Next-Generation Ultrasound Imaging Methods and Systems for Time-Resolved Vascular Diagnostics

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Oct 7, 2024

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Research Portfolio in Vascular Ultrasound Innovations

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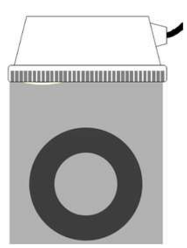
Key question: Can we image dynamic events using ultrasound?

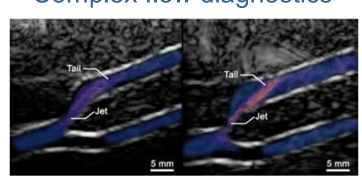
Context: Time-resolved visualization of cardiovascular dynamics

High-frame-rate imaging method design

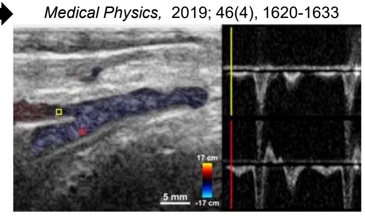


Enabling system hardware development

Complex flow diagnostics



Medical Physics, 2019; 46(4), 1620-1633



TUFFC, 2019; 66(4), 656-669

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Clinical Challenge To Be Addressed: Early Diagnosis of Atherosclerosis

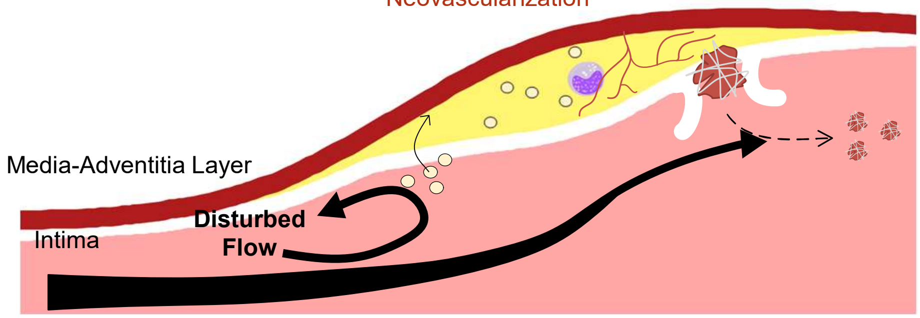
Significance: Atherosclerosis affects 25% of all adults

Healthy Artery | **Initiation** | **Progression** | **Vulnerability** → **Stroke**

Disturbed Flow-Induced Endothelial Dysfunction

LDL Deposition
Plaque
Neovascularization

Plaque Rupture & Release of Emboli



Disturbed flow mapping: Key to identification of plaque development

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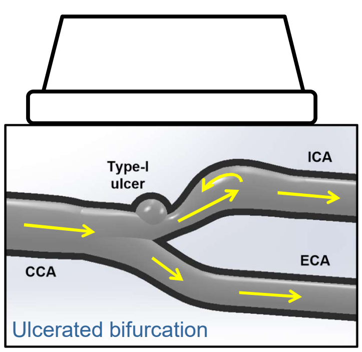
Can Current Ultrasound Technology Effectively Detect Disturbed Flow?

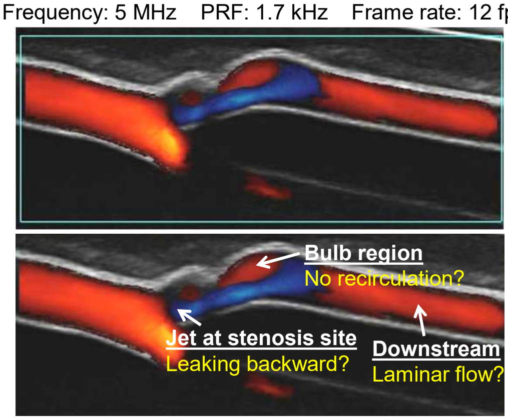
Case illustration: Carotid bifurcation imaging



Ulcerated bifurcation

"Anatomically realistic flow phantoms"
Ultrasound Med. Biol., Sept 2013

Color Flow Imaging Cineloop (SonixTouch)
Frequency: 5 MHz PRF: 1.7 kHz Frame rate: 12 fps



Issue 1: Spurious colors – Ascribed to scan angle and vessel geometry

Issue 2: Insufficient frame rate – Can't track disturbed flow dynamics

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Color Encoded Speckle Imaging: Our First Diagnostic Ultrasound Innovation

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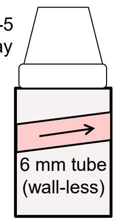
High-frame-rate duplex rendering of flow dynamics

Flow trajectory: Depicted by flow speckle motion

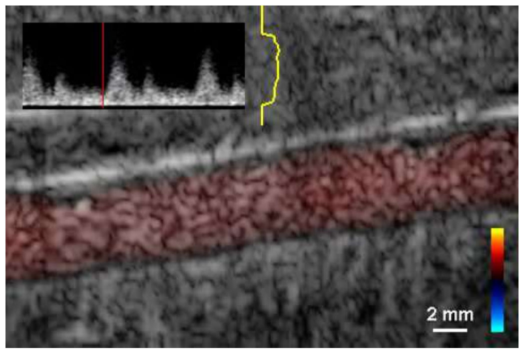
Flow speed: Highlighted by Doppler-based velocity color codes



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: 5 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?

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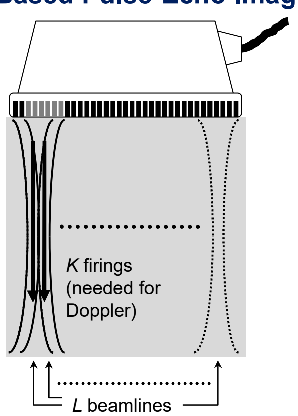
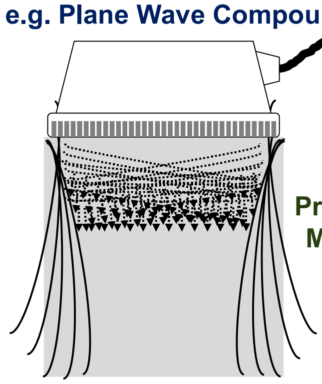
Strategy: Reduce num. firings needed for each image frame

Conventional Approach
Line-Based Pulse-Echo Imaging



K×L firings per frame

New Approach: Broad-View Imaging
e.g. Plane Wave Compounding



Preferred Method

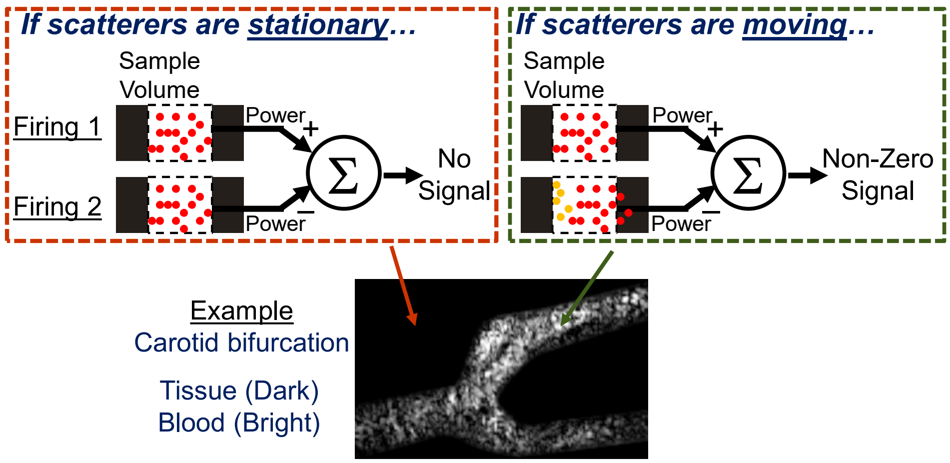
Frame rate = PRF / N_{angle}

** >1,000 fps readily achievable **

Visualizing Flow Trajectories: How?

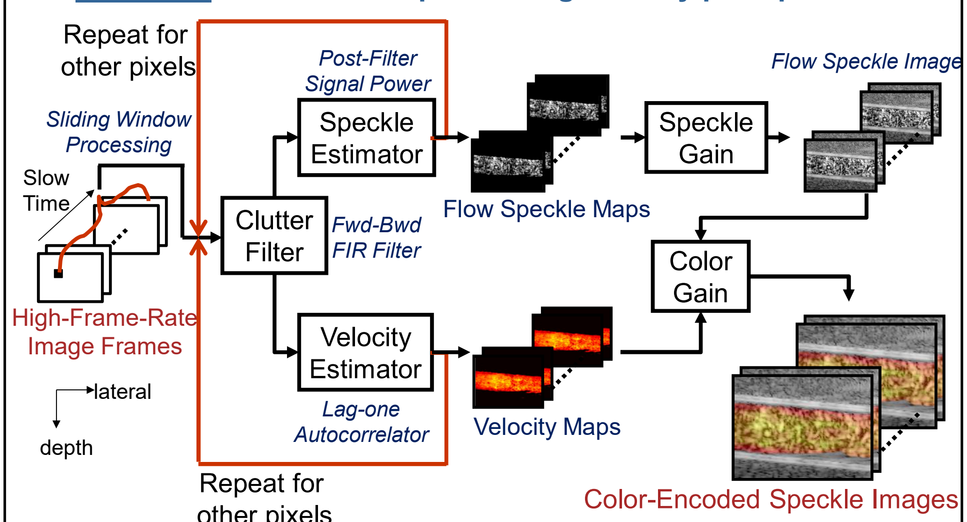
Strategy: Extract blood speckles from acquired signal

Leverage on blood signal decorrelation at same position between firings



CESI: General Signal Processing Chain

Approach: Perform flow processing at every pixel position



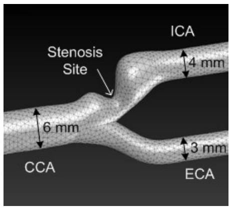
Carotid Bifurcation Imaging: An Example of CESI in Action

Profile: Carotid Pulse (72 bpm)

Systolic flow rate: 5 mL/s

Peak Reynolds number: 1074 *

*Note: Laminar flow **



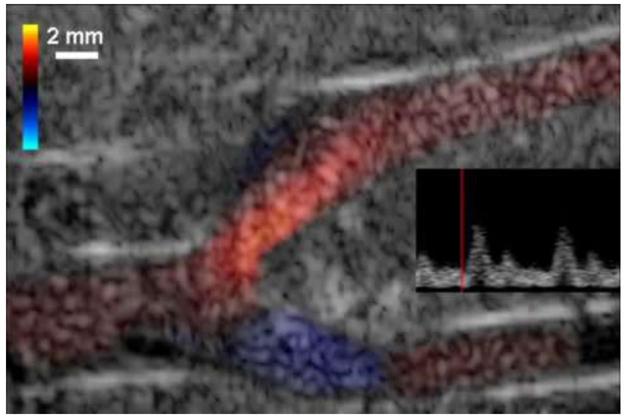
DAQ Parameters

U/S Freq: 7 MHz

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

Effective frame rate: 2,000 fps

Playback rate: 60 fps



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

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

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Challenge: How to Realize CESI in Practice?

Not a straightforward task!

Clinical scanners are nowadays designed using an embedded approach

Compact, transportable, real-time *…but not reconfigurable*

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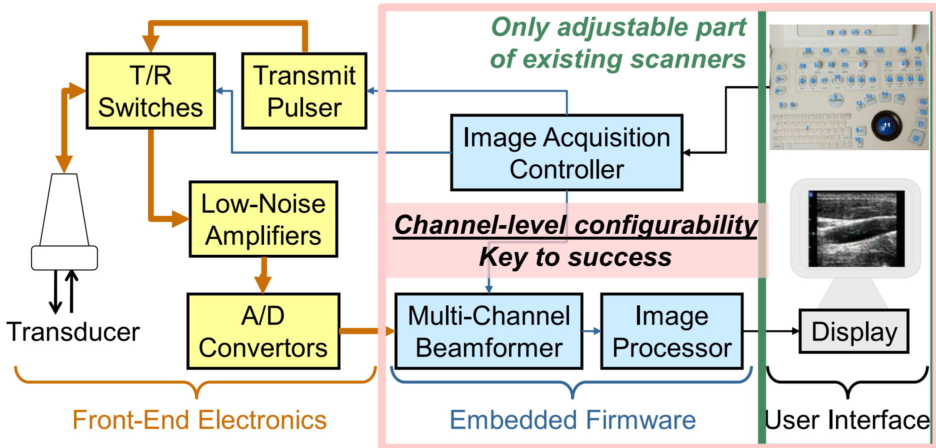
Realizing High-Frame-Rate US Imaging: Essential System Design Considerations

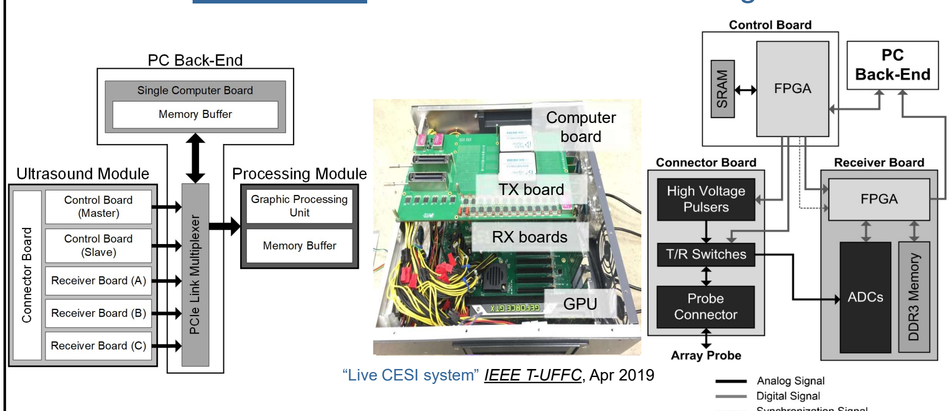
Key components of an ultrasound system



Designing an open-platform scanner with channel-level reconfigurability is critical

Our Software-Oriented Live CESI System Design: An Overview

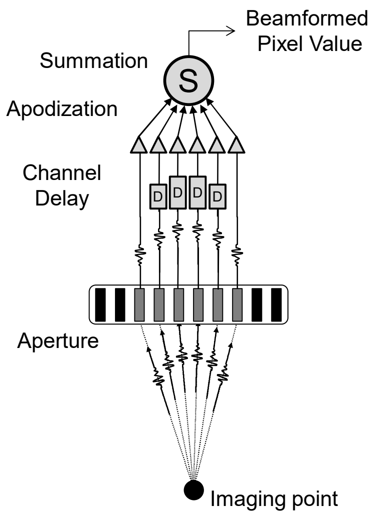
Key feature: A modular hardware design



"Live CESI system" *IEEE T-UFFC*, Apr 2019

Each module is regarded as a PCIe device interfacing with the system

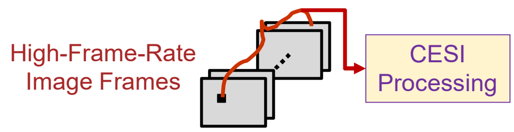
GPU Beamformer: A Core Signal Processing Module of Live CESI Platform



Common practice in US imaging: Form aperture from a group of array elements

- Operational goal: Coherently sum echoes from all elements
- Solution: Apply time delays to different array channels based on geometric arguments

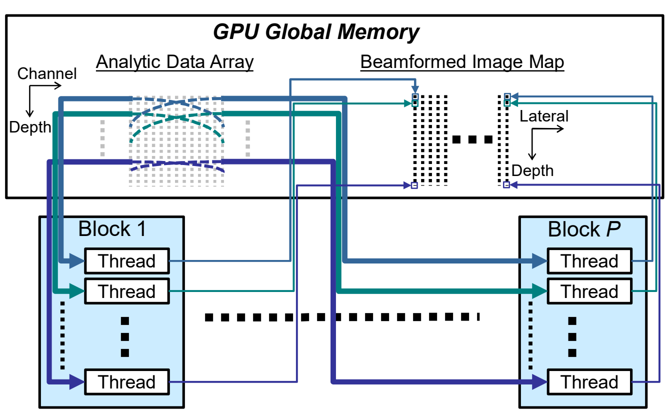
Same process is repeated in forming all image pixels and multiple frames



Delay-and-Sum Operation of GPU Beamformer: Illustration for One Frame

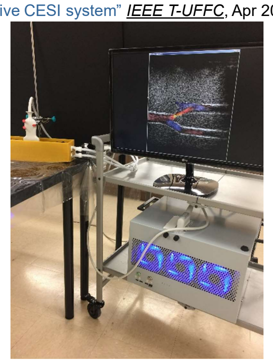
Design rule: Each thread computes one beamformed pixel

Steps included: 1) Delay calculation, 2) Data retrieval, 3) Interpolation, 4) Weighted summation



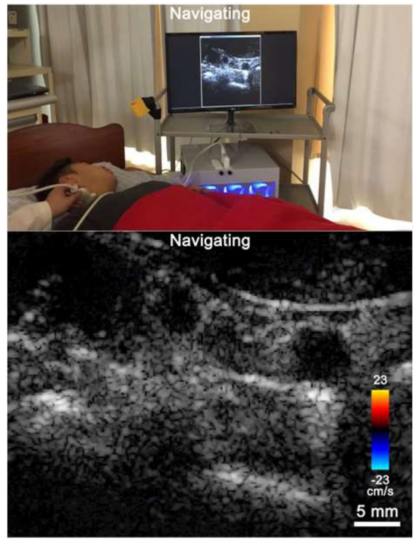
Live CESI Platform in Operation

"Live CESI system" *IEEE T-UFFC*, Apr 2019



System Parameters	
# Channels	192
Channel Sampling Rate	25/50 MHz
Pulse Rep. Freq.	Up to 10 kHz
Raw Data Streaming Rate	Up to 4.8 GB/s
GPU Processing Capacity	11 trillion ops/s

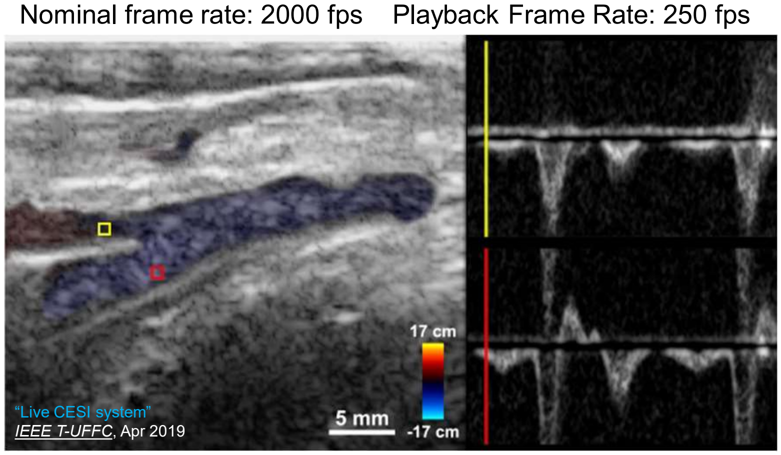
Live Imaging Mode (for navigation)



In-Vivo Application Example: Brachial Bifurcation with Retrograde Flow

On-Demand Replay: Fine temporal resolution to track flow dynamics

Nominal frame rate: 2000 fps   Playback Frame Rate: 250 fps



Key observation: Dynamics of arterial flow during systolic phase

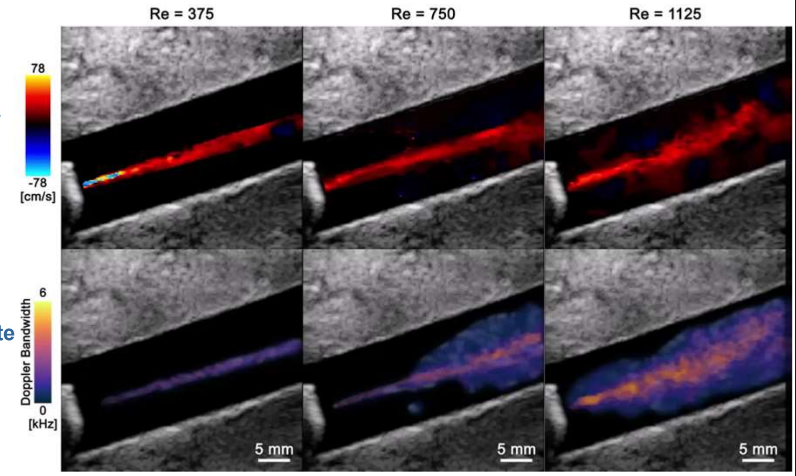
Another New Solution: Doppler Ultrasound Bandwidth Imaging (DUBI)

High frame rate visualization of local unstable flow

Principle: Unstable flow ➔ Large velocity range ➔ Higher Doppler bandwidth

Color Doppler Mode

High-Frame-Rate DUBI



"High-frame-rate DUBI for flow instability mapping" *Med. Phys.*, Apr. 2019

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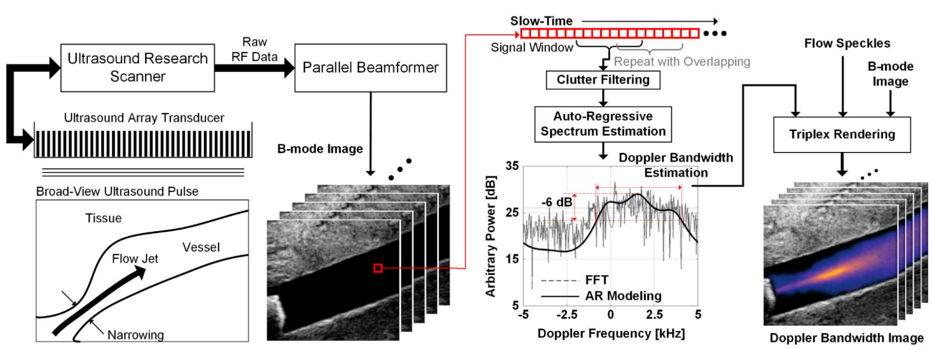
DUBI: Overview of Technical Principles

Three key concepts for high-frame-rate Doppler bandwidth mapping

1. Broad-view acquisition **2. Pixel-based Doppler processing**
3. Auto-regressive spectral analysis



"High-frame-rate DUBI for flow instability mapping" *Med. Phys.*, Apr. 2019

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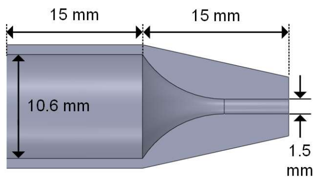
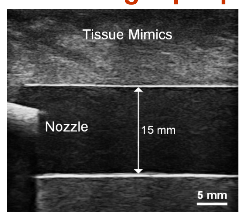
Evaluating the Performance of DUBI in Identifying Unstable Flow

1. Devise a nozzle flow model using rapid prototyping technique

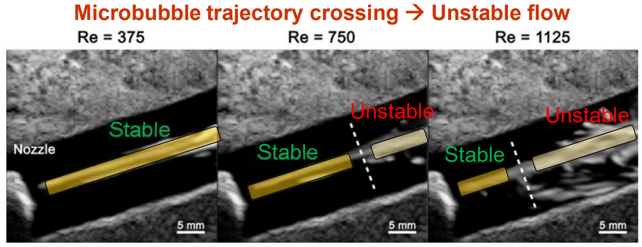




Flow Conditions in Reynolds Number *Re*	Flow Rate [ml/s]
250	1.2
375	1.8
500	2.3
625	2.9
750	3.5
875	4.1
1000	4.7
1125	5.2
1250	5.8

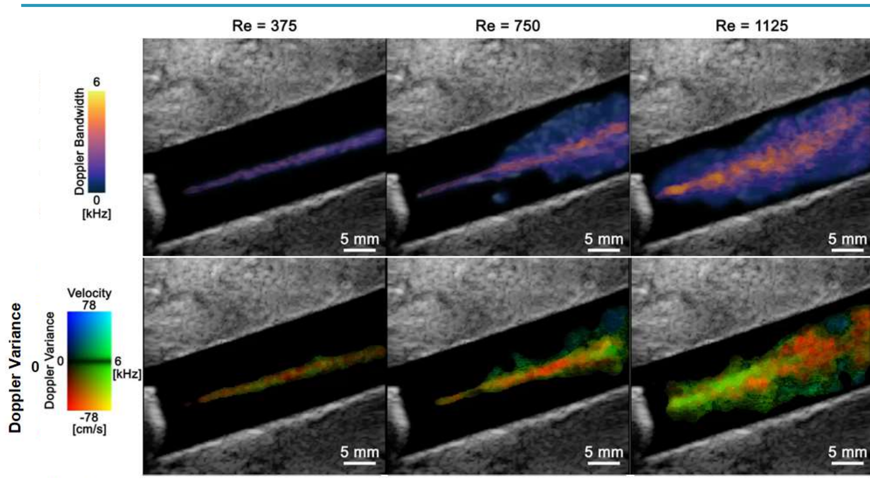
2. Using CEUS to the regions for comparison

Microbubble trajectory crossing → Unstable flow



Identify stable and unstable flow regions for quantitative analysis

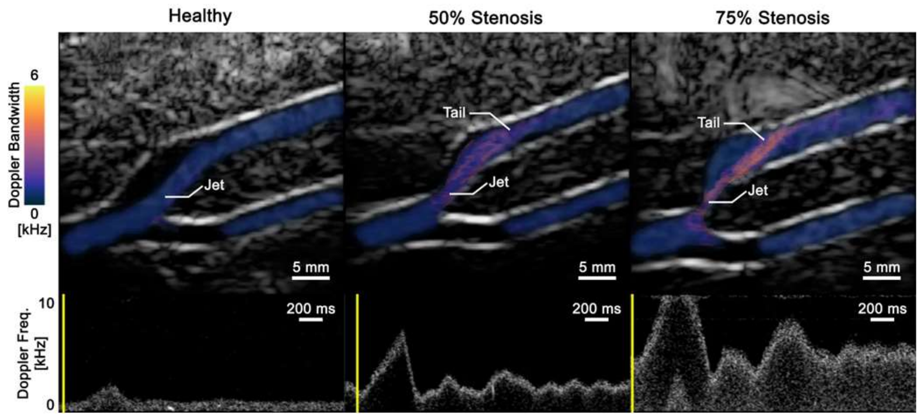
DUBI Can Highlight Unstable Flow Region at Different Conditions



Key Observations: DUBI performs better than Doppler variance imaging

1. Doppler Bandwidth correlates with Reynolds number
2. The positions of the unstable flow are highlighted by DUBI

Case Demonstration: Carotid Bifurcations of Different Stenoses



Key Obs: DUBI can visualize the spatiotemporal dynamics of unstable flow

1. Formation of unstable flow at flow jet tail
2. Propagation of unstable flow towards downstream
3. Doppler bandwidth increases as degree of stenosis increases

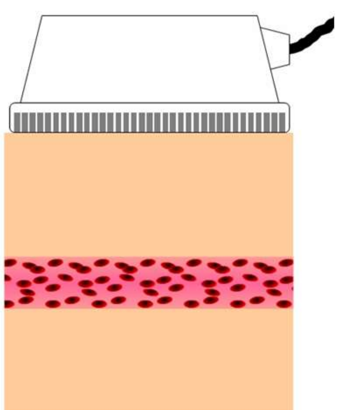
Beyond DUBI: Flow Vector Estimation and Visualization

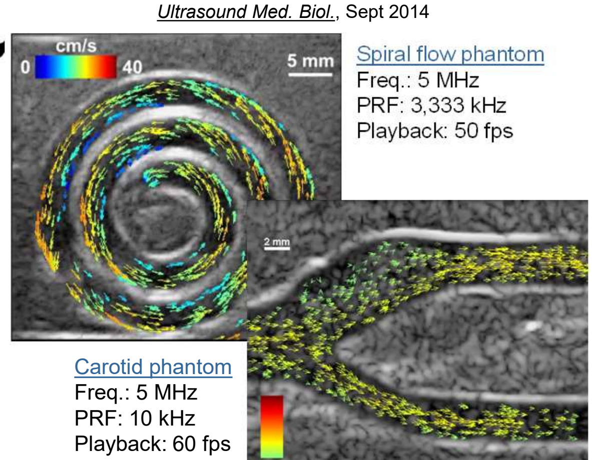
High frame rate tracking of multidirectional flow

Solution: Multi-angle vector Doppler

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

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





Spiral flow phantom
Freq.: 5 MHz
PRF: 3,333 kHz
Playback: 50 fps

Carotid phantom
Freq.: 5 MHz
PRF: 10 kHz
Playback: 60 fps

VPI – Vector Projectile Imaging: Overview of Dynamic Visualization Algorithm

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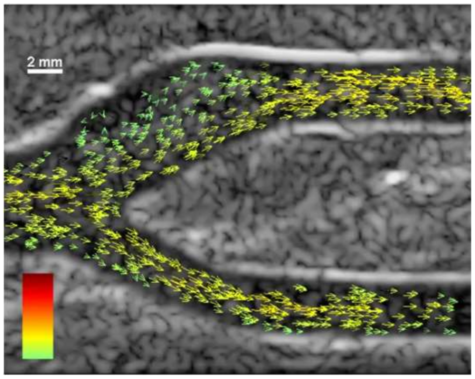
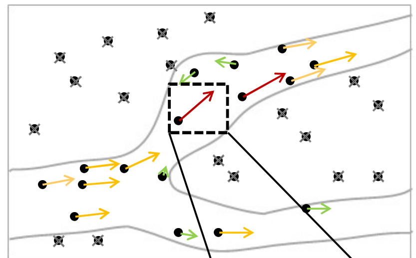
General approach: Dynamic update of inter-frame vector position

Scenario: Healthy carotid bifurcation

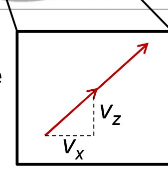


"Vector projectile imaging of complex flow patterns"
Ultrasound Med. Biol., Sept 2014

Step 1: Define launch points



Step 2: Update vector position



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

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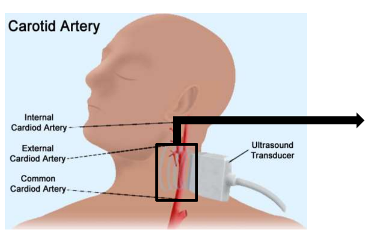
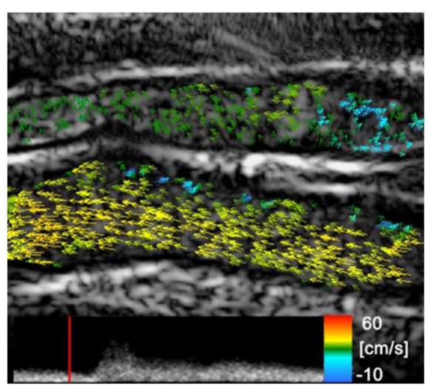




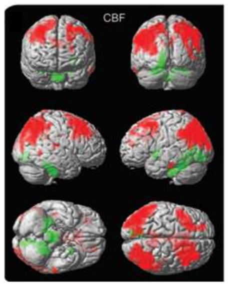
Nominal imaging rate: 1666 fps
Playback at 50 fps

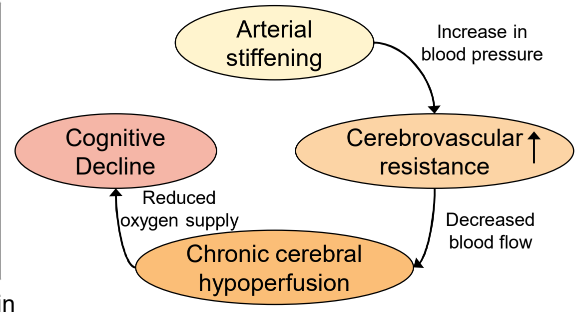
Differences in arterial and venous flow speeds & directions can be consistently visualized

Beyond Atherosclerosis: Other Vascular Pathologies Also Need New Diagnostic Tools

One major problem: Vascular cognitive impairment

Affects 16.8% of Canadians aged 65 and over





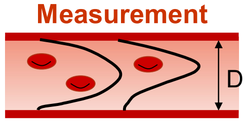
Red Region: Reduction in both cognitive test score and cerebral blood flow%

Brain blood flow quantification: Key to identification of cerebral hypoperfusion ➔ Early detection of cognitive decline

%adopted from Chen, et al. (2011) "Voxel-level comparison of ASL perfusion MRI and FDG-PET in AD".

How Can We Measure Cerebral Blood Flow Rate?

Basic method: Centerline Velocity Measurement

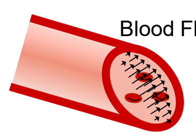


$$Q_{blood\ flow} = \frac{\pi D^2 v_{max}}{8}$$

Shortfalls

1. Does not account for asymmetric flow profile
2. Can only measure one vessel at a time

Inter-Frame Speckle Correlation Analysis

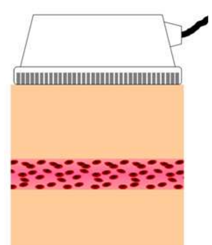


$$Q_{blood\ flow} = \int_A J\, dA$$

Caveat

High frame rate is critical to avoid excessive decrease in correlation

Solution to Frame Rate Limitation: Broad-View Imaging

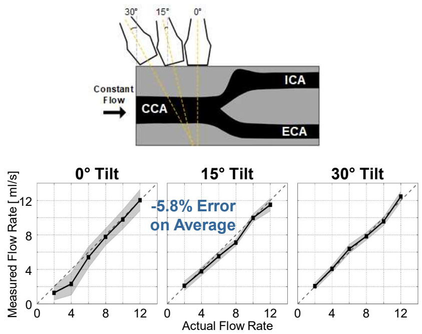


Achievable Frame Rate: >1000 fps

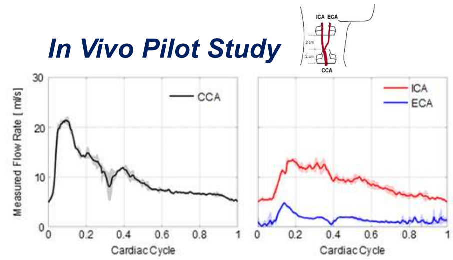
Technical basis for our proposed volume flow estimation framework

Preliminary Data on the New Volume Flow Estimation Technique

In Vitro Calibration



In Vivo Pilot Study



Flow Rate Estimation Summary [ml/s]

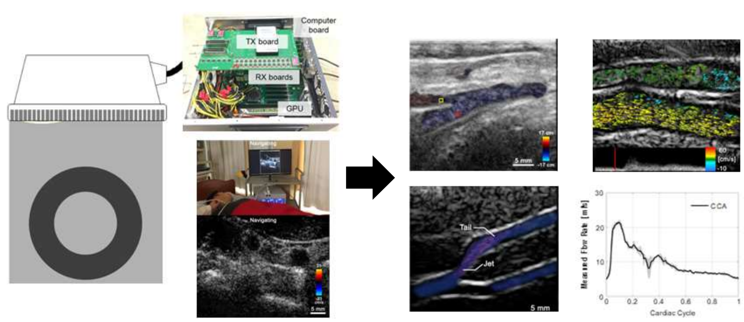
Vessel	Mean	Min.	Max.
CCA	7.8±1.4	6.2	9.9
ICA	6.2±1.3	5.1	8.6
ECA	1.6±0.6	0.6	2.1

7.8

Next step: Pursue pilot study on cerebral blood flow measurements in different age groups

Other related studies: 1) Adaptive flow detection, 2) Automated vessel identification, 3) Validation with other tools

Conclusion – Vascular Ultrasound is in the Midst of a Makeover



Ultimate goal: Enable early detection of vascular diseases

1) Achieve high-sensitivity mapping of vascular pathologies using our imaging innovations
2) Translation of innovations from bench-side to bedside