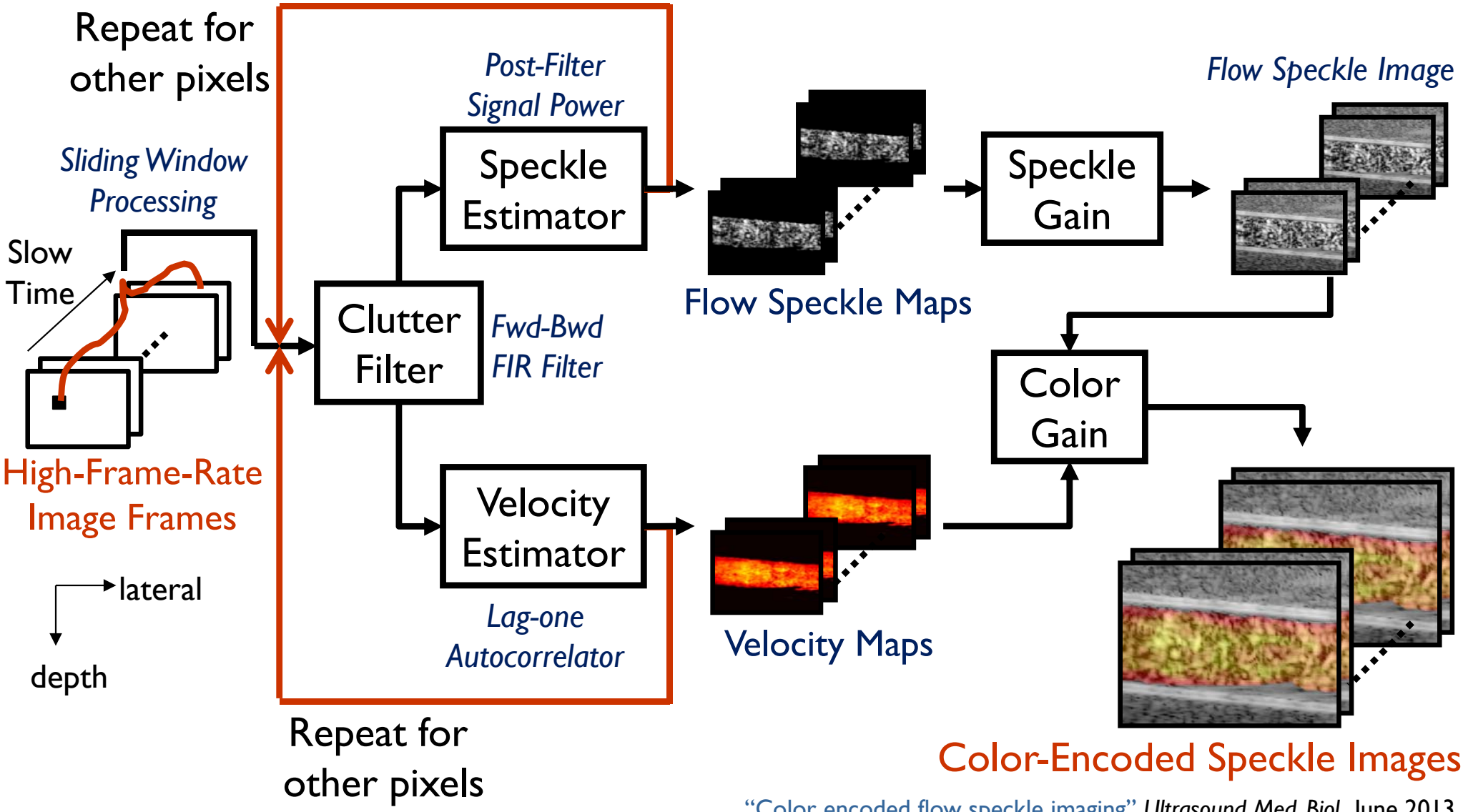
Tissue (Dark)

Blood (Bright)



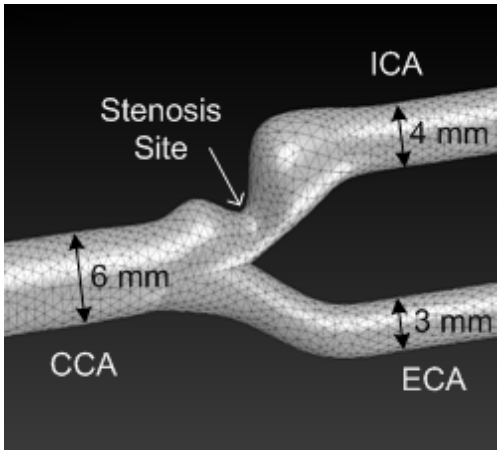
CESI: General Signal Processing Chain

Approach: Perform flow processing at every pixel position



"Color encoded flow speckle imaging" *Ultrasound Med. Biol.*, June 2013

Carotid Bifurcation Imaging: An Example of CESI in Action

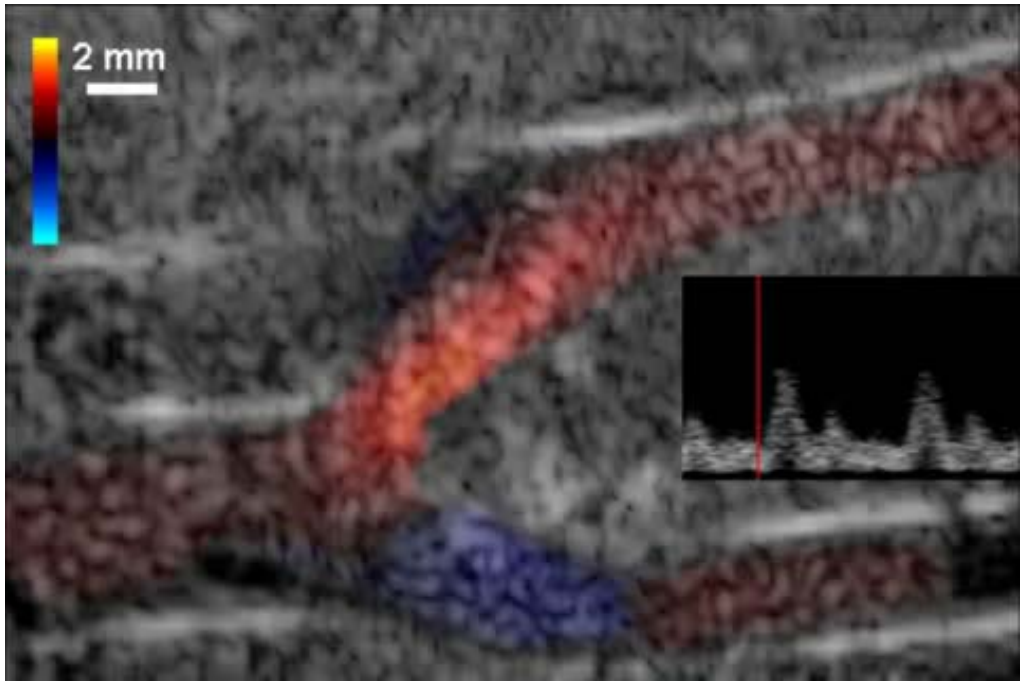


Profile: Carotid Pulse (72 bpm)

Systolic flow rate: 5 mL/s

Peak Reynolds number: 1074

* *Note: Laminar flow condition* *



DAQ Parameters

U/S Freq: 7 MHz

Firing method: Plane wave compounding

compound angles: 5 (-10°, -5°, 0°, +5°, +10°)

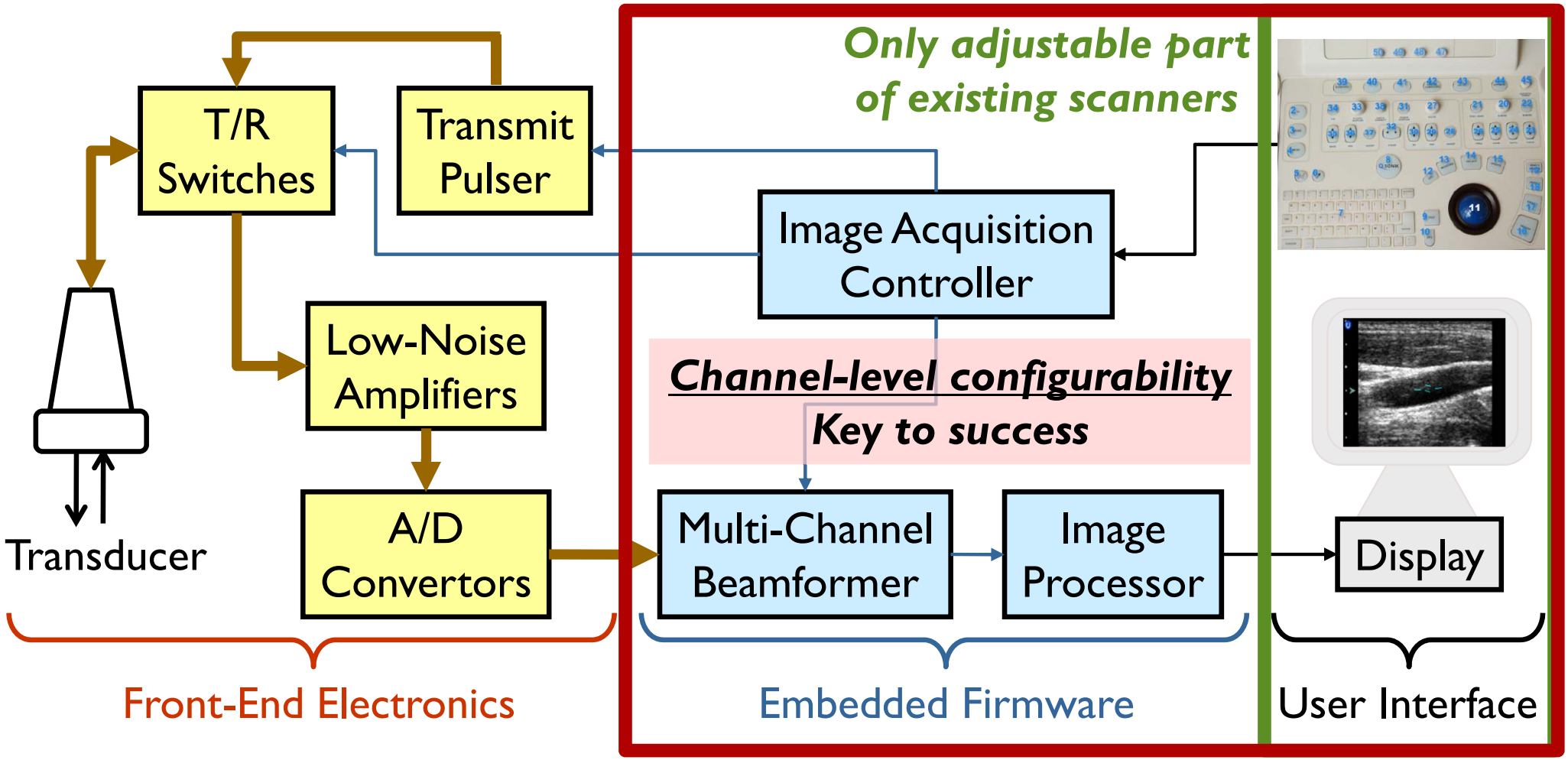
Effective frame rate: 2,000 fps

Playback at 60 fps

Key features visualized: ***Jet and Recirculation***

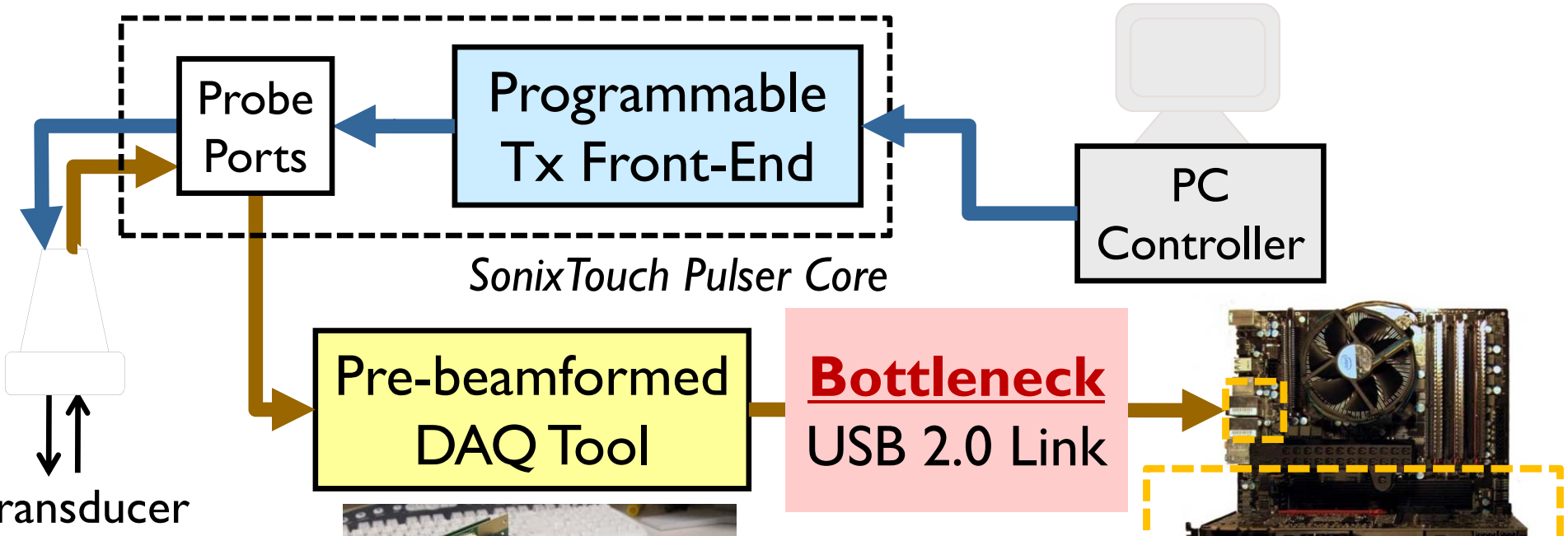
Flow speckles and color encoding: Complementary role in providing coherent flow visualization

Hardware Realization of CESI: Our Venture into the Channel Domain



First Version of Channel-Domain Imaging Platform: Overview and Limitations

Programmable platform: Controlled Tx/Rx of every channel



Memory Buffer:
Enough for 10000+ firings (for ~10 cm imaging depth)



"Pre-Beamformed DAQ Tool"
IEEE Trans. UFFC, Feb 2012

"GPU Beamformer"
IEEE Trans. UFFC, Aug 2011

Requirements for Live Data Streaming: Beamline Doppler Imaging vs. CESI

Example scenario: Flow imaging at 5cm depth

Conventional Doppler

# sample per channel:	3072
# Channel:	1
(only streaming beamformed data)	
Byte per Sample:	2
Data size per firing:	6kB
PRF:	3.3kHz
Transfer rate needed:	20MB/s

Can be handled by a USB 2.0 link

Live CESI

# sample per channel:	3072
# Channel:	128
Byte per Sample:	2
Data size per firing:	768kB
PRF:	3.3kHz
Transfer rate needed:	2.5GB/s

~~USB 2.0: 20MB/s~~

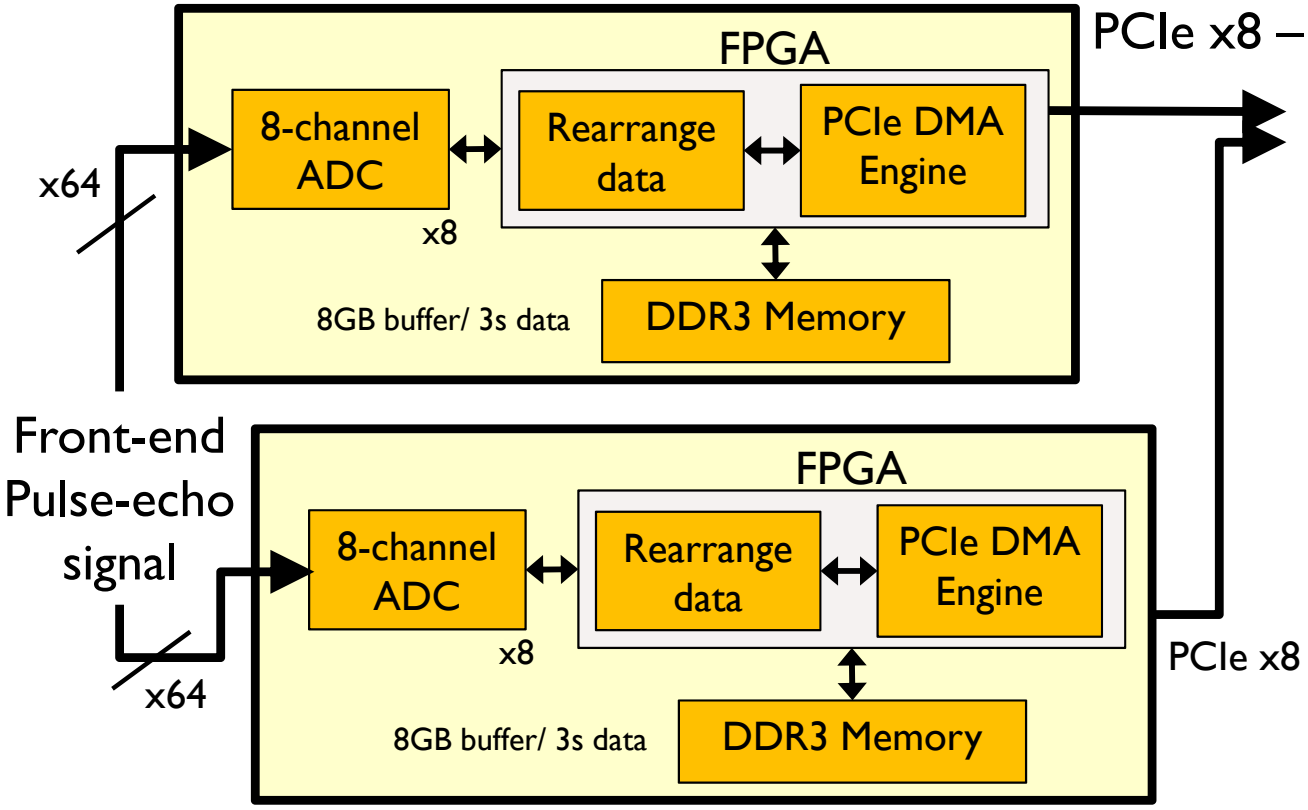
~~USB 3.0: 400MB/s~~

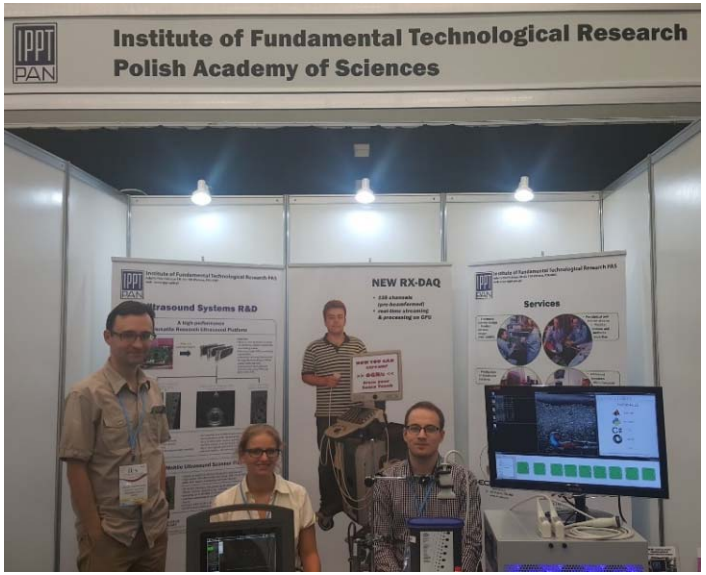
More feasible streaming solution: PCIe 2.0 x16 (6.4 GB/s)

RX-DAQ: A Modularized Design for Live Streaming of Channel-Domain Data

Key feature: Two PCIe x8 links (each for 64-channel live streaming)

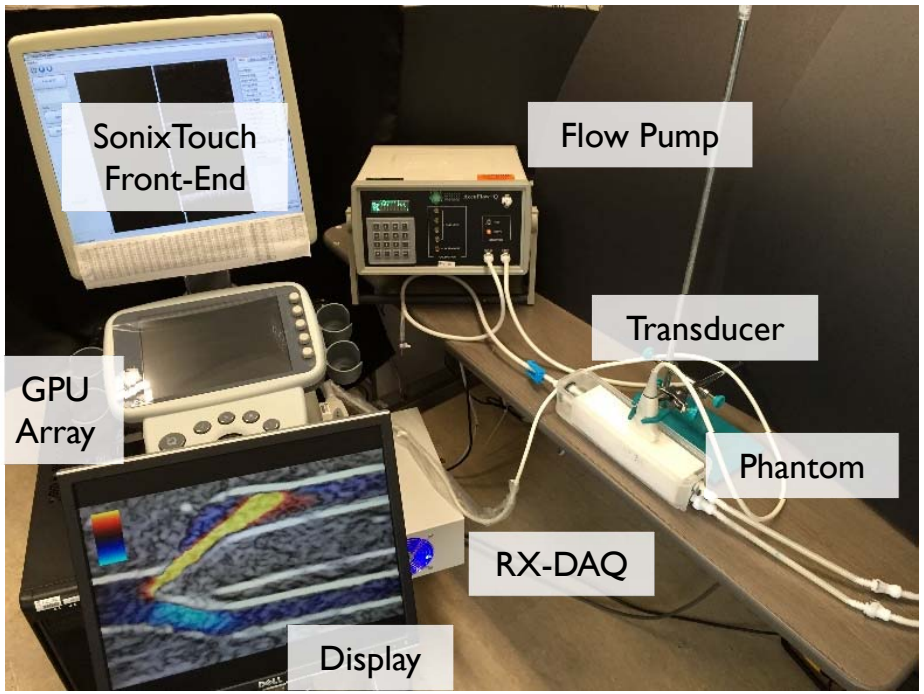
Developed by Polish Academy of Sciences





Walczak et al. *IEEE Ultrasonics Symposium*, Sept 2014

Second Version of Color Encoded Speckle Imaging Platform: General Overview



128-Channel Composite Imaging Platform

Multi-Channel Pulser

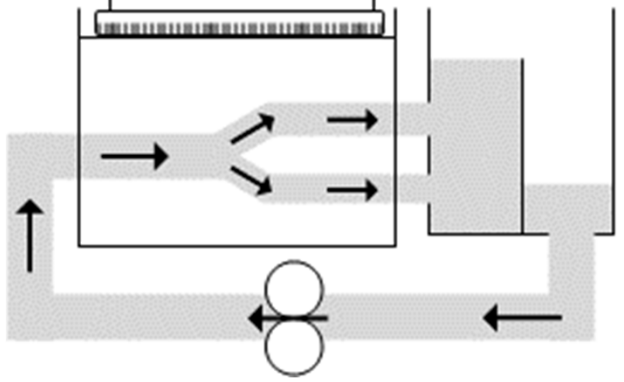
SonixTouch Front-End

Channel Data Acquisition Boards

RX-DAQ (IPPT Invention)

PCI-Express x16 Data Link >6GB/s

Array Transducer



Pulsatile Flow Circuit

Six-GPU Array

GTX-590 Dual-GPU Cards (x3)

Total cores: 3,072



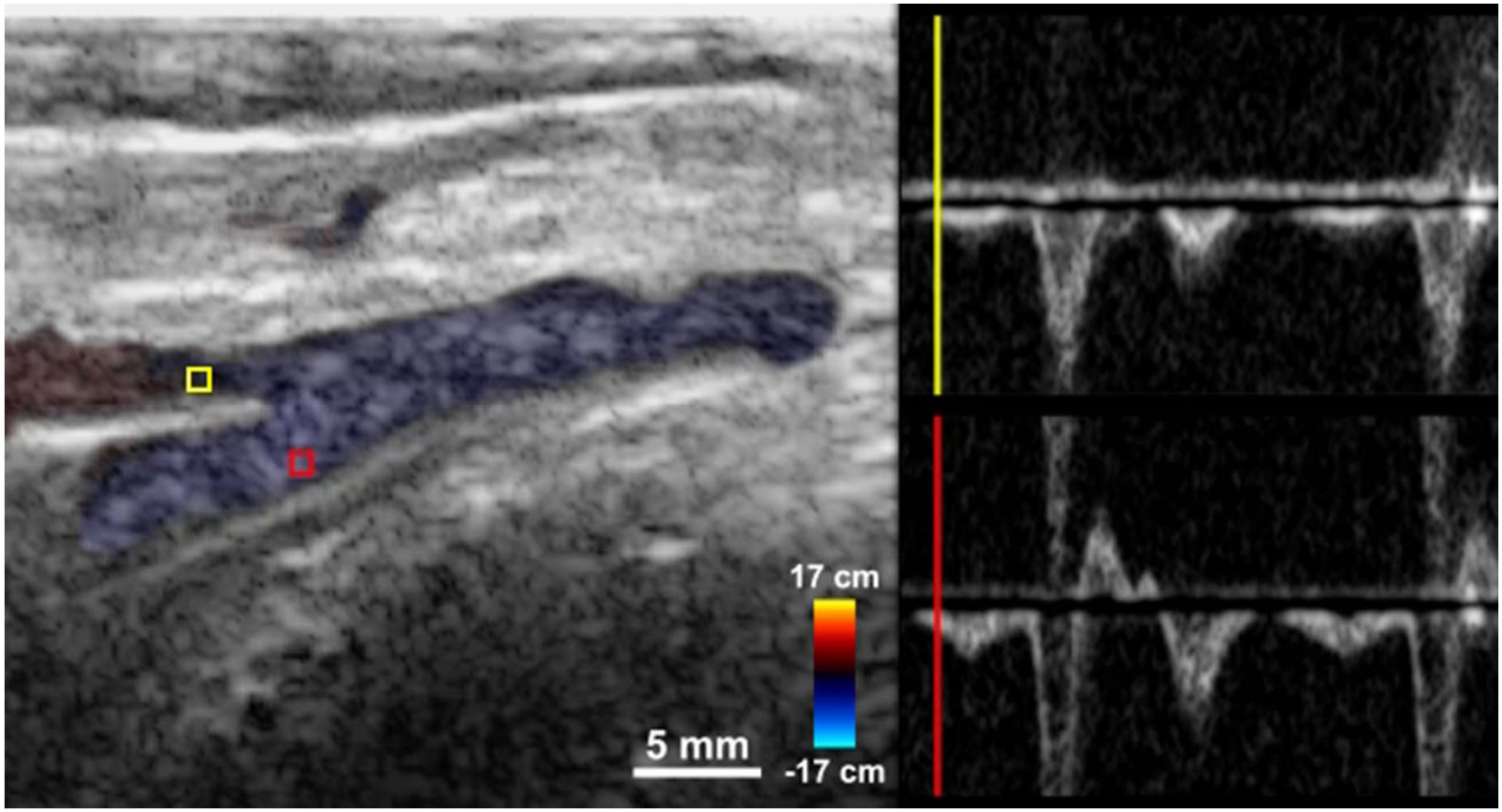
GPU Beamforming → CESI Processing → Display

GPU Processing Array

Case Example: Brachial Bifurcation with Backward Flow

Key feature: High temporal resolution to capture dynamic event

Nominal frame rate: 2000 fps Playback Frame Rate: 50 fps



"Live CESI Platform" *IEEE Trans. UFFC*, Apr 2019

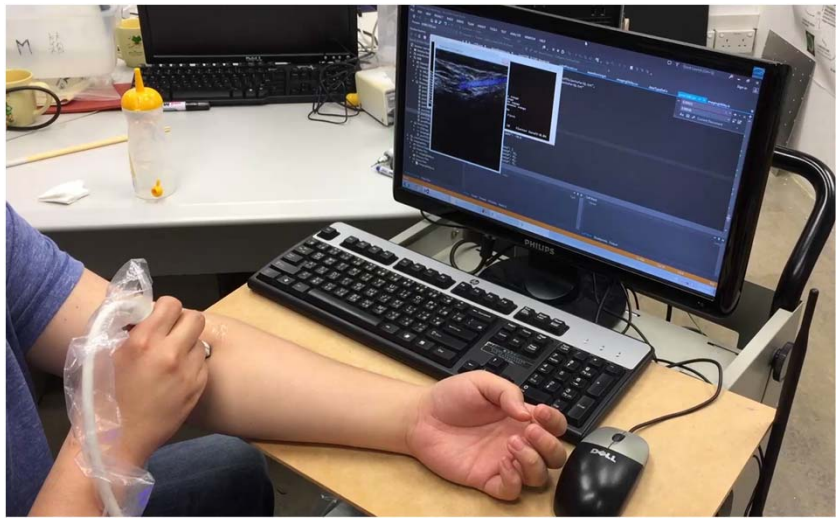
Key event: Dynamics of backward flow during end of systole

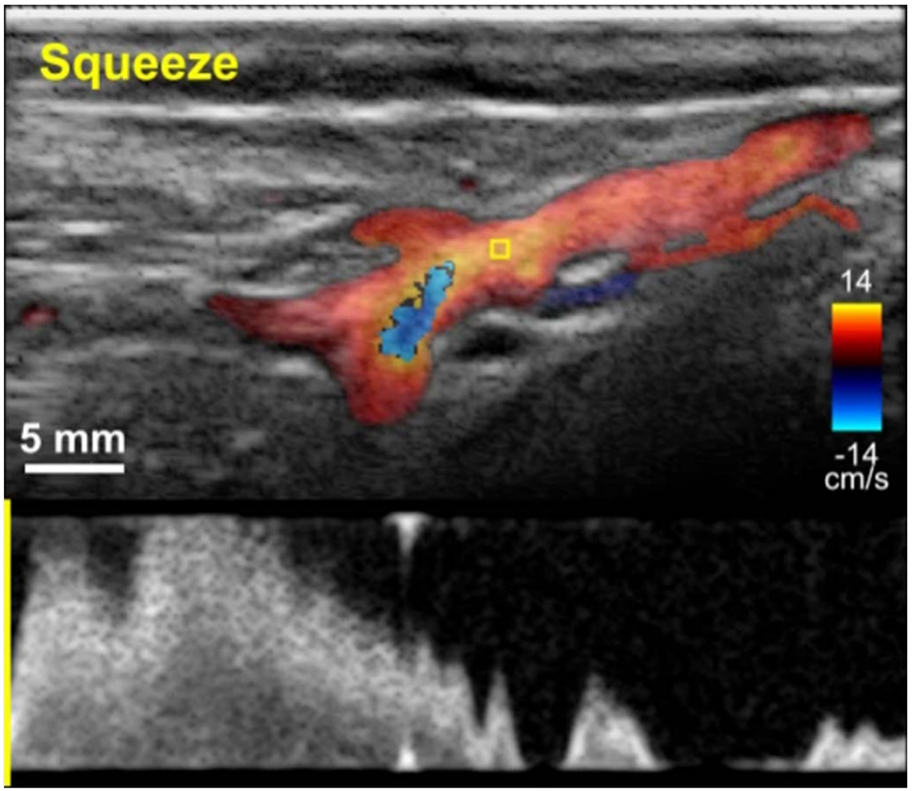
Case Example 2: Acceleration and Deceleration of Blood Flow in Brachial Vein

Key feature: Large data buffer to capture dynamic event

Nominal frame rate: 2000 fps
Playback Frame Rate: 50 fps

"Live CESI Platform" *IEEE Trans. UFFC*, Apr 2019





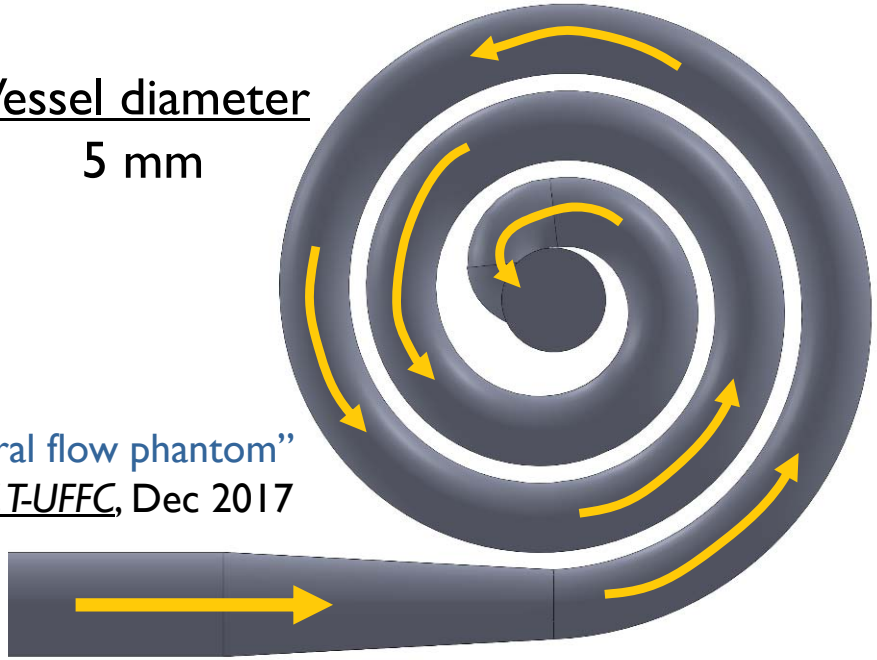
Key event:

1. Increase in venous blood flow due to muscle contraction
2. Reduced blood flow right after muscle relaxation

Doppler Color Coding: Always Intuitive?

Caveat: Red/blue colors assigned based on axial flow direction

***Example:* Archimeadean Spiraling Flow Model**

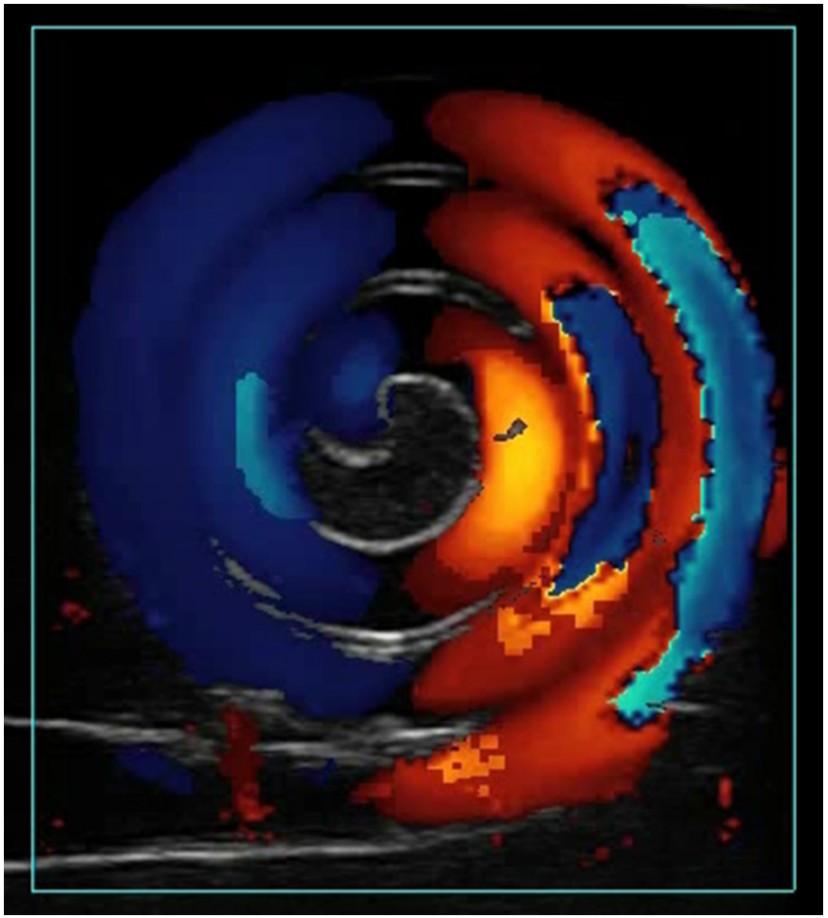


Vessel diameter
5 mm

"Spiral flow phantom"
IEEE T-UFFC, Dec 2017

Peak inflow rate: 7 ml/s
Pulse rate: 60 bpm

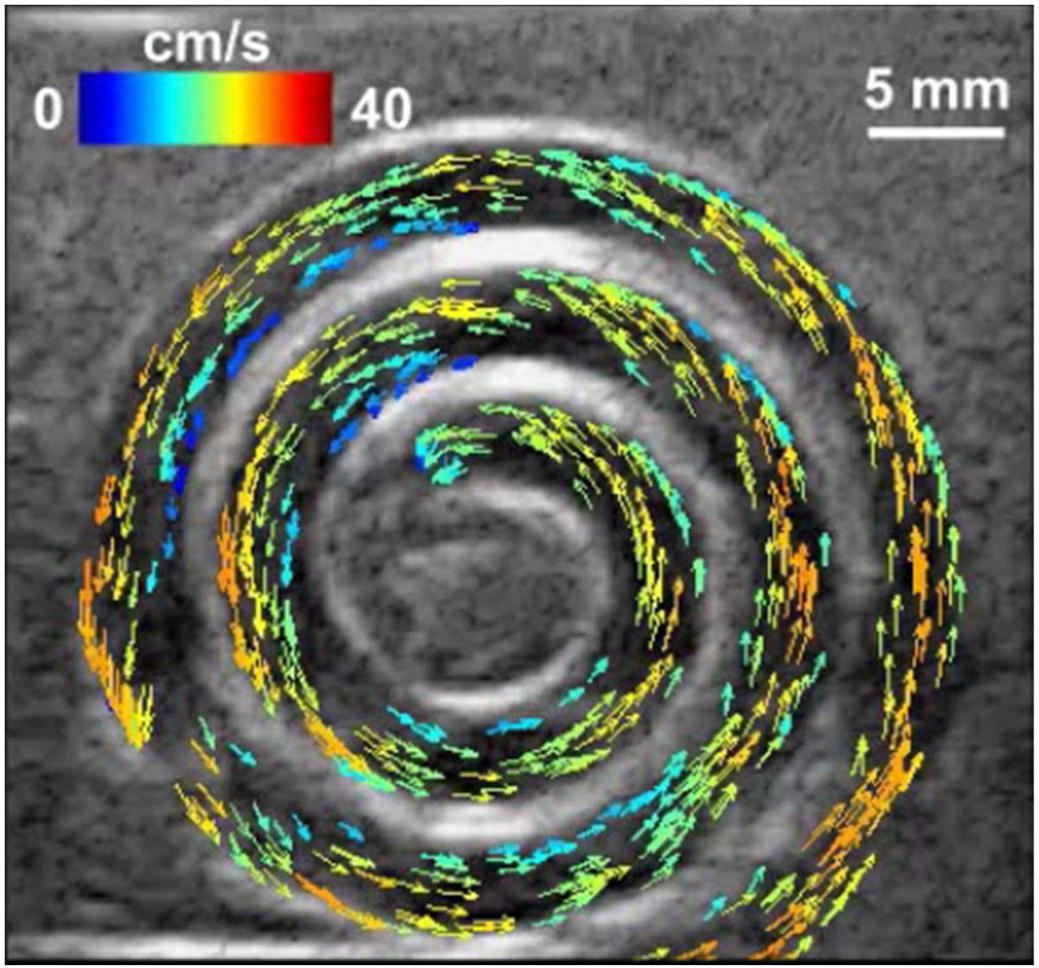
Color Flow Imaging Cineloop (SonixTouch)
Frequency: 5 MHz PRF: 2.5 kHz Frame rate: 12 fps



Spurious colors: Ascribed to tortuous vessel orientation

Overview of Our Imaging Innovation: Vector Projectile Imaging

"Spiral flow phantom" *IEEE Trans. UFFC*, Dec 2017



DAQ rate
3,333 fps

Playback
50 fps

High-frame-rate visualization of multi-directional flow

Projectile motion

Depicts both flow speed and direction

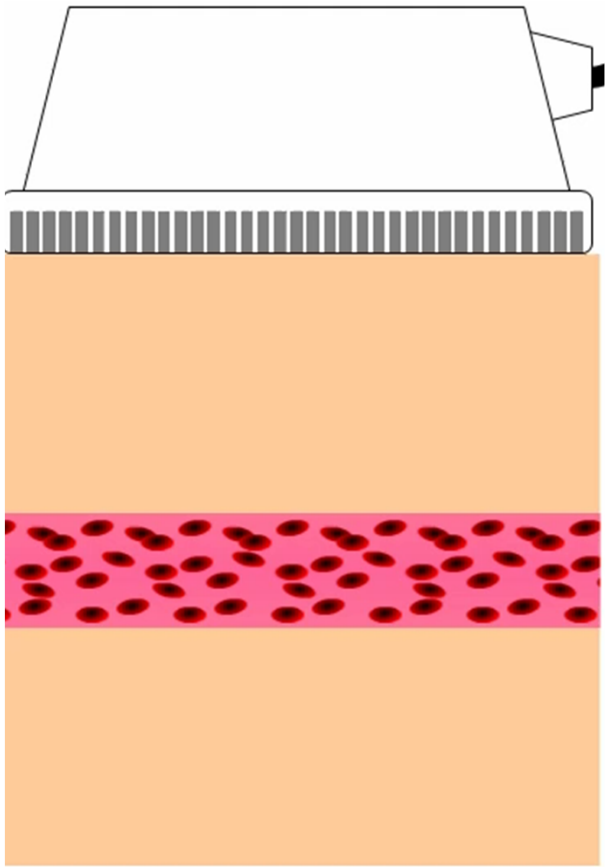
Vector length and color

Further highlights flow speed

High Frame Rate Flow Vector Derivation: Overview of Technical Principles

General approach: Multi-angle vector Doppler

Simplest case: Doppler sensing at two different steering angles



Angle 1: $f_{D1} = \frac{2f_o}{c_o}|v|\cos(\theta_1 - \alpha)$

Angle 2: $f_{D2} = \frac{2f_o}{c_o}|v|\cos(\theta_2 - \alpha)$

$$\cos(A - B) = \cos A \cos B + \sin A \sin B$$

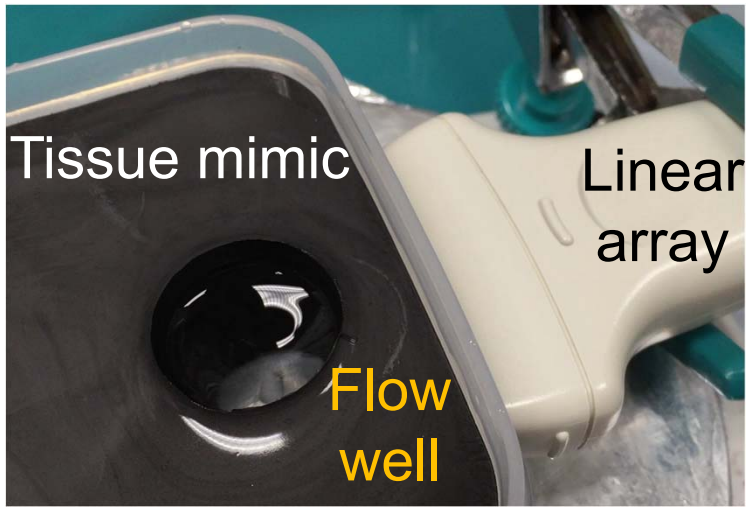
$$f_{D2} = \frac{2f_o}{c_o}(|v|\cos\alpha\cos\theta_2 + |v|\sin\alpha\sin\theta_2)$$

$v_x = |v|\cos\alpha$ — Lateral speed

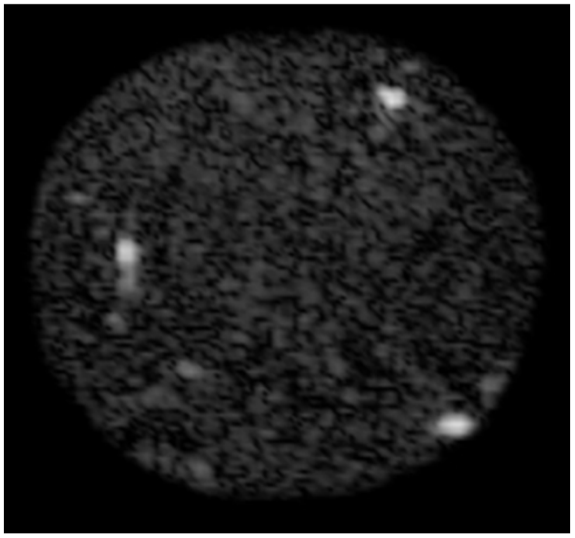
$v_z = |v|\sin\alpha$ — Axial speed

Pitfalls of Cross-Beam Vector Doppler: Case Analysis on Vortical Flow

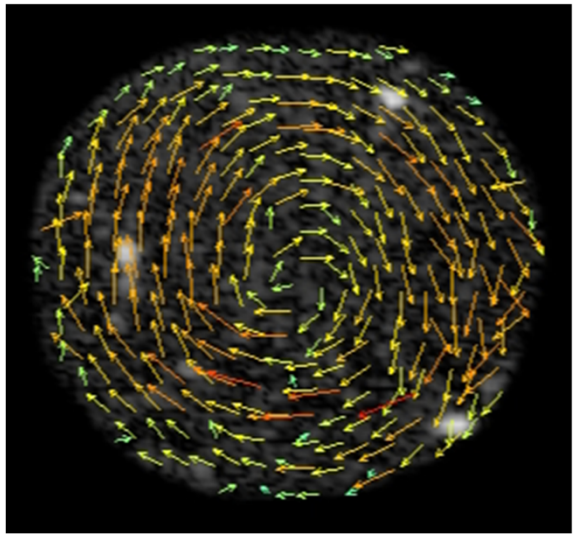
Experimental Scenario



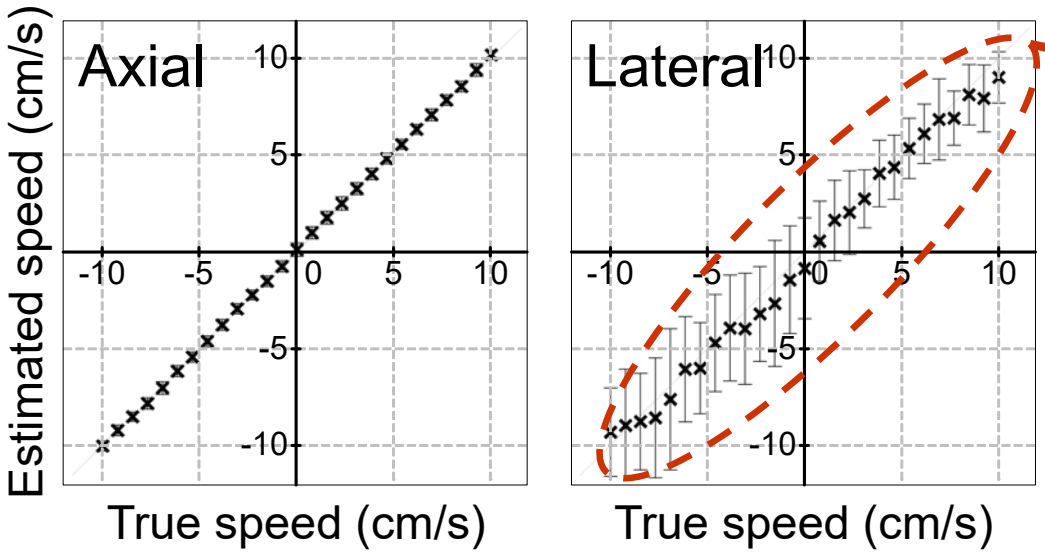
B-flow



X-Beam Vector Dopp.



Estimation error analysis



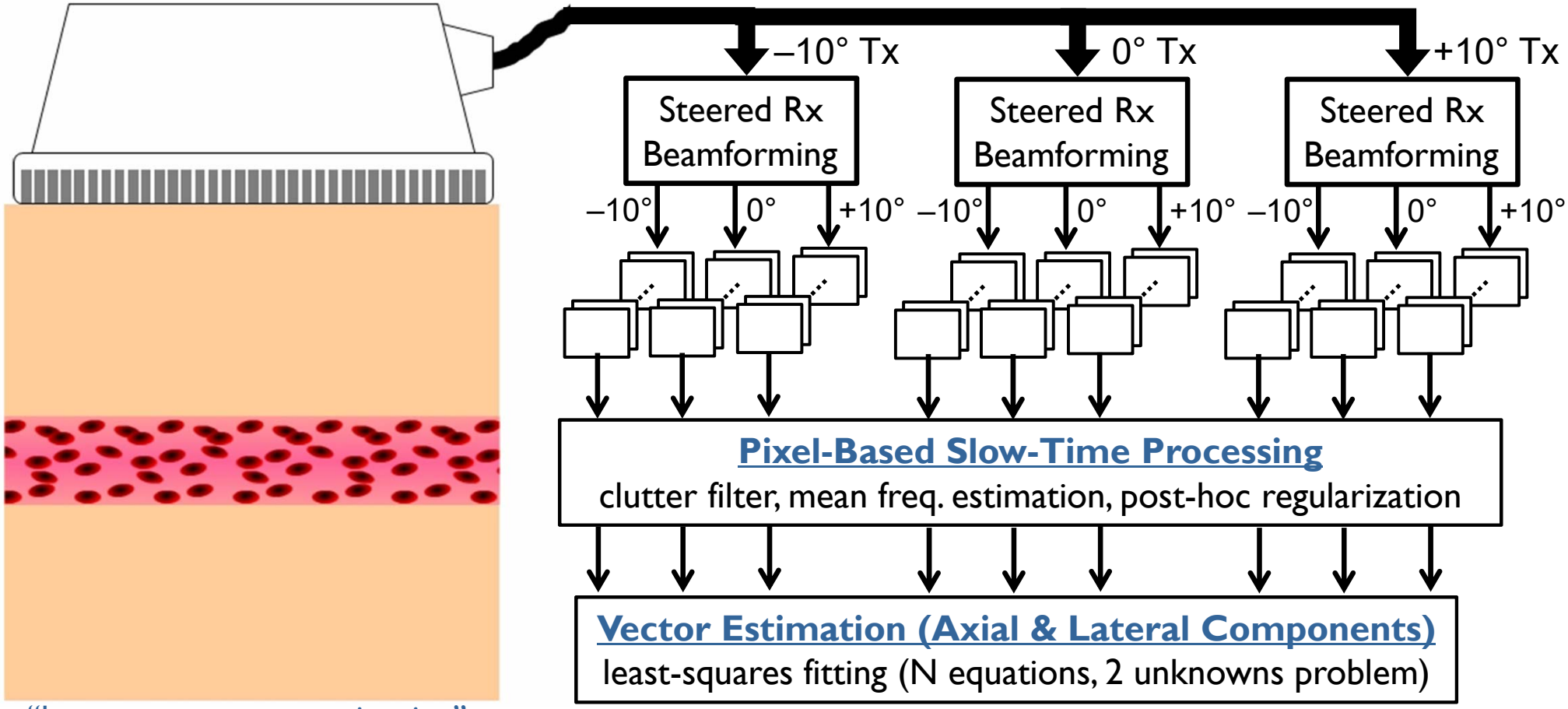
Key problem

High variance in lateral direction

Towards Robust Flow Vectorgraphy: Multi-Angle Least-Squares Vector Doppler

Solution: Perform multi-angle imaging on both Tx and Rx

Convert vector Doppler to an N-equations, two-unknowns problem



"Least-squares vector estimation"
IEEE Trans. UFFC, Nov. 2016

Our Least-Squares Flow Vector Estimator: Mathematical Overview

Matrix form of multi-angle Doppler equation set for *M*-Tx, *N*-Rx angles

$$\begin{bmatrix} f_{11} \\ \vdots \\ f_{MN} \end{bmatrix} = \frac{f_o}{c_o} \begin{bmatrix} \cos\theta_{T1} + \cos\theta_{R1} & \sin\theta_{T1} + \sin\theta_{R1} \\ \vdots & \vdots \\ \cos\theta_{T,M} + \cos\theta_{R,N} & \sin\theta_{T,M} + \sin\theta_{R,N} \end{bmatrix} \begin{bmatrix} v_x \\ v_z \end{bmatrix}$$

Measurand vector **u** | Angle matrix **A** | Flow vector **v**

$$\mathbf{u} = \mathbf{A}\,\mathbf{v}$$

Pseudoinverse operation

$$\mathbf{v} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\,\mathbf{u}$$

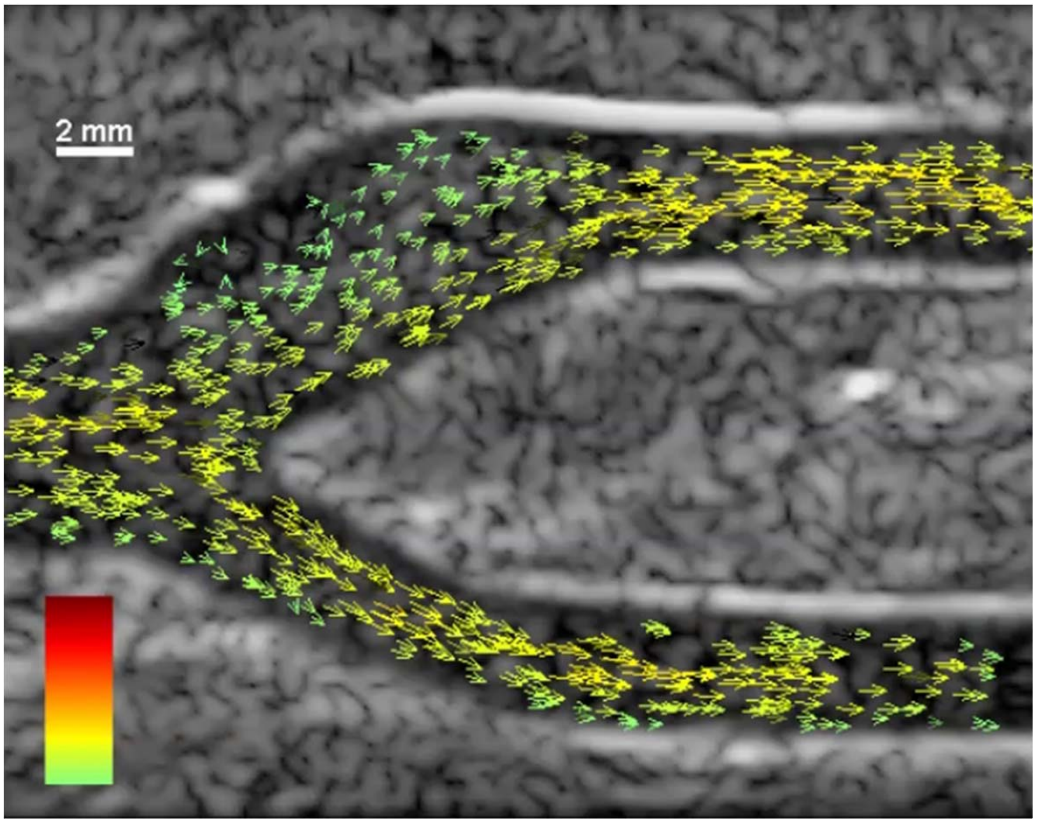
Key property

Flow vector **v** is a solution with minimum mean-squared error

Our New Dynamic Rendering Technique: VPI – Vector Projectile Imaging

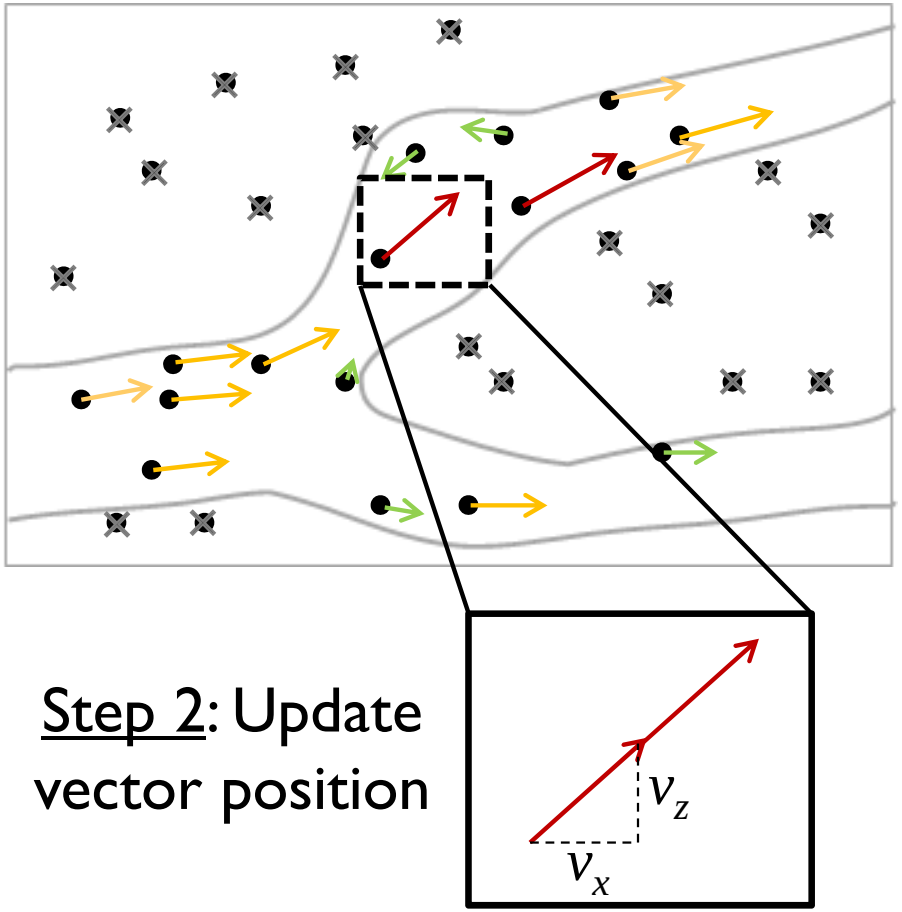
General algorithm: Dynamic update of inter-frame vector position

Scenario: Healthy carotid bifurcation



"Vector projectile imaging of complex flow patterns"
Ultrasound Med. Biol., Sept 2014

Step 1: Define launch points

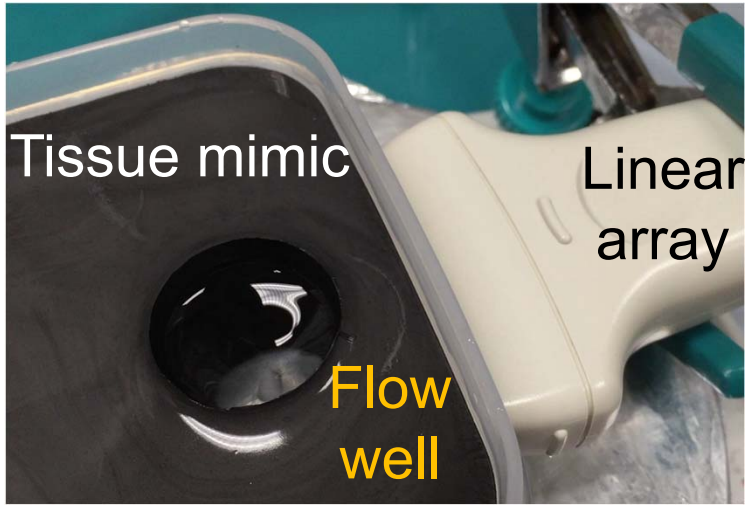


Step 2: Update vector position

Importance of Robust Flow Estimator for Consistent Dynamic Vector Rendering

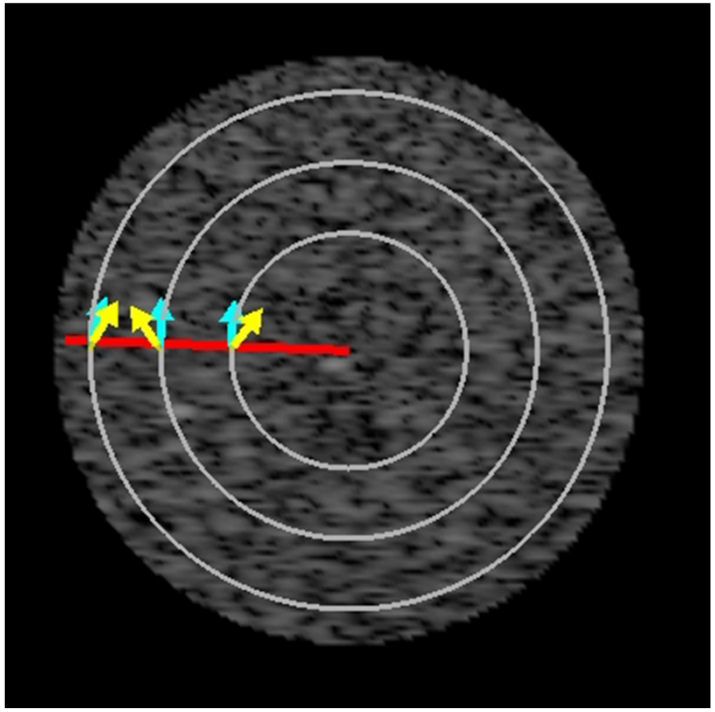
Case demonstration on vortical flow model

Experimental scenario



Cross-beam vector Doppler →
5-Tx, 5-Rx least squares →

Projectile traces (over 3 circular tracks)



DAQ rate: 10 kHz

Playback rate: 25 fps

Projectiles stay on expected flow path only if flow vectors are estimated consistently

VPI can Achieve Time-Resolved Rendering of Complex Flow in Stenosed Vessels

Scenario: Carotid bifurcation with 50% eccentric stenosis

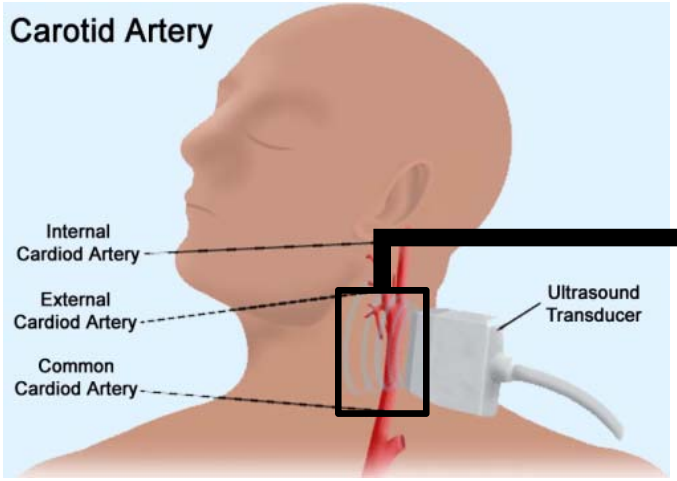
Imaging configuration: 3 Tx (–10°, 0°, +10°), 3 Rx (–10°, 0°, +10°)

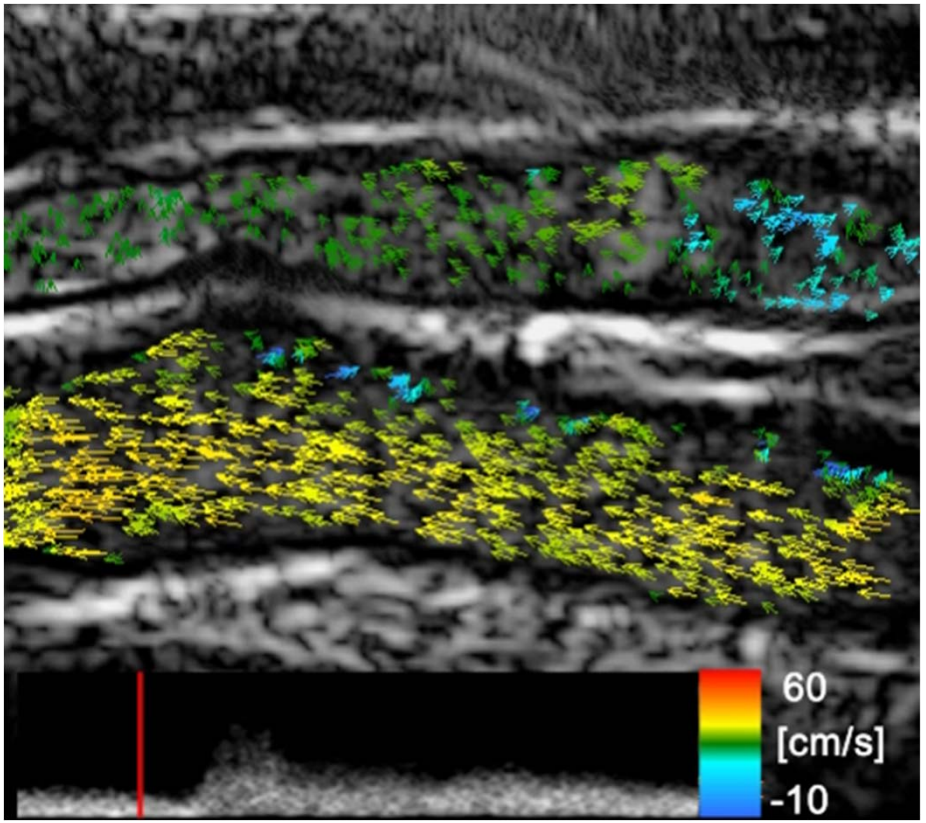


DAQ rate: 10 kHz **VPI frame rate**: 416 fps (60 fps playback)

Key event visualized: Spatiotemporal dynamics of flow jet and two recirculation zones

Pilot Trial In-Vivo: Parallel Imaging of Carotid Artery and Jugular Vein





Nominal imaging rate: 1666 fps

Playback at 50 fps

Differences in arterial and venous flow speeds & directions can be consistently visualized

Latest Endeavors: Translation of VPI Towards Vascular Diagnostics

Plan: Creating a new diagnostic mode on clinical scanners

A collaborative effort with the ultrasound industry



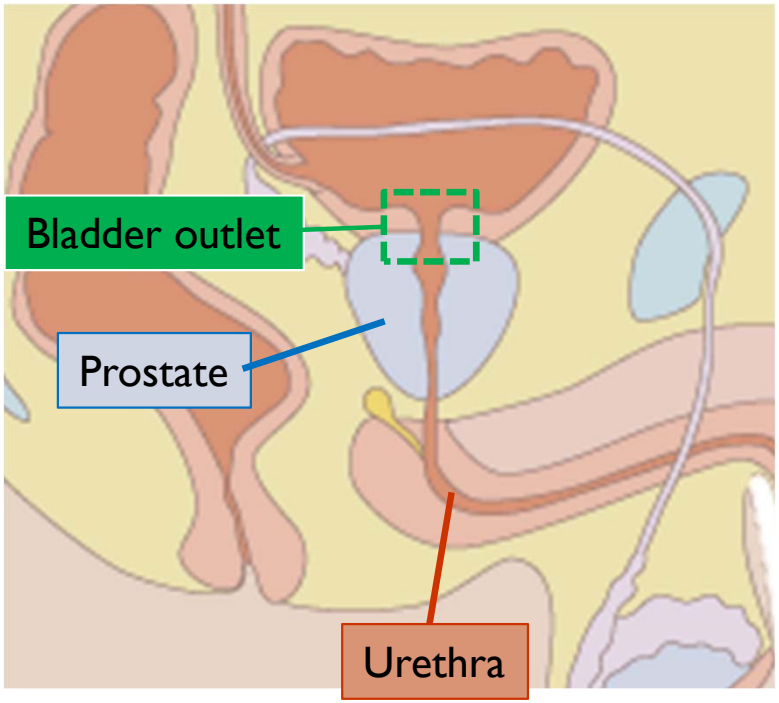
November 2015

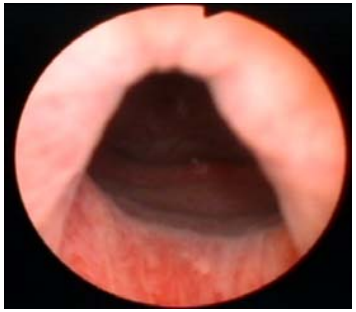
Future Trends: Can VPI Be Applied to Study Other Complex Flow Phenomena?

One potential application area: Urinary flow visualization

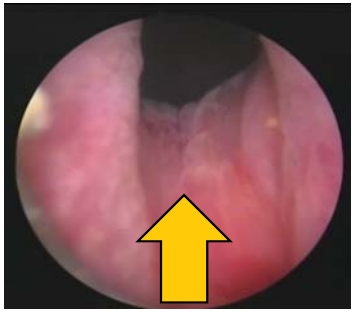
Help evaluate patients with urinary voiding symptoms

Male pelvic organs

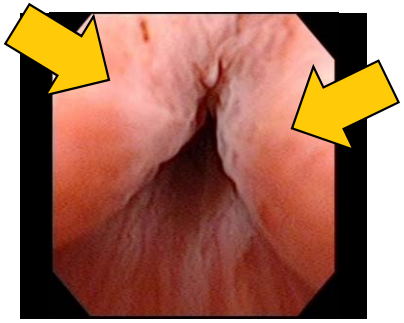




Normal



Bladder Outlet Obstruction (BOO)



Benign Prostatic Hyperplasia

Time-resolved vector flow visualization can help reveal the severity of voiding dysfunction

Initial Result: VPI Shows Significant Flow Turbulence in Diseased Urinary Tract

Flow events in bladder outlet obstruction model

Flow Rate: 7ml/s

Maximum |v|: 2.43m/s

Narrowed Bladder Outlet

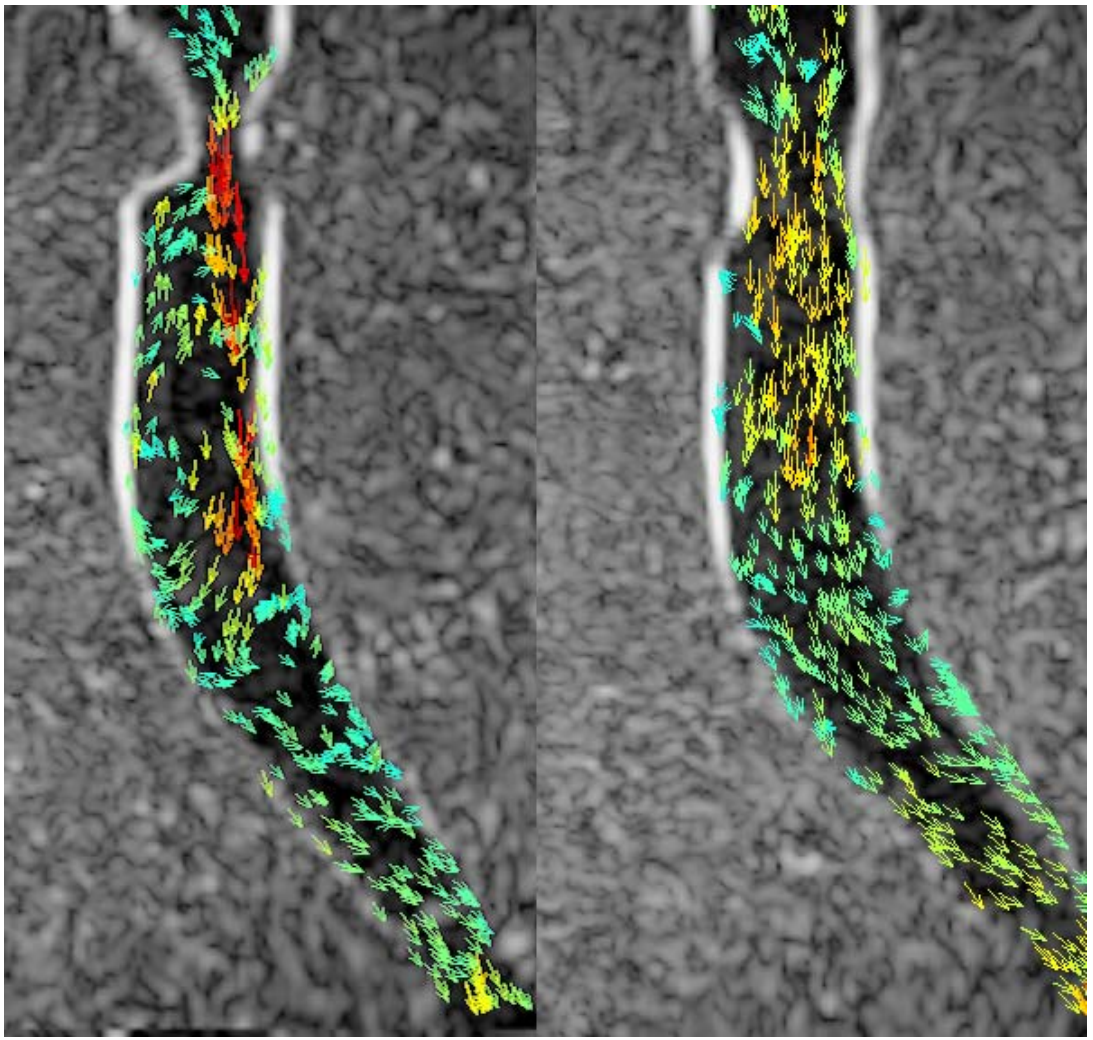
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Flow Jet at Prostatic Urethra

↓

Flow Recirculation
Flow & Structural Interaction

Diseased Normal



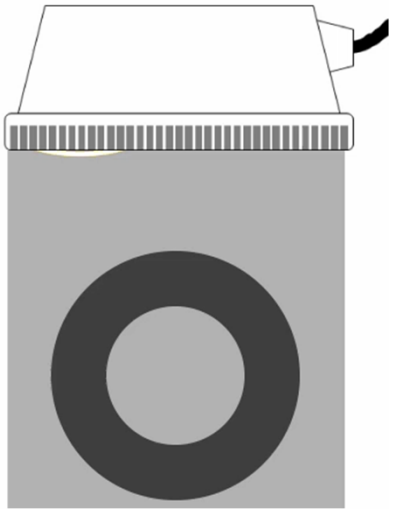
"Vector flow visualization of urinary flow dynamics"
Ultrasound Med. Biol., Nov 2017

Conclusion – High-Frame-Rate Ultrasound Imaging can be Achieved

Key niche: Image dynamic events in human body

Main application: Time-resolved visualization of cardiovascular dynamics

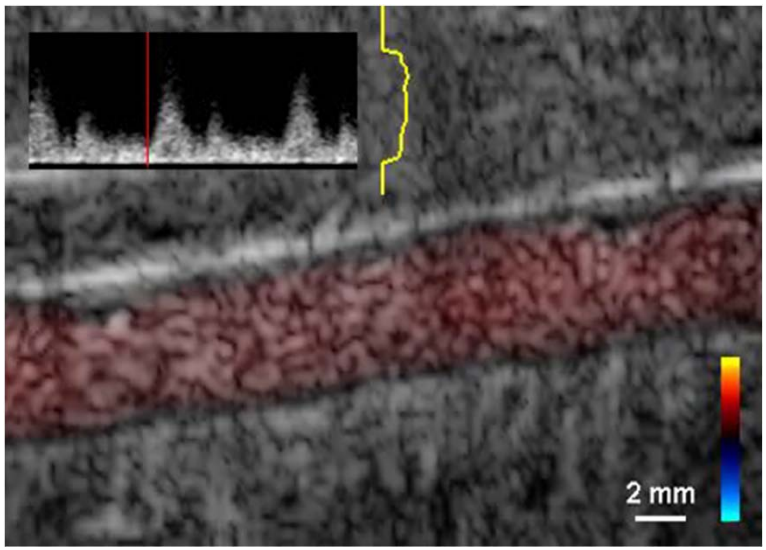
High frame rate imaging paradigm design



Enabling hardware development



High frame rate flow imaging



Ultrasound Med. Biol., 2013; 39(6): 1015-1025

Related Readings

(1) *IEEE Trans. UFFC*, 2011; 58(8): 1698-1705. "GPU-based beamformer for synthetic aperture imaging"

(2) *IEEE Micro*, 2011; 31(5): 54-65. "Ultrasound imaging: to GPU or not to GPU?"

(3) *IEEE Trans. UFFC*, 2012; 59(2): 243-253. "Pre-beamformed data acquisition system"

(4) *Ultrasound Med. Biol.*, 2013; 39(6): 1015-1025. "Color encoded speckle imaging (CESI)"

(5) *Ultrasound Med. Biol.*, 2014; 40(9): 2295-2309. "Vector projectile imaging (VPI)"

(6) *IEEE Trans. UFFC*, 2016; 63(11): 1733-1744. "Pre-beamformed data acquisition system"

(7) *IEEE Trans. UFFC*, 2017; 64(12): 1840-1848. "Spiral flow phantom"

(8) *Ultrasound Med. Biol.*, 2017; 43(11): 2601-2610. "VPI of urinary flow"

(9) *IEEE Trans. UFFC*, 2019; 66(4): 656-669. "Live CESI platform"