CFU research Part 2: Fast Vector Flow Imaging, Super Resolution and 3D VFI

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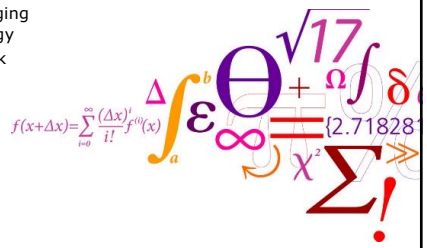

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Department of Electrical Engineering

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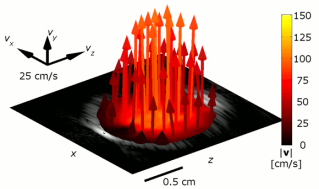
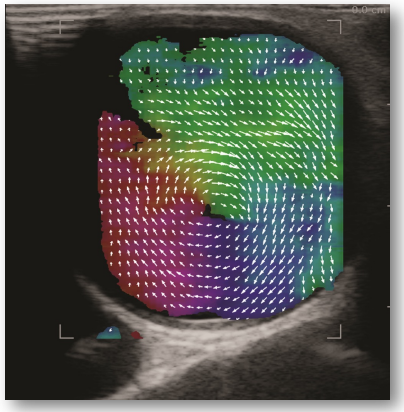
Front-line research in Ultrasound

- Can we measure 3-D flow fast with only 124 transducer elements?
- Can we break the speed-accuracy trade
- Can we see brain function and epileptic attack?
- Can we resolve structures below the resolution limit?



2

Systolic blood flow in ascending aorta of a patient with aortic valve stenosis (short axis view)



Hansen et al. Ultrasonic Imaging, Vol. 35, No. 4, 2013

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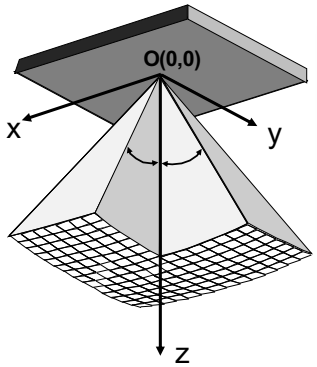
3-D Imaging and Matrix Probes

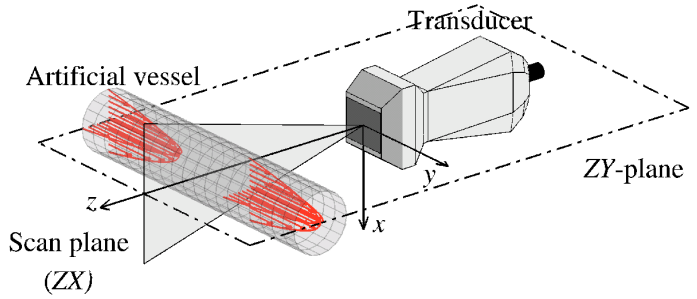


32 x 32 = 1024 element
Matrix Probe from Vermon

4

3D Measurement situation

- Cross-sectional scan of vessel:



5

Measurement equipment

1024 elements → 1024 channels

Jensen et al. IEEE UFFC, No. 9, 2013

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SARUS experimental scanner

- 1024 channels and 70 MHz/12 bits sampling for 140 Gbytes/s
- Arbitrary transmission of coded signals
- 320 high-end FPGAs for real-time processing
- More than 128 Gbytes RAM for several seconds of data
- Capable of 25.600 billion mults/s
- Can perform real-time SA imaging at 32 frames/s

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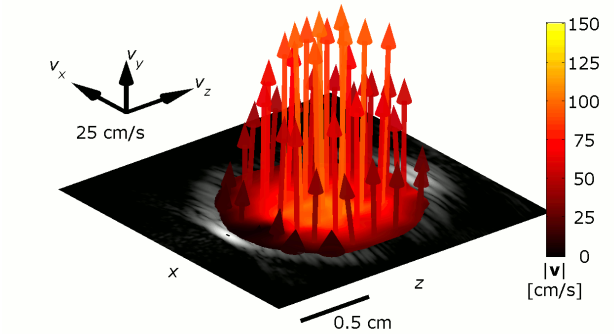
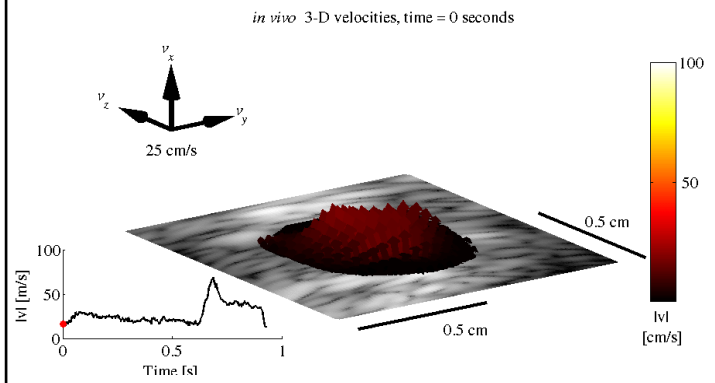
3D vector flow image



8

3-D *in-vivo* flow in Carotid Artery



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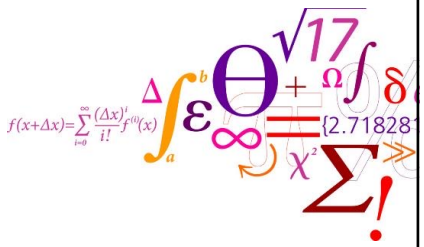
Synthetic aperture and plane wave velocity imaging



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Limitations of current ultrasound systems

- Only one transmit focus
- Frame rate is limited especially for blood flow and 3D imaging

$$f_r = \frac{c}{2DN_dN_l} = \frac{1540}{2 \cdot 0.15 \cdot 100 \cdot 8} = 6\,Hz$$

- Velocity estimation is poor due to few data samples
- Velocity estimation is angle dependent - no transverse velocity can be estimated

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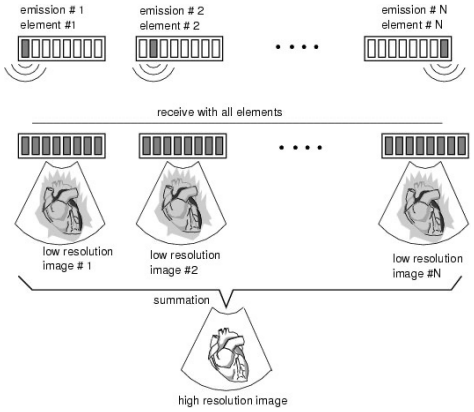
Synthetic aperture imaging



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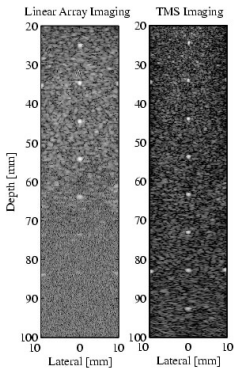
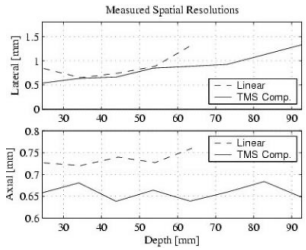
Performance Using 8.5 MHz Linear Array Transducer

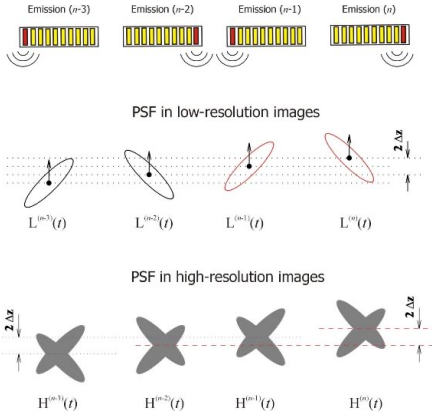


Dynamic Range: 50 dB

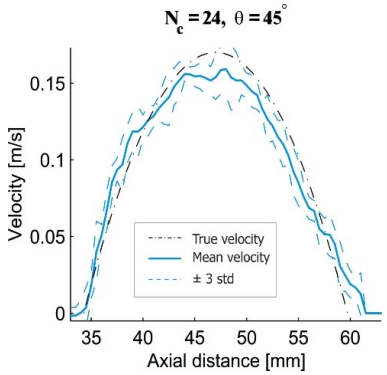


- ~50% increase in penetration depth
- Lateral resolution performance better after aperture is fully opened at ~55mm
- Axial resolution improved due to better utilization of bandwidth

Synthetic Aperture Flow Imaging



Parabolic Profiles from Flow Rig

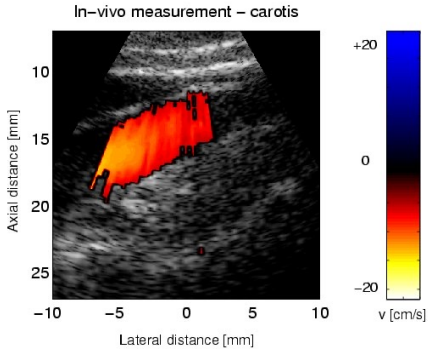


Parabolic velocity profile

Standard deviation relative to maximum: 3%

Only 24 emissions for whole image

In-vivo SA Flow Image

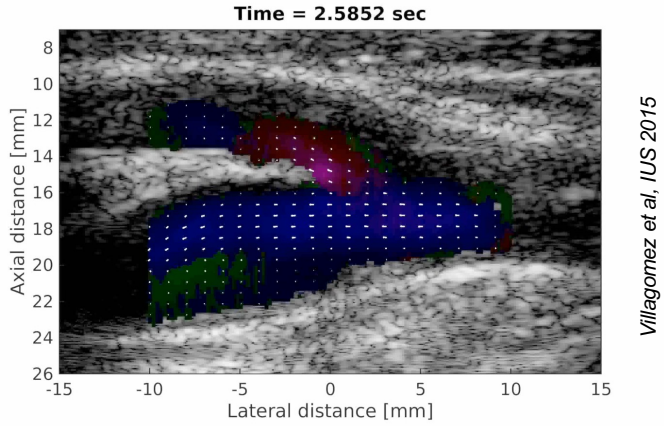


24 emissions used
500 used in traditional systems
-> ***20 times faster***

More than 200 images/sec to 15 cm depth

900 images/sec at 4 cm

SA Vector Flow Imaging in Carotid bifurcation
Frame Rate: 2000 Hz



Villagomez et al, IUS 2015

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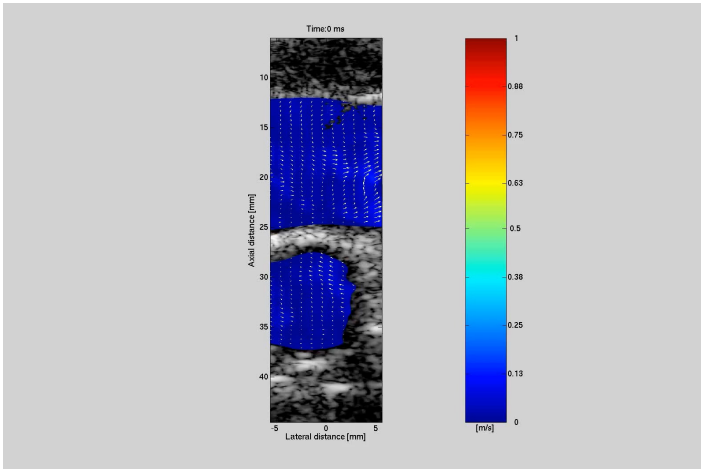

The jugular vein and carotid artery

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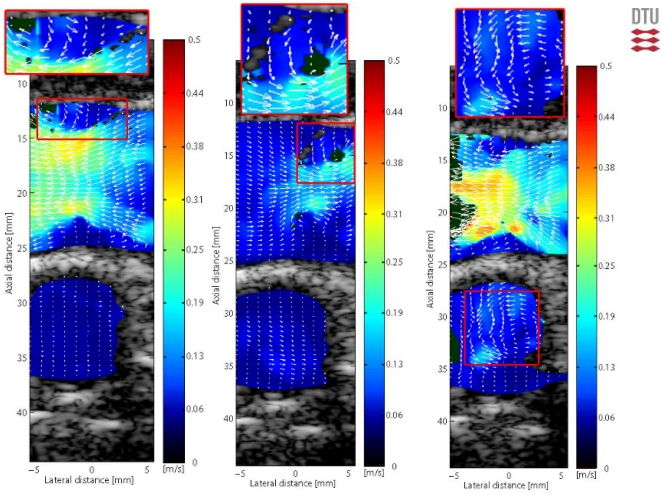

The jugular vein and carotid artery

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Problem with Fully Populated Arrays

- *2D full array*
- *1024 channels, should be 4096*
- *Expensive!*

- *New row-column Array prototype*
- *124 channels*
- *Less expensive*

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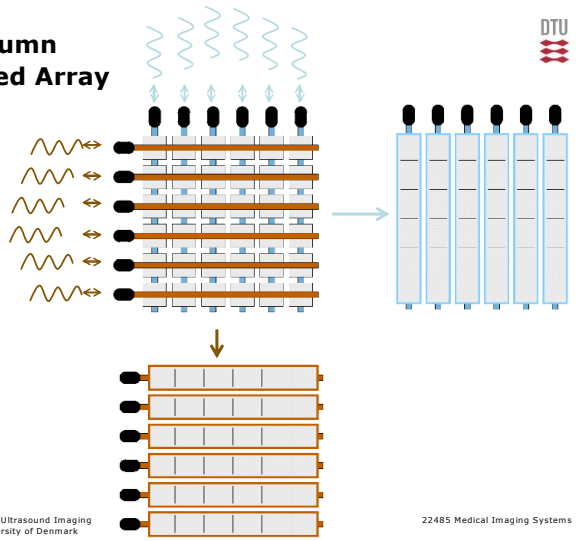
Row-Column Addressed Array



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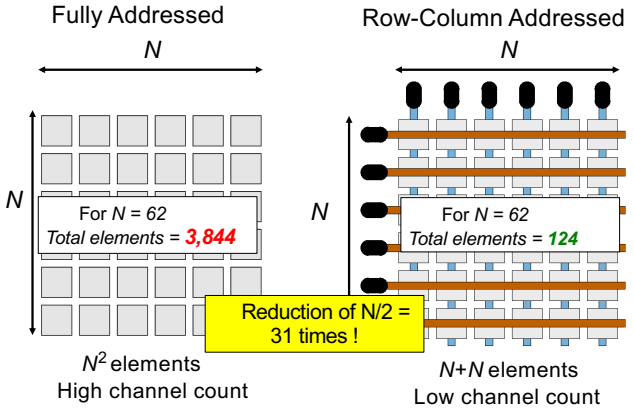
Reduction of the Number of Channels



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Advantages of Row-Column Arrays

Matrix Array	RC Array
• Focusing is dependent on N^2 – Resolution: FWHM = $\lambda D/W$ = $\lambda D/(N\ pitch)$ – Double resolution leads to 4 times number of elements	• Focusing dependent on N – Resolution scales linearly – Double resolution – double number of elements
• Penetration depth depends on area – Many elements needed – Sparse arrays suffer in penetration	• Penetration depends on area – Area = $(N\ pitch)^2$ – Double number of elements gives four times area

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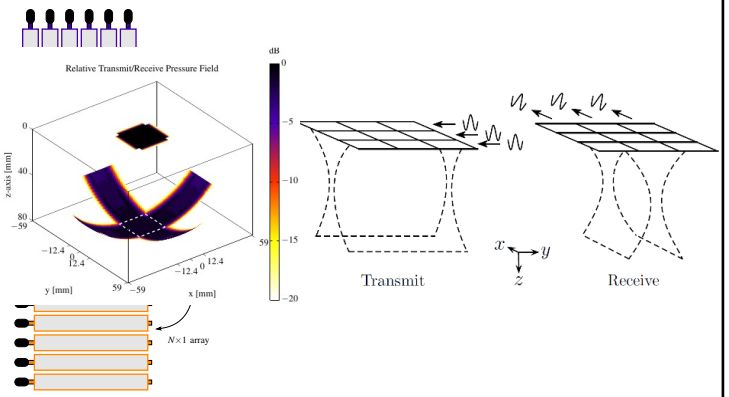
Row-Column Imaging



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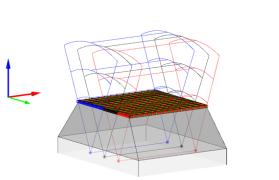
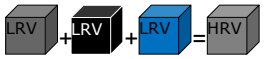
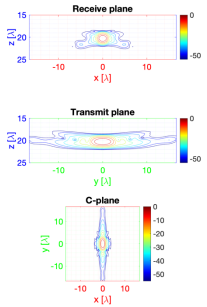
Volumetric Synthetic Aperture Imaging using a Row-Column Array







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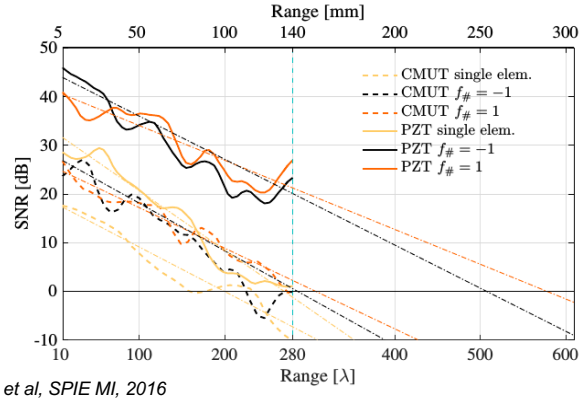
SNR and Penetration Depth



Bouzari et al, SPIE MI, 2016

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Video of RC Imaging

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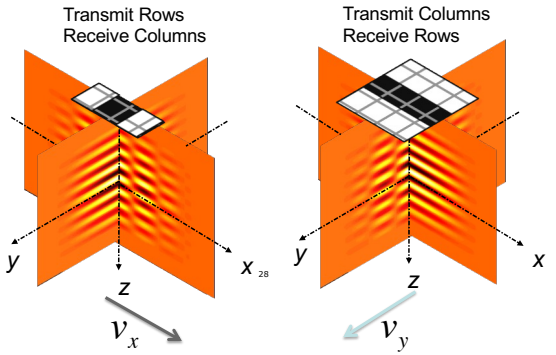
Transverse Oscillation for a 3D array



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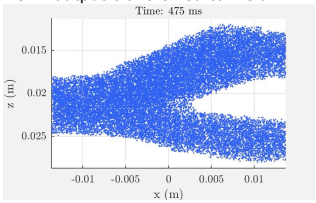
Simulation setup for 62+62 row-column array

- Carotid bifurcation flow simulated using CFD
- CFD output transferred to Field II



Simulation parameters	
Pulse cycle duration	1.2 s
Peak inlet velocity	80 cm/s
Non-rigid walls	Yes
Aqusition parameters	
Number of elements	62+62
Pitch	0.27 mm
Center frequency	3 MHz
Number of emissions	12
Transmit/receive F#	-2/1
Pulse repetition frequency	10 kHz

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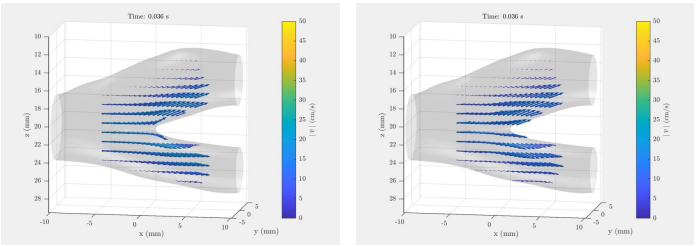
Row-column vector flow in carotid bifurcation

Actual velocity

Estimated velocity



Frame rate: >200 Hz

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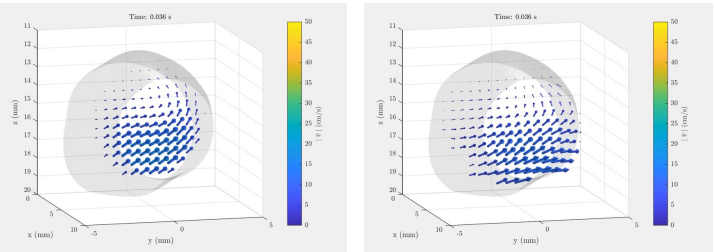
Row-column vector flow in carotid bifurcation

Actual velocity

Estimated velocity



Frame rate: >200 Hz

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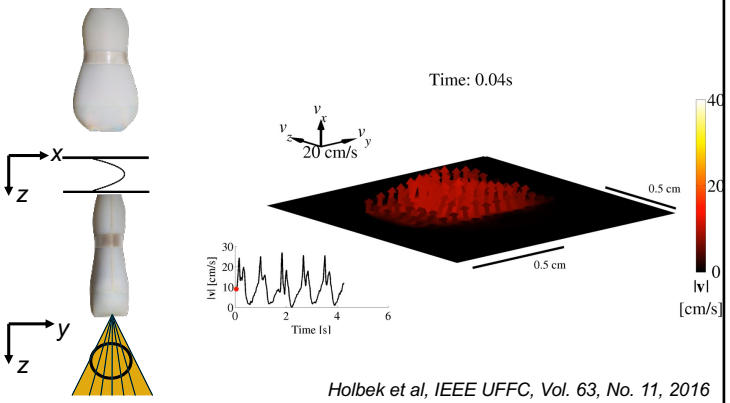
Steered Emission Sequence Pulsatile Flow



Holbek et al, IEEE UFFC, Vol. 63, No. 11, 2016

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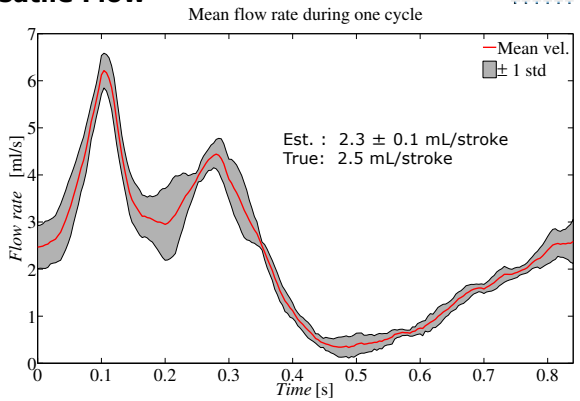
Steered Emission Sequence
Pulsatile Flow



Holbek et al, IEEE UFFC, Vol. 63, No. 11, 2016

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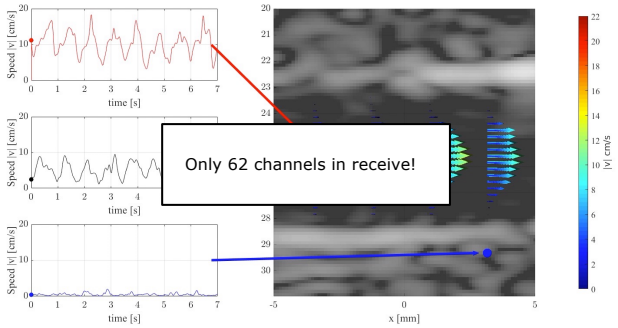
Pulsating flow phantom



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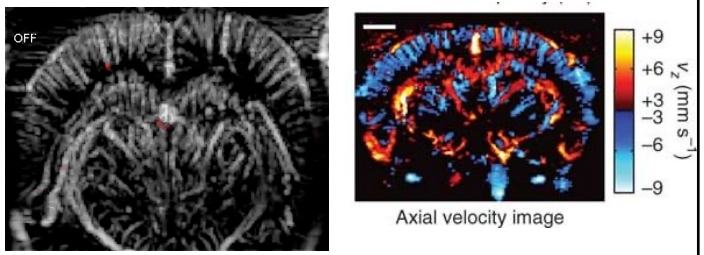
Very low velocity flow

Vasculatur

Velocity map



Mace et al.: *Functional ultrasound imaging of the brain*, Nature Methods 8, 662–664 (2011)

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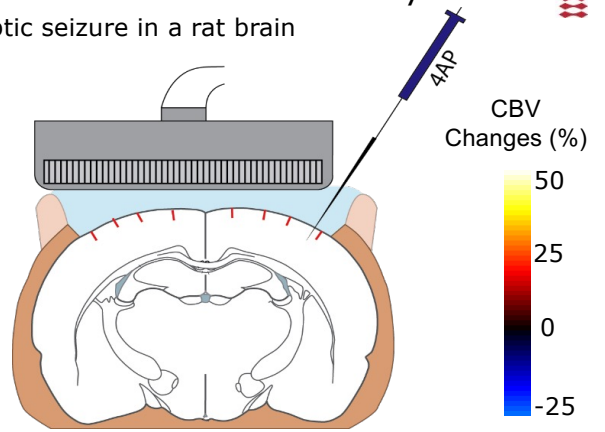
Brain Disorders and Nervous Systems

Epileptic seizure in a rat brain



Courtesy of: E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink, M. Tanter, *Nature Methods*, July 2011

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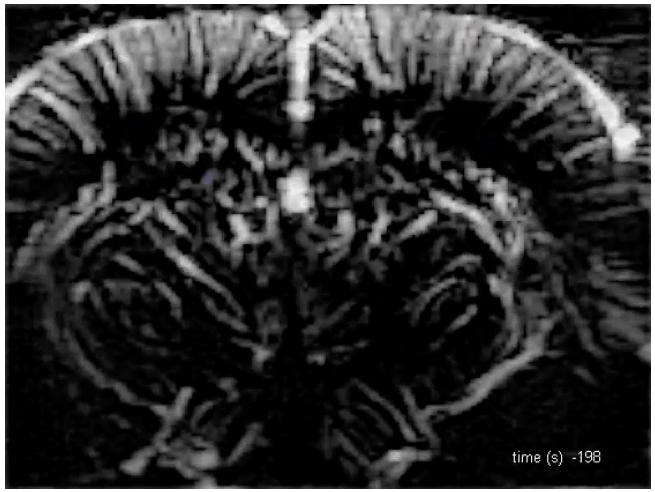

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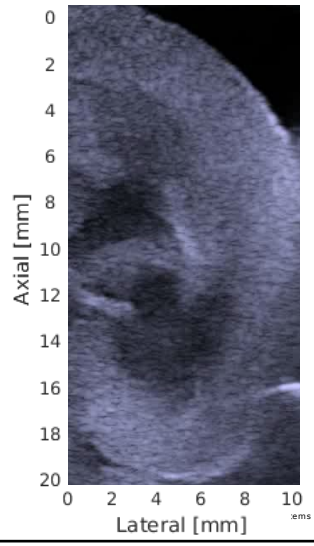
Can we attain super resolution imaging of the smallest vessels in the body?



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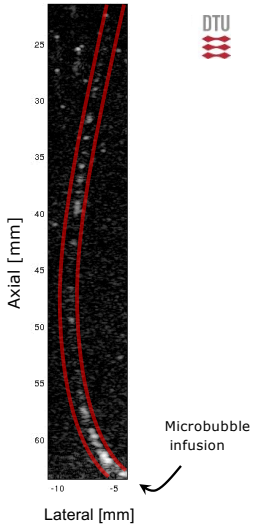
Microbubble tracking for super resolution imaging

- Phantom tube, 200 µm
- Microbubbles injected



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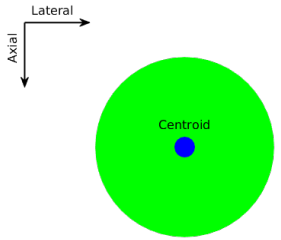
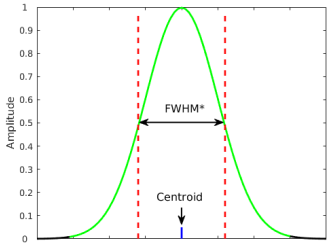
Microbubble Characteristics

- Diffraction -> Point Spread Function
- Weighted centroid -> Exact Position





*FWHM = Full Width at Half Maximum

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Super Resolution Imaging (SRI)

- Results in very high resolution images of micro vasculature
- Ultrasound imaging of gas-filled contrast agents (bubbles)
- Sparse distribution of bubbles
- Center of gravity found and tracks made from bubble flow

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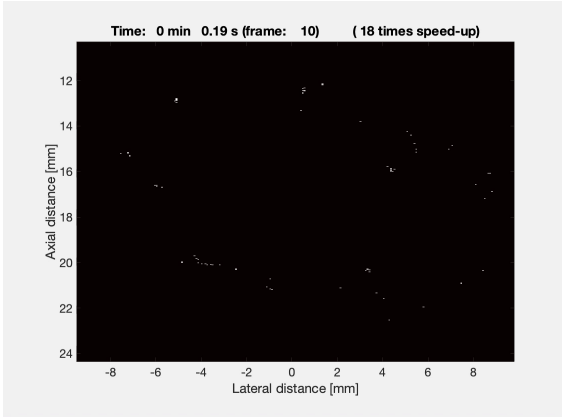
Super Resolution Imaging (SRI)



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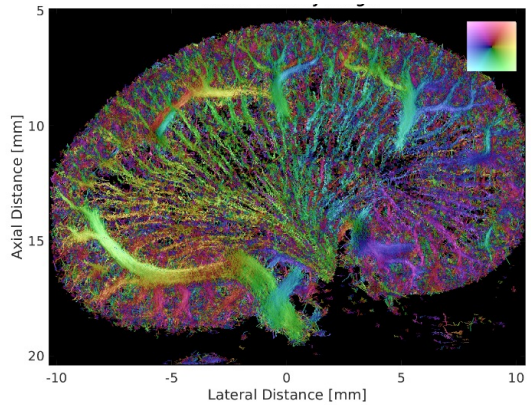
SRI Vector Velocity Image



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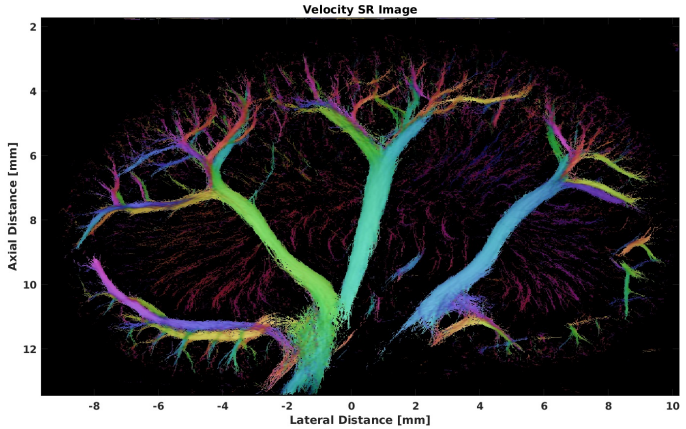
SRI vector velocity image



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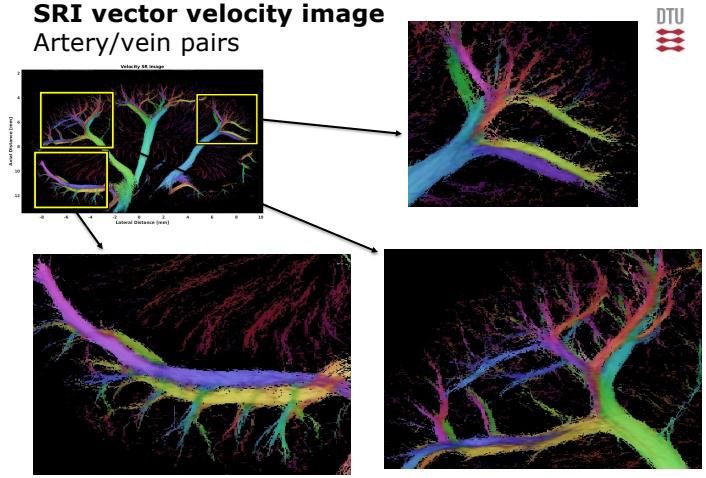
SRI vector velocity image
Artery/vein pairs



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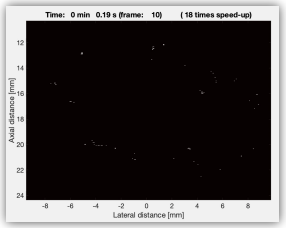
Problems with Current Super Resolution Imaging

1. Time is a limit
   - Currently 1 – 10 min acquisition time
   - Movement of probe and organ
   - Blood flow and pressure changes over time so organ volume can vary
2. Bubble trouble
   - Enough but not too many
   - Bubbles are lost over time
   - Bubbles are killed by the emission pressure from the probe
   - Low MI gives low SNR for image



10 min Super Resolution

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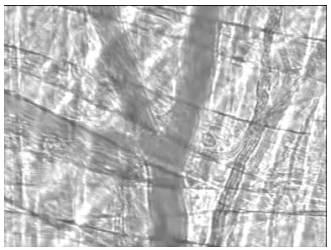
SURE:
SUper Resolution ultrasound imaging using Erythrocytes

- Erythrocytes as tracking target:
  - Use advanced imaging to visualize the erythrocytes
  - Track speckle pattern to track motion
- Benefits
  - Abundance of targets
  - Full MI can be used
  - Fast imaging



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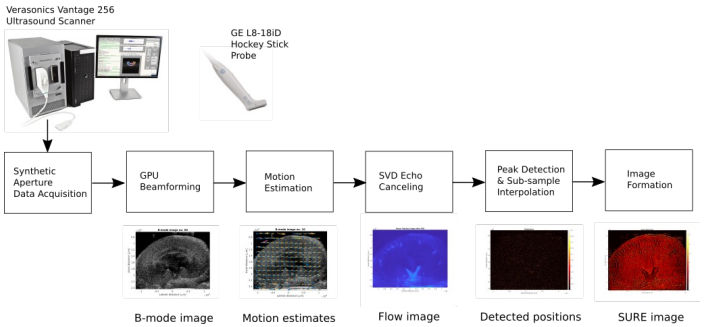
SURE pipeline stages



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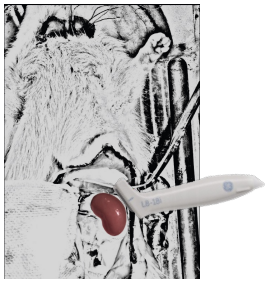
Scanning of Sprague-Dawley rats



- 10 MHz scan frequency
- SA sequence with 12 emissions
- Frame rate of 416.7 Hz
- Verasonics Vantage 256 scanner
- GE L8-18i Hockey stick probe

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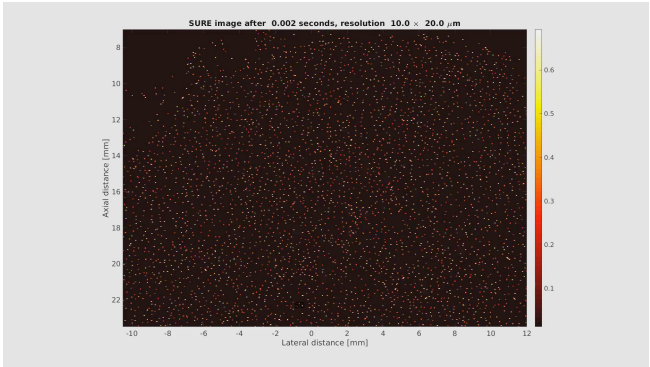

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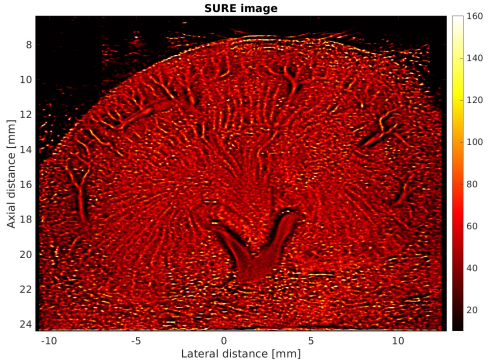

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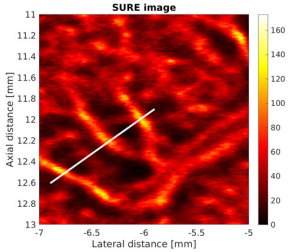
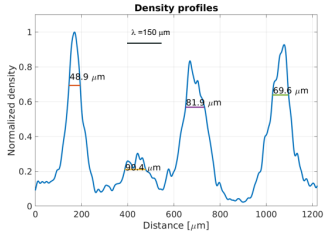
Resolution *in vivo*





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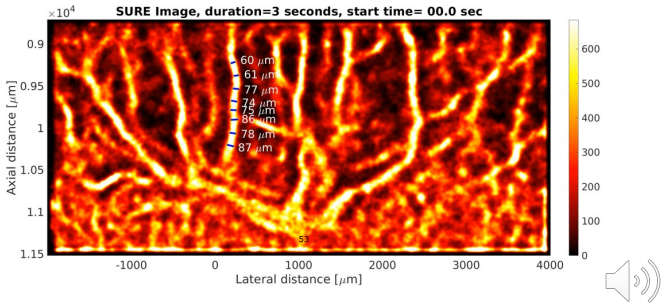
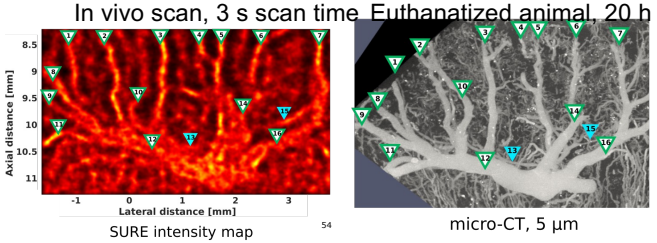
Repeatability:
SURE video: 3 s of data, Different starting times



Comparison of SURE image and μCT
5 μm voxel size

In vivo scan, 3 s scan time. Euthanatized animal, 20 h scan

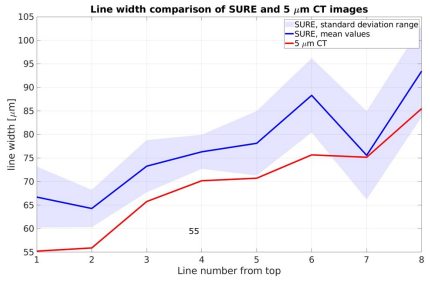


SURE intensity map

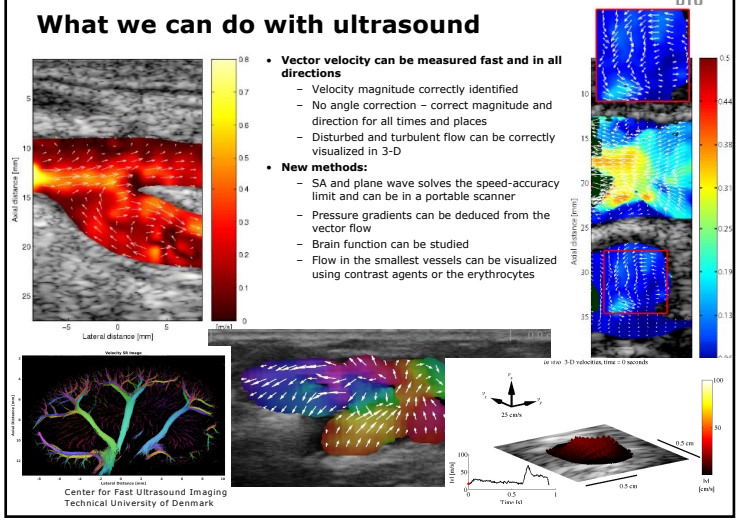
micro-CT, 5 μm

Poster: B2P-24: MSR-P: Comparison of 2D Sure and 3D CT Imaging of Cortical Vessels in a Rat Kidney

Micro CT with 5 μm resolution and SURE comparison



What we can do with ultrasound



- **Vector velocity can be measured fast and in all directions**
  - Velocity magnitude correctly identified
  - No angle correction – correct magnitude and direction for all times and places
  - Disturbed and turbulent flow can be correctly visualized in 3-D
- **New methods:**
  - SA and plane wave solves the speed-accuracy limit and can be in a portable scanner
  - Pressure gradients can be deduced from the vector flow
  - Brain function can be studied
  - Flow in the smallest vessels can be visualized using contrast agents or the erythrocytes

Center for **F**ast **U**ltrasound imaging - **CFU**

Collaboration between:
DTU Health Tech
Rigshospitalet
Panum – University of Copenhagen

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