Research in Advanced Medical Ultrasound Imaging at Center for Fast Ultrasound Imaging (CFU)

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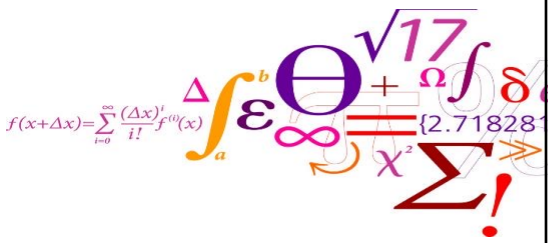

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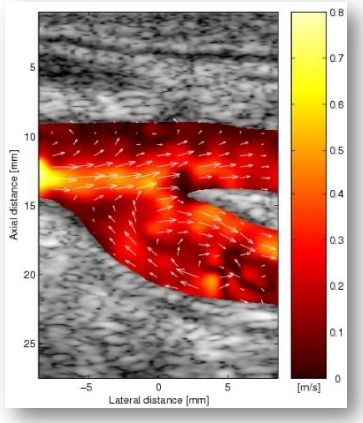
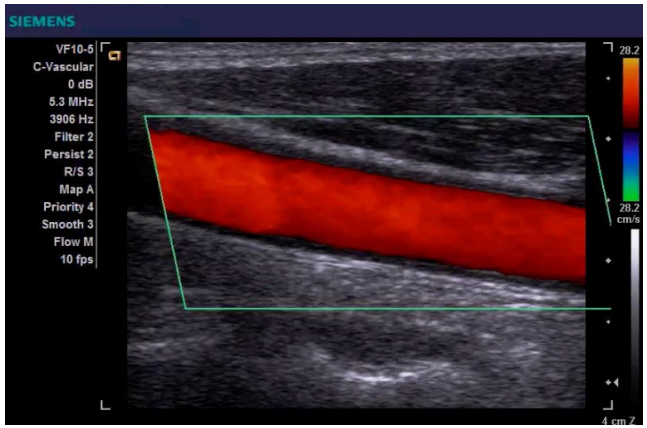
Front-line research in Ultrasound

- Part 1:
  - How can we measure the true blood velocity in the clinic?
  - Can we measure pressure non-invasively
- Part 2:
  - Can measure 3-D flow fast?
  - Can we break the speed-accuracy trade-off?
  - Can we resolve structures below the resolution limit?



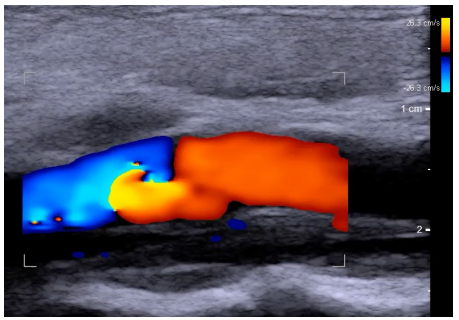
2

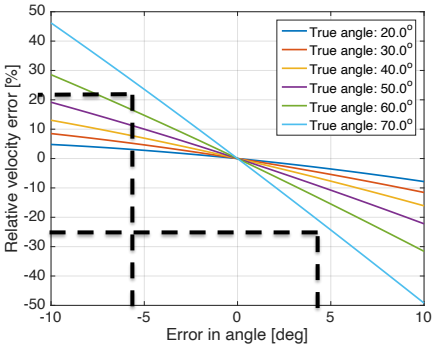
Modern color flow mapping



3

Angle Problem





At 70° a 5° angle error gives a velocity error of more than +/-20%

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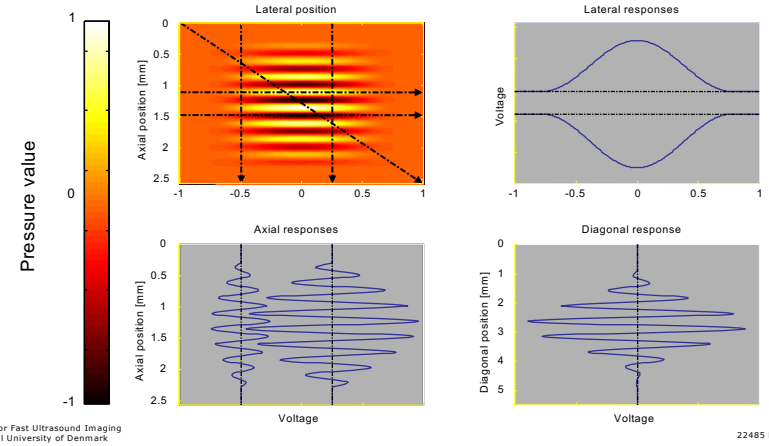
Normal velocity measurement:
Sound field oscillates in ultrasound direction



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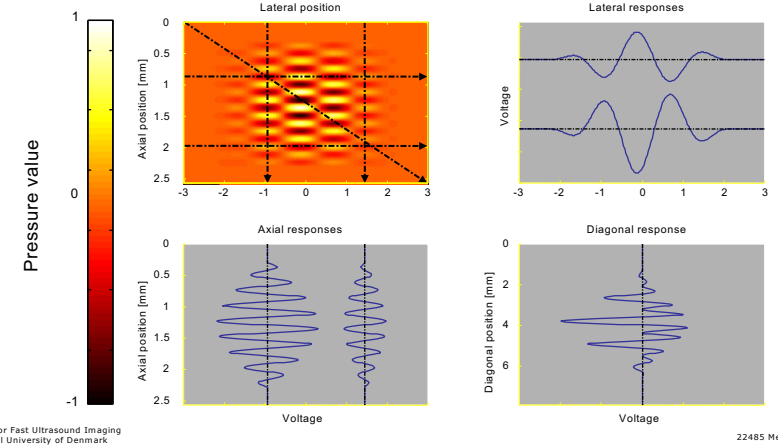
New vector velocity:
Sound field also oscillates across beam



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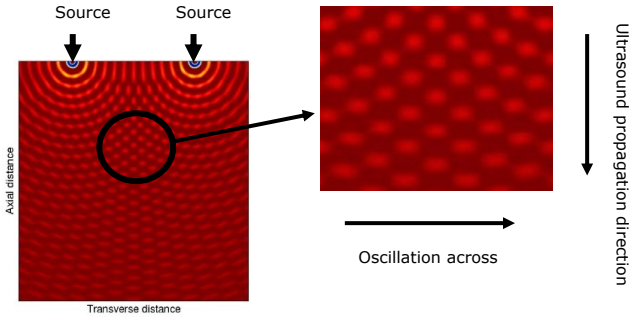
Simple generation



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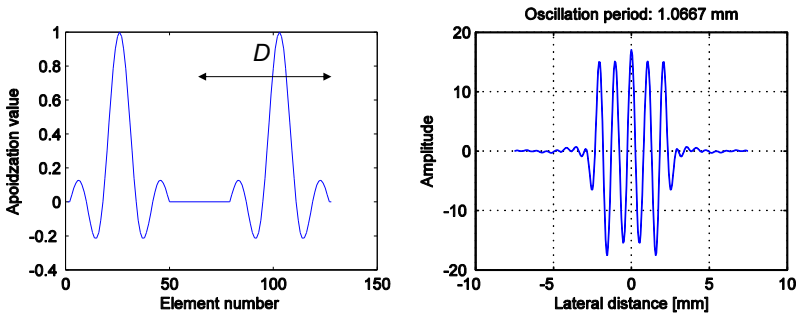
$$\lambda_x = \frac{2z\lambda_z}{D}$$

z – depth
D – distance between peaks
λ_z – axial wavelength
λ_x – Lateral oscillation period



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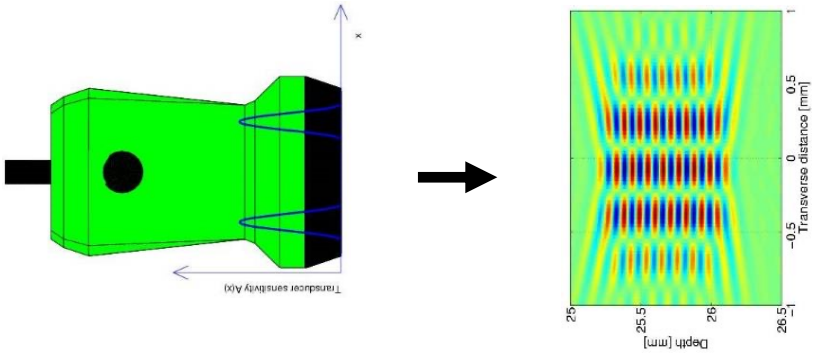
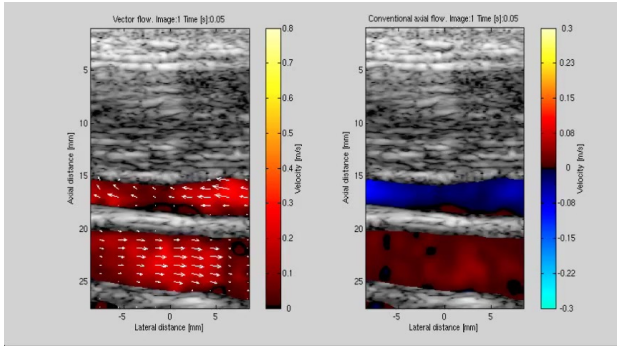
Generation for a transducer



RASMUS

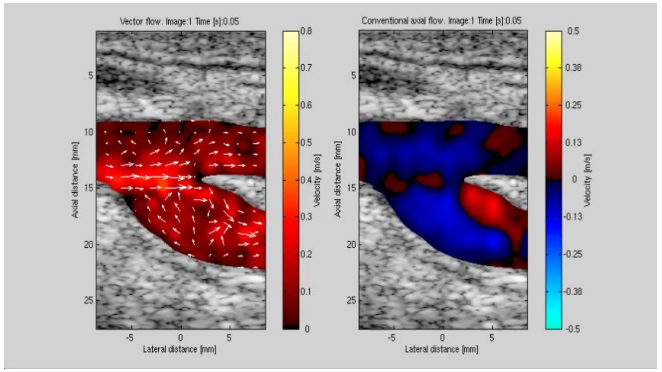
- Remotely Accessible Software programmable Multi-channel Ultrasound System
- Can be used for synthetic aperture, real-time, *in-vivo* data acquisition
- Made solely for research purposes

In-vivo vector velocity for carotid artery and jugular vein



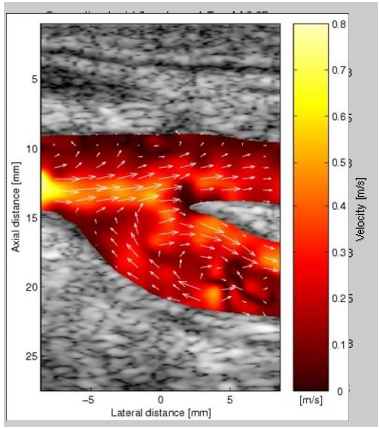
New method *Conventional method*

Velocity in carotid bifurcation



New method *Conventional method*

Complicated flow in bifurcation



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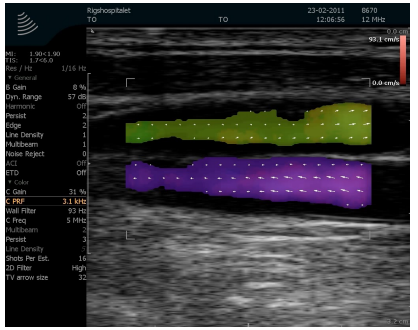
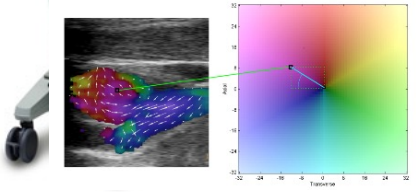
Commercial implementation: BK Medical ProFocus scanner, FDA approved January, 2012





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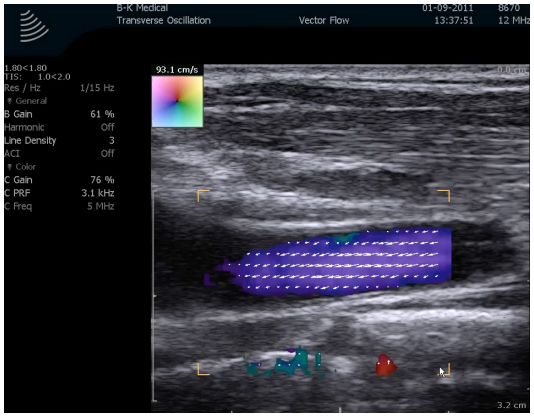
Scanning of the carotid artery



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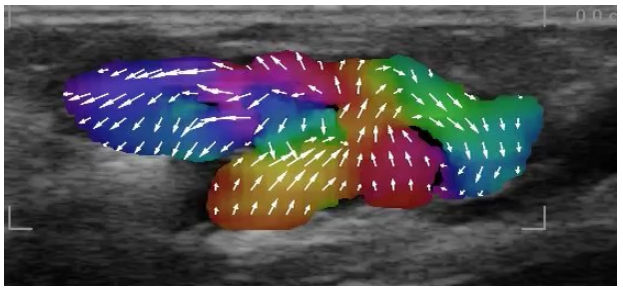
Vein-artery connection for kidney hemodialysis patient



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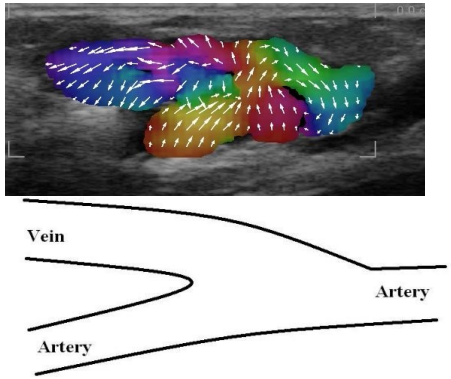
Anatomy of vein-artery graft



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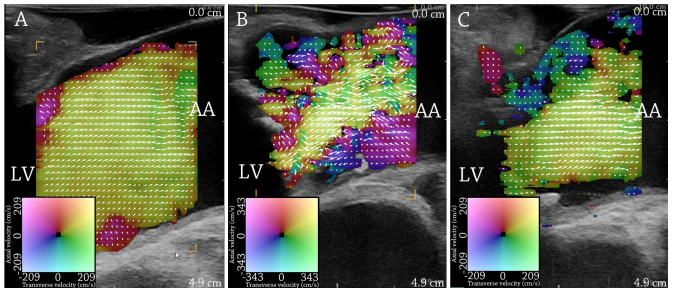
Systolic flow for aortic valve stenosis
Before and after valve replacement



Normal Aortic Stenosis Replaced valve

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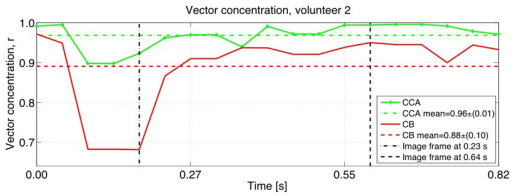
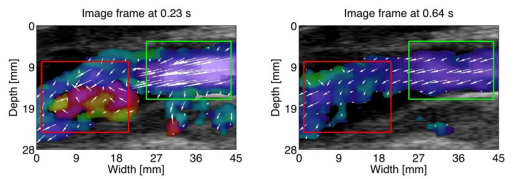
Vector Concentration carotid artery during a heart cycle



: Common carotid artery
: Carotid sinus



Pedersen MM et al. Novel Flow Quantification of the Carotid Bulb and the Common Carotid Artery with Vector Flow. Ultrasound Med Biol. 2014

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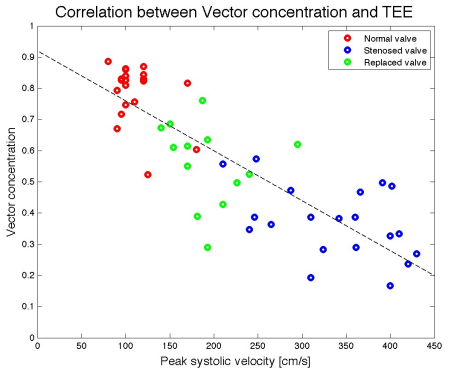
Vector Concentration



Hansen KL et al. Intra-operative Vector Flow Imaging Using Ultrasound of the Ascending Aorta among 40 Patients with Normal, Stenotic and Replaced Aortic Valves. Ultrasound Med Biol. 2016

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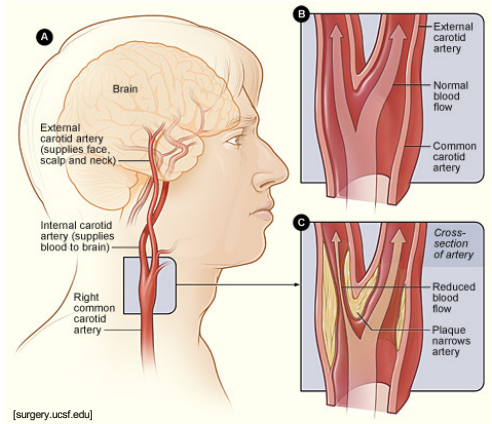
Diagnostic value of pressure differences



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Invasive vs. Non-invasive

Foto by Jacob Bjerring Olesen

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Estimating pressure gradients from Navier-Stokes equation

Pressure gradient

Temporal acceleration

Neglect gravitation as patient lies down

$$\rho\left[\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right]=-\nabla p+\rho\mathbf{g}+\mu\nabla^2\mathbf{v}$$

$$m\cdot a=F$$

Spatial acceleration

Neglect viscosity due to large vessels

The TO method can estimate both spatial and temporal acceleration

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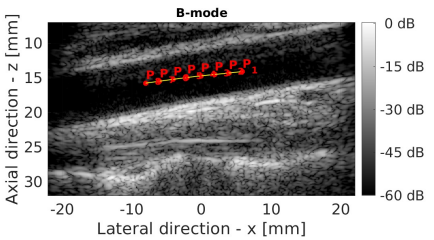
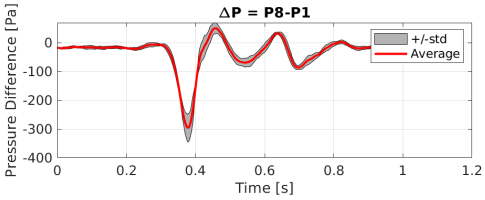
Healthy Volunteer Example





100 Pa is 0.75 mmHg

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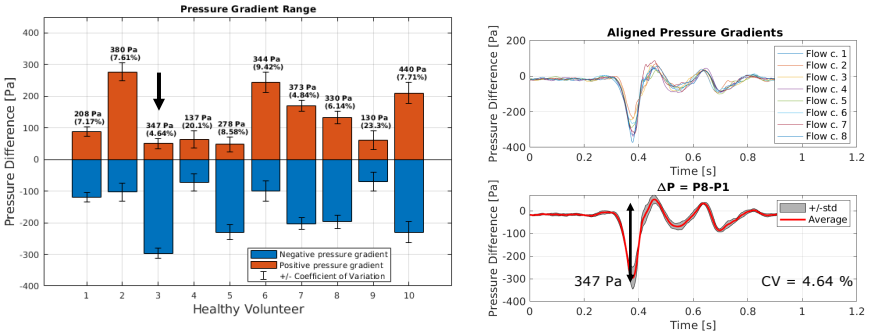
Healthy Volunteers



Average coefficient of variation is 9.95%

Averange range of pressure differences is 297 Pa

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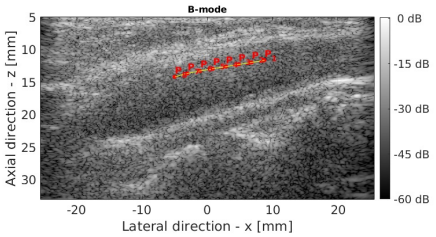
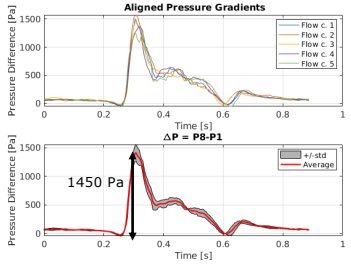
Patient Data: Post-stenosis





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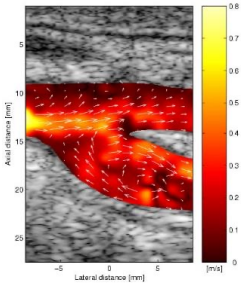
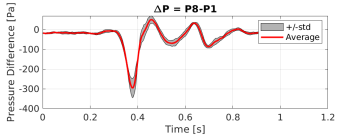
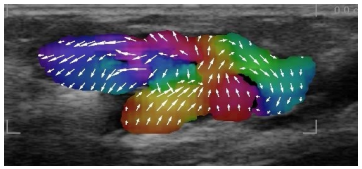
Vector Flow Imaging



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
- Pressure gradients can be estimated





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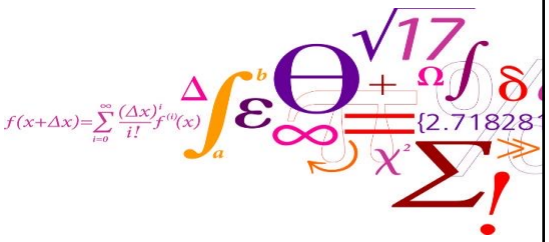
Synthetic aperture imaging



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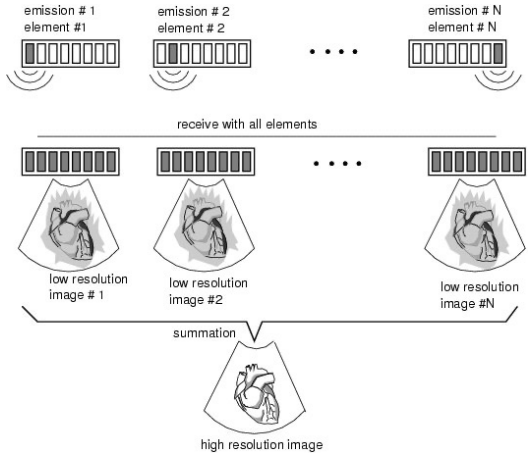
Limitations of current ultrasound systems

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

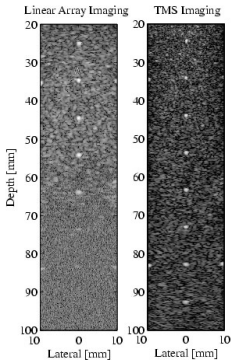
$$f_r = \frac{c}{2DN_dN_l} = \frac{1540}{2 \cdot 0.15 \cdot 100 \cdot 8} = 6\,Hz$$

- Velocity estimation is poor due to few data samples

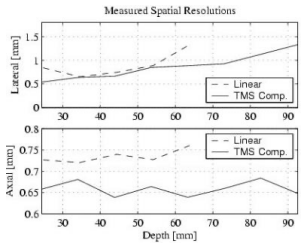
Synthetic aperture imaging



Performance Using 8.5 MHz Linear Array Transducer

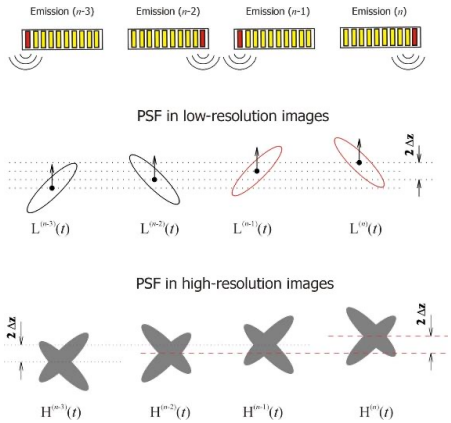


Dynamic Range: 50 dB

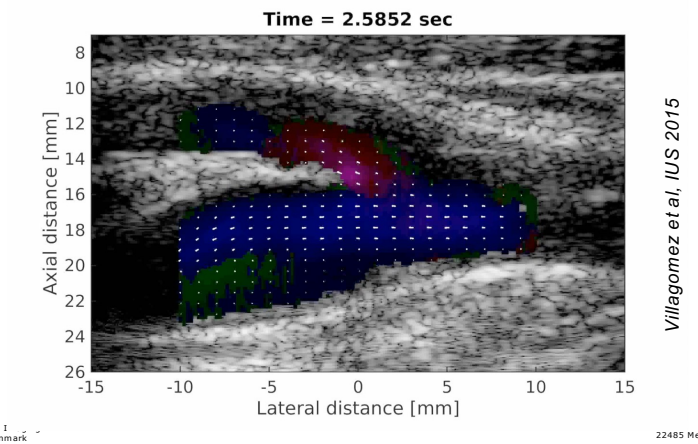


- ~50% increase in penetration depth
- Lateral resolution performance better after aperture is fully opened at ~55mm
- Axial resolution improved due to better utilization of bandwidth

Synthetic Aperture Flow Imaging



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



Villagomez et al, IUS 2015

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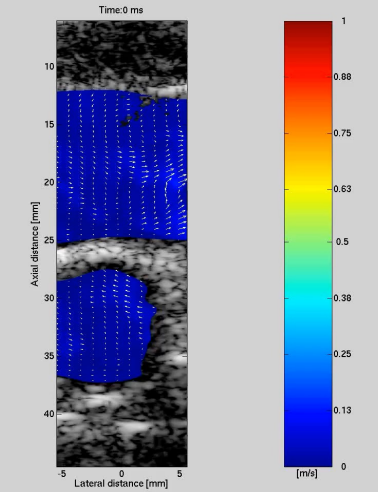
Jugular vein and carotid artery



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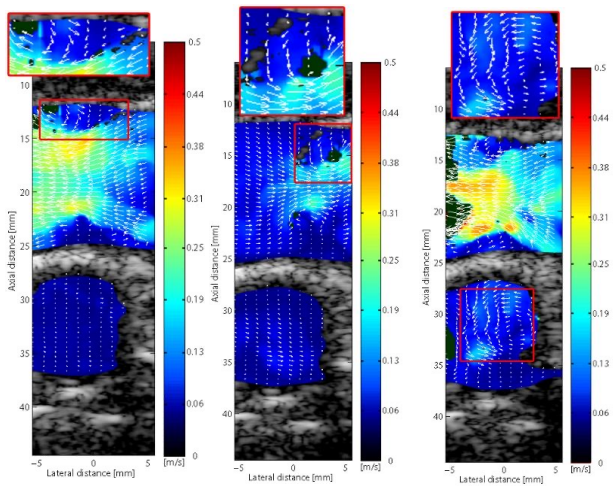

The jugular vein and carotid artery

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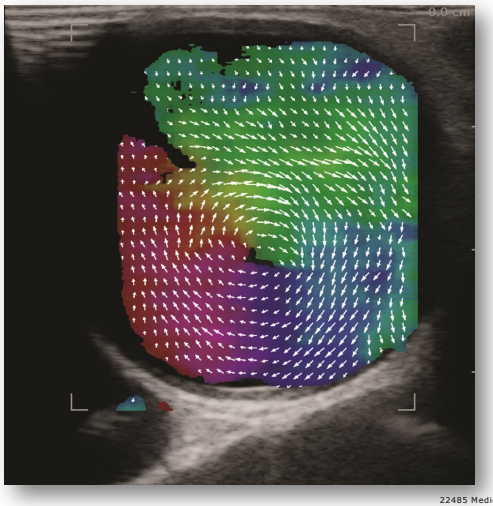
Systolic blood flow in ascending aorta of a patient with aortic valve stenosis (short axis view)



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

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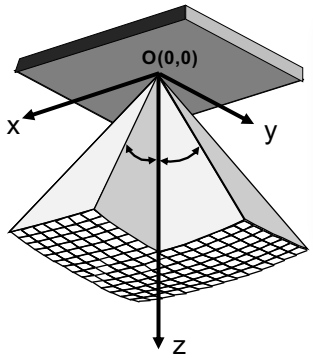
3-D Imaging and Matrix Probes



32 x 32 = 1024 element
Matrix Probe from Vermon

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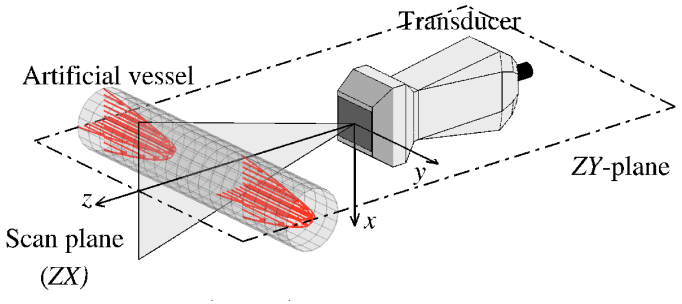
3D Measurement situation

- Cross-sectional scan of vessel:



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Measurement equipment

1024 elements → 1024 channels

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

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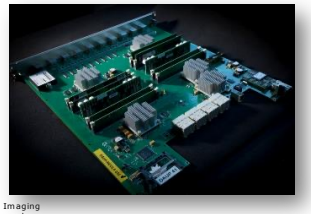
SARUS experimental scanner

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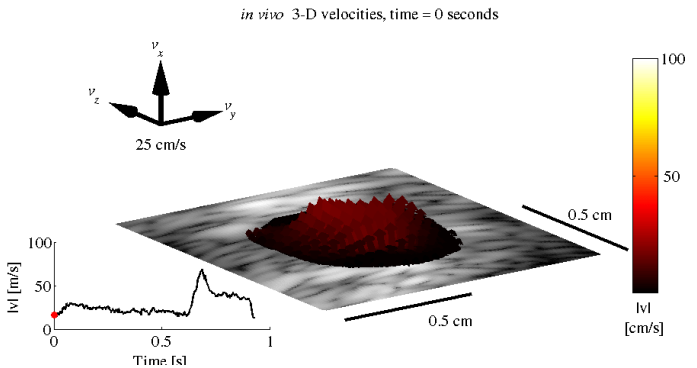
3-D *in-vivo* flow in Carotid Artery



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Problem with Fully Populated Arrays

- *2D full array, 6 cabels*
- *1024 channels, should be at least 4096*
- *Size: 16 x 16 λ*
- *Expensive!*

- *New row-column Array prototype*
- *128 + 128 channels*
- *Size: 128 x 128 λ*
- *Less expensive*
- *Normal cable*

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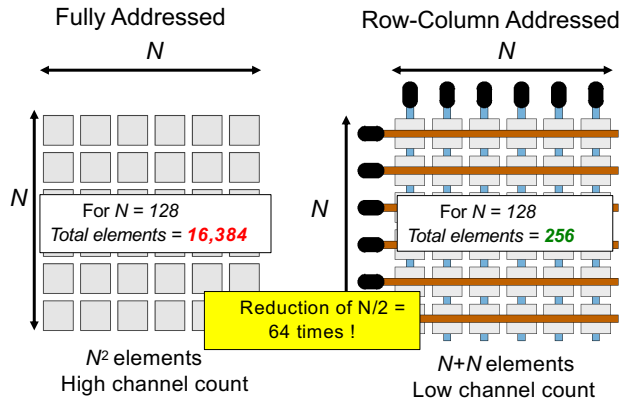
Row-Column Array
Reduction of the Number of Channels



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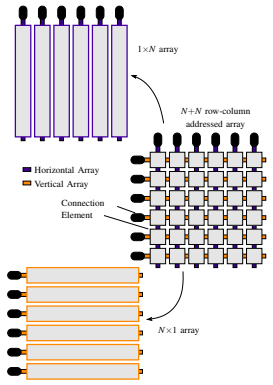
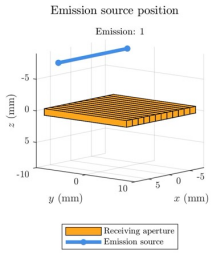
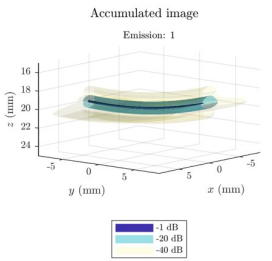
3-D Row-Column Imaging



1. Transmit of cylindrical waves by rows
   48 virtual sources, 32 elements, F#=-0.7
2. Receive on all columns
3. Dual-stage real-time GPU beamformer for low resolution planes and volume extrapolation





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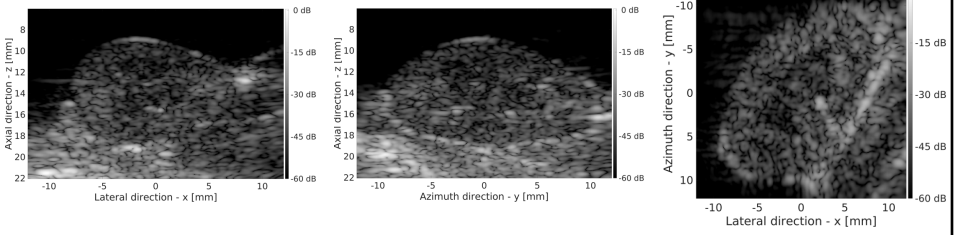
In vivo images of rat kidney

60 dB dynamic range



x-z plane (left, normal view) *y-z plane (orthogonal view)* *C-plane in y-x directions*

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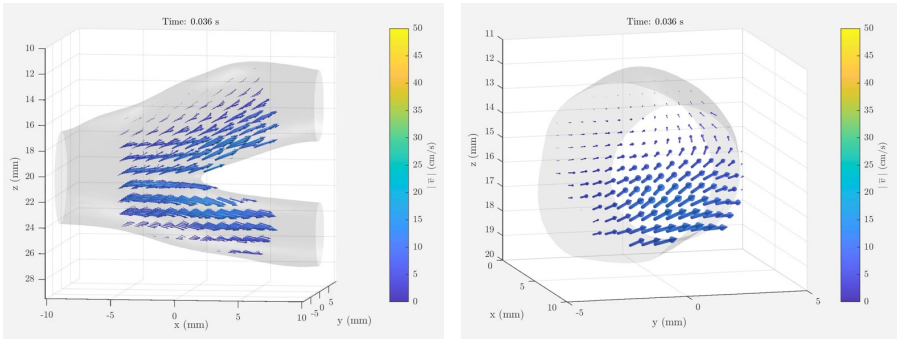
Tensor Velocity Imaging: 3-D Velocity Vector in 4-D: Space + Time



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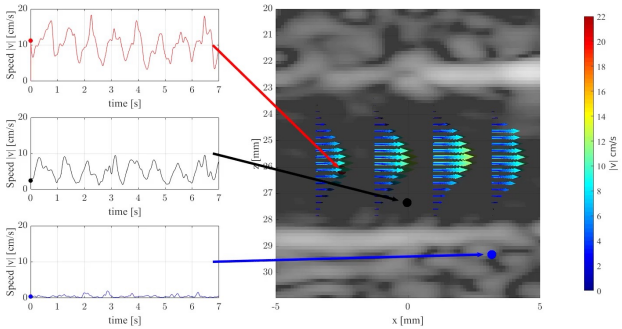
Quantitative Tensor Velocity Imaging



Tensor velocity imaging: 3D velocity vector in 4D using 62+62 RC array

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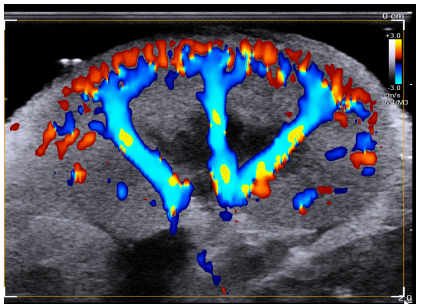
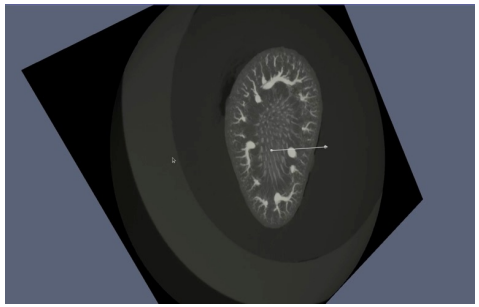
Vasculature in a rat kidney

- CFM from GE scanner of main vasculature
- Actual vascular bed – 3D micro-CT scan with 20 μm voxels





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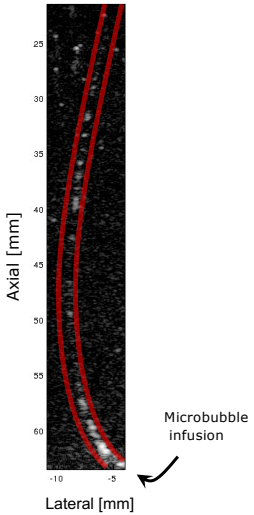
Microbubble tracking for super resolution imaging

- Phantom tube, 200 µm
- Microbubbles injected



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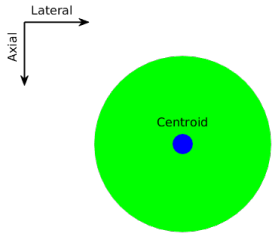
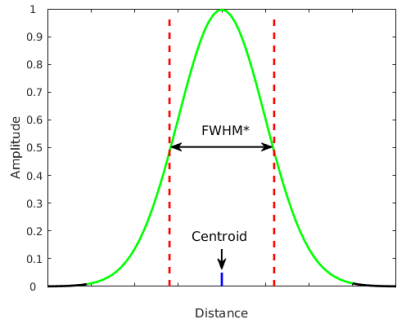
Microbubble Characteristics

- 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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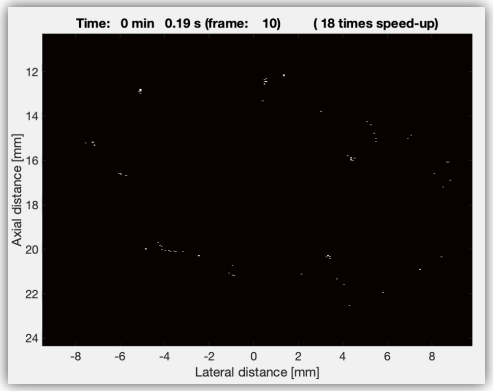
Super Resolution Imaging with Contrast Agents

- Sparse distribution of contrast agent injected
- Amplitude modulation or pulse inversion sequence used
- Position of individual bubbles followed
- Image made from tracking bubbles
- Can reveal the micro-vasculature and it's velocity



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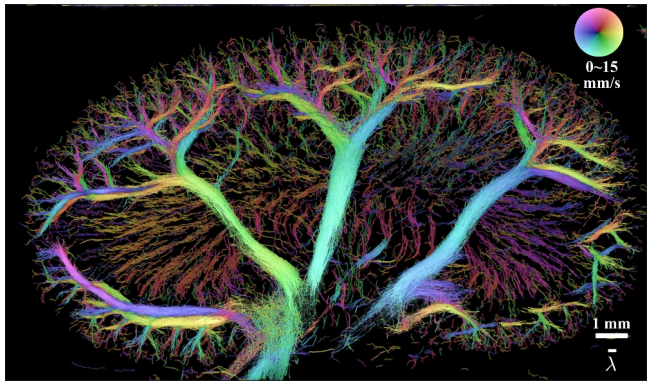
Directional Velocity SRI of Rat Kidney

Hierarchical Kalman Tracking



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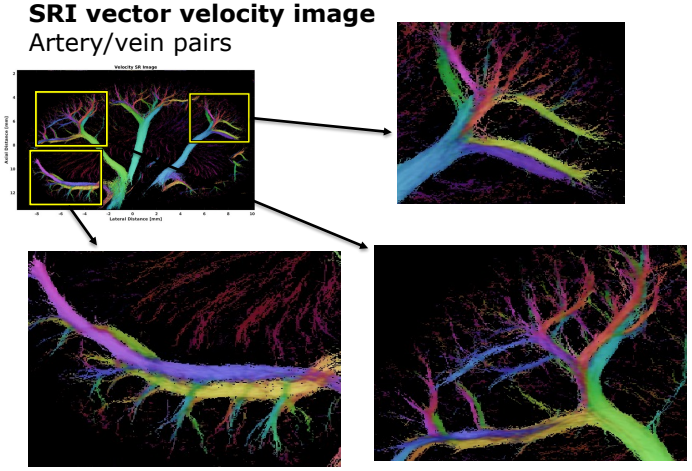
SRI vector velocity image

Artery/vein pairs



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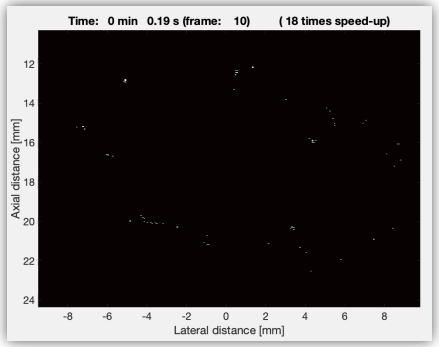
Problems with Current Super Resolution Imaging

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 Image

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SURE:
SUper Resolution ultrasound imaging using Erythrocytes

- Erythrocytes as tracking target:
  - Use advanced imaging to visualize erythrocytes
    - Motion estimation and compensation
    - Tissue subtraction
  - Peaks in speckle pattern indicates flow positions
- Benefits
  - Abundance of targets
  - Full MI can be used
  - Fast imaging
- Challenges
  - Can we compensate for tissue motion?
  - Are peaks inside vessels?
  - Do we attain super resolution?
  - How fast is it?
  - Is it consistent?

Optical video of Erythrocytes in tissue

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SURE 3-D Processing Pipeline

Verasonics Vantage 256
Ultrasound Scanner

Vermon 128 + 128
Row-column 6 MHz
matrix probe

Synthetic Aperture Data Acquisition → GPU dual stage Beamforming → Transverse Oscillation Tensor Motion Estimation → SVD Echo Canceling → 3D Peak Detection & Sub-sample Interpolation → 3D Volume Formation

Motion estimates | Flow image | Detected positions | SURE image

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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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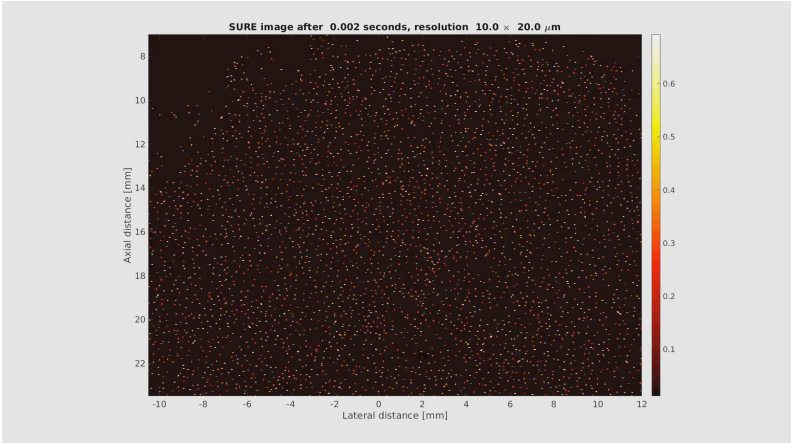

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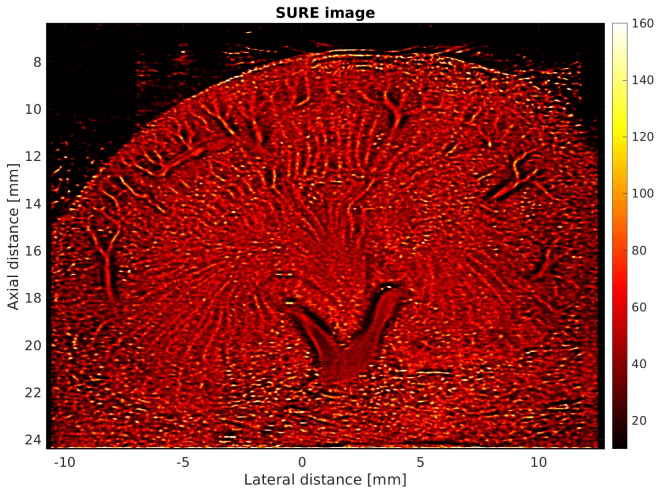

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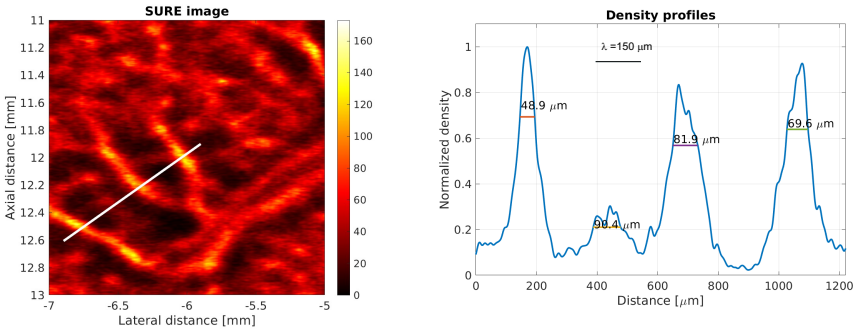
Resolution *in vivo*



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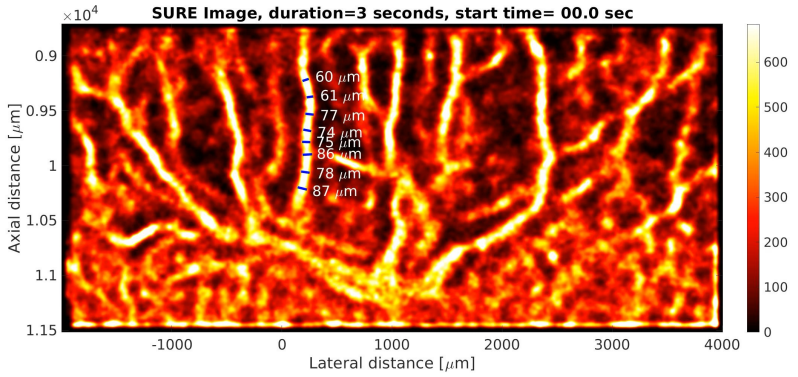
Repeatability:
SURE video: 3 s of data, Different starting times



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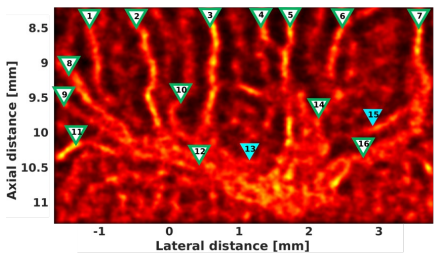
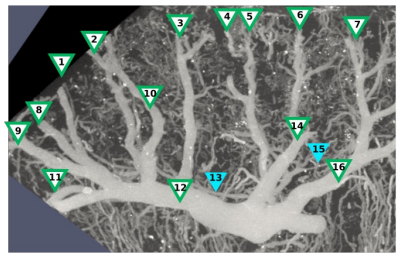
Comparison of SURE image and µCT
5 µm voxel size

In vivo scan, 3 s scan time



SURE intensity map

Euthanatized animal, 20 h scan time



micro-CT, 5 µm

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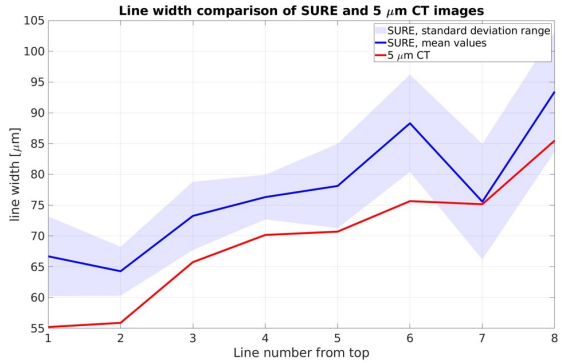
Micro CT with 5 µm resolution and SURE comparison



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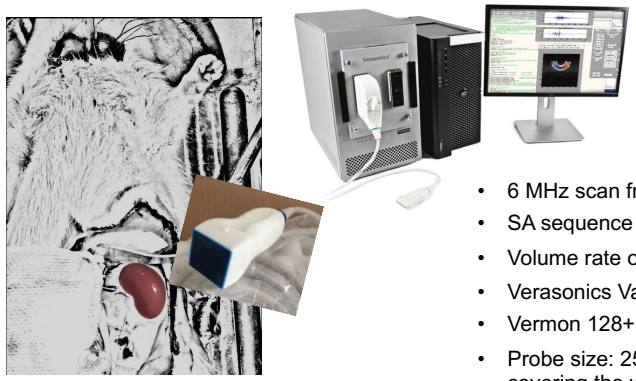
Scanning of Sprague-Dawley Rats



- 6 MHz scan frequency
- SA sequence with 48 emissions
- Volume rate of 250 Hz
- Verasonics Vantage 256 scanner
- Vermon 128+128 RC probe
- Probe size: 25.6 x 25.6 mm covering the whole kidney

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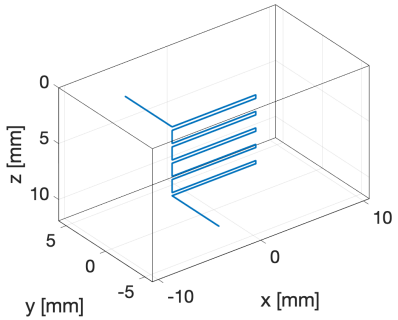
3-D Printed Phantom



- 3-D printed hydrogel micro-phantom, 10 μm voxels
- Size: 20.0 × 12 × 12 mm³
- Single cylindrical 100 μm radius channel
- Parallel tubes with one channel:
  - Center separations: 300 μm to 260 μm
  - Wall-to-wall distances: 100 μm to 60 μm
- Infused at 0.1 μL/s with SonoVue in a 1:1 dilution (high density scattering)

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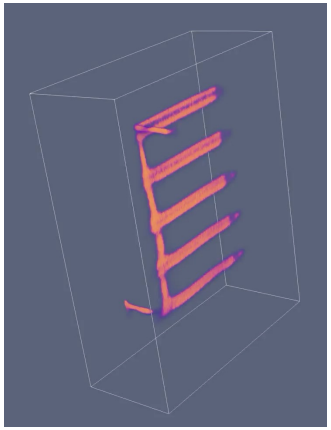
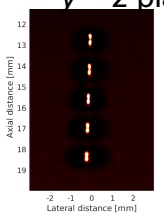
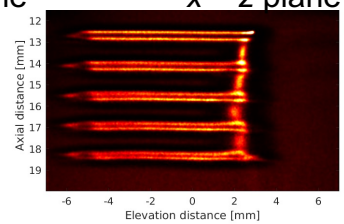
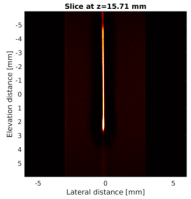


y – *z* plane



x – *z* plane





x - *y* plane

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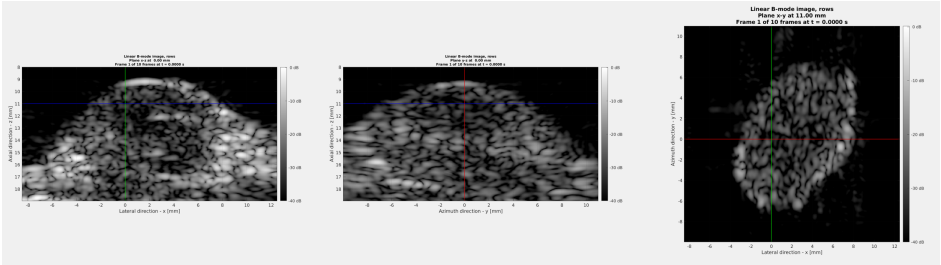
B-mode Volume Slices



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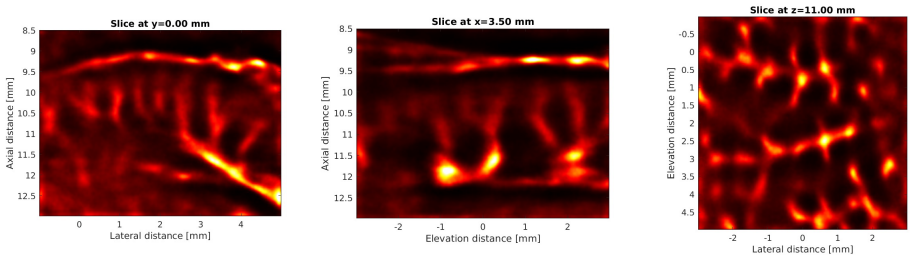
3-D Volume of Rat Kidney Cortex



Planes: $x - z$ $y - z$ x - y

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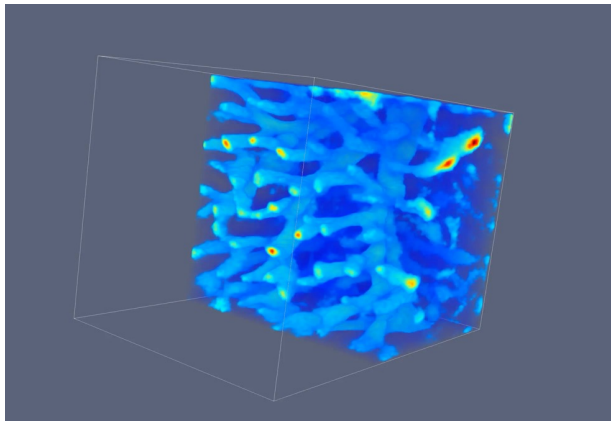
Volume Rendering of Kidney Cortex



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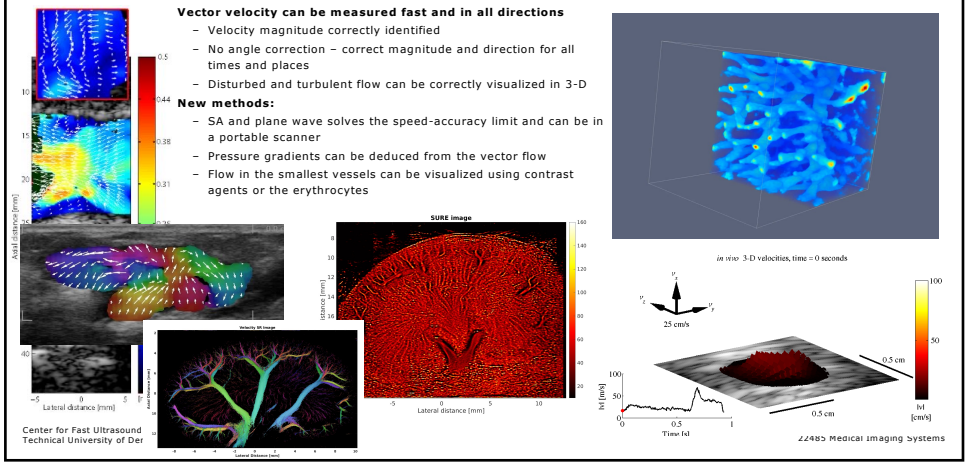
What we can do with ultrasound

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
- Flow in the smallest vessels can be visualized using contrast agents or the erythrocytes



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