Danmarks Tekniske Universitet

Advanced Ultrasound Imaging 2024

Synthetic Aperture Velocity Imaging

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SA Velocity Imaging

Part I:

Synthetic aperture and plane wave velocity imaging

Center for Fast Ultrasound Imaging
Department of Health technology

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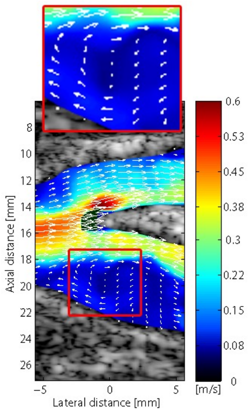
Outline

- Limitations of current ultrasound system
- Potentials and problems of synthetic aperture imaging for motion
- Solving the problems with vector flow and motion
- Ideal sequences for SA imaging for all modes



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Limitations of current ultrasound systems

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

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

- Velocity estimation is poor due to few data samples
- Impossible to see perfusion

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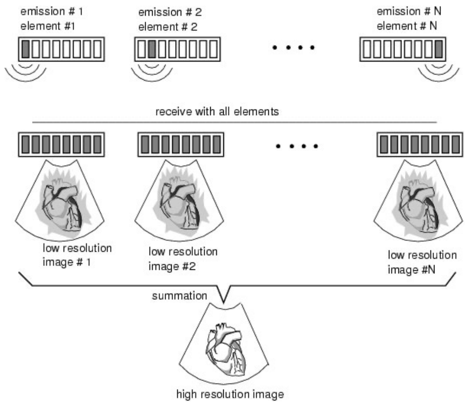
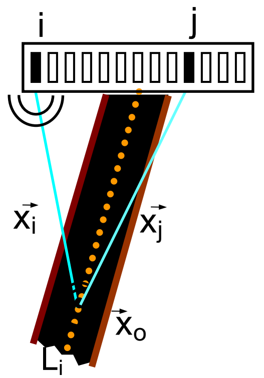
Synthetic aperture imaging



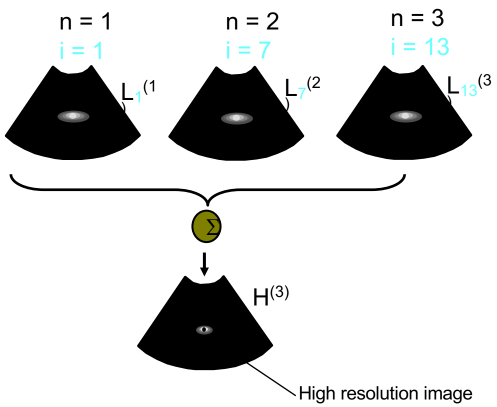
Making a Low Resolution Image



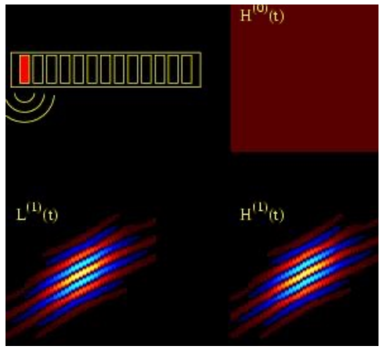
$$L_i(\vec{x}_o) = \sum_{j=1}^{N_{xdc}} a_{ij} r_{ij}(\tau_{ij}(t))$$

$$\tau_{ij} = \frac{|\vec{x}_i| + |\vec{x}_j|}{c}$$

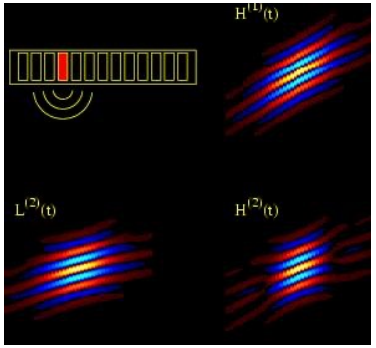
Making a High Resolution Image



Build-up of Focusing



Build-up of Focusing



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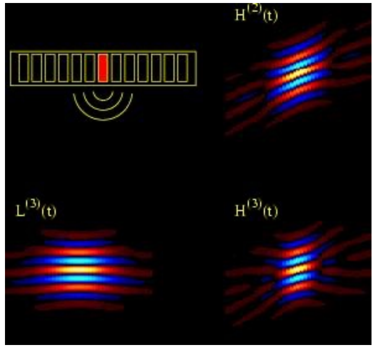
Build-up of Focusing



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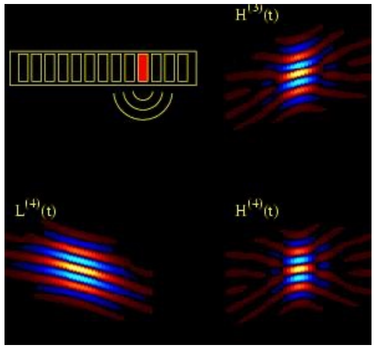
Build-up of Focusing



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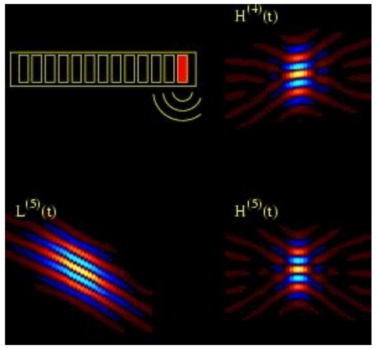
Build-up of Focusing



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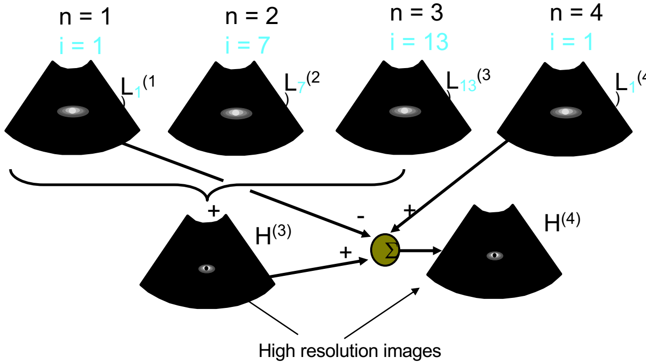
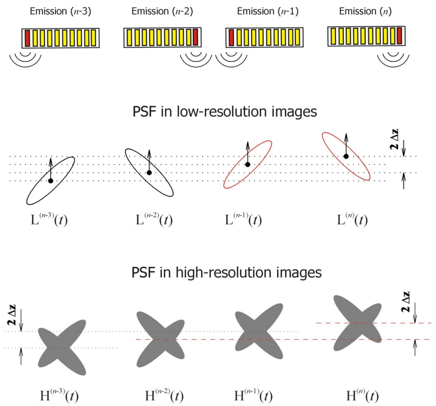
Recursive Ultrasound Imaging



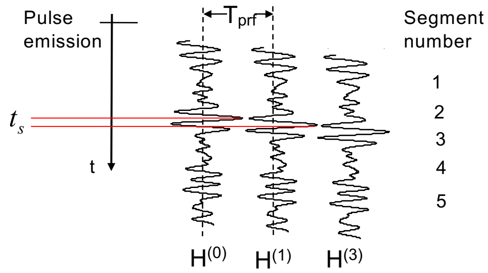
Synthetic Aperture Solution

- Benefits
  - Ideal focusing in transmit and receive
  - De-coupling of frame rate and number of emissions
  - Very high frame rates (at f_{prf})
- Drawbacks
  - Limited depth of penetration
  - No systems are available
  - Cannot do flow
- The rest is about how to solve these problems

Synthetic Aperture Flow Imaging



Cross-correlation Velocity Estimator



1. Cross-correlate segments from two consecutive high-resolution images

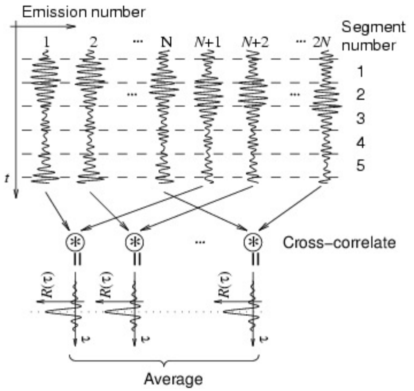
2. Find offset t_s of maximum in cross-correlation function.

$$t_s = \frac{2|\vec{v}|\cos\Theta}{c} T_{prf}$$

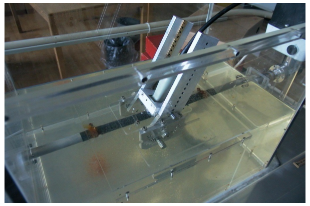
The estimated axial velocity V_n is:

$$\hat{v}_n = \frac{c\hat{t}_s}{2T_{prf}}$$

Recursive Cross-correlation

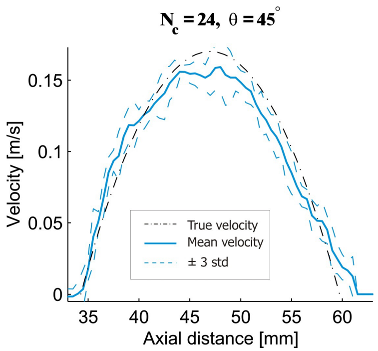


Flow Measured in Flow Rig



- Re-circulating flow rig
- 64 elements, 7 MHz linear array transducer
- 45 degrees flow angle
- 4 emission centers using 11 elements and 20 μs chirp
- 6 x 4 emissions used in estimates

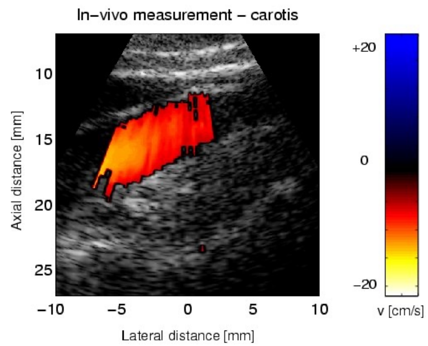
Parabolic Profiles from Flow Rig



Parabolic velocity profile

Standard deviation relative to maximum: 3%

In-vivo SA Flow Image

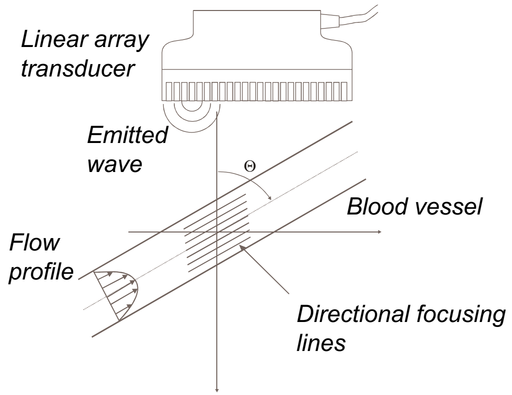


24 emissions used
500 used in traditional systems
-> ***20 times faster***

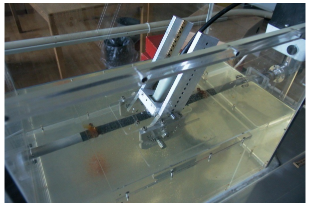
More than 200 images/sec to 15 cm depth

900 images/sec at 4 cm

Directional Velocity Estimation

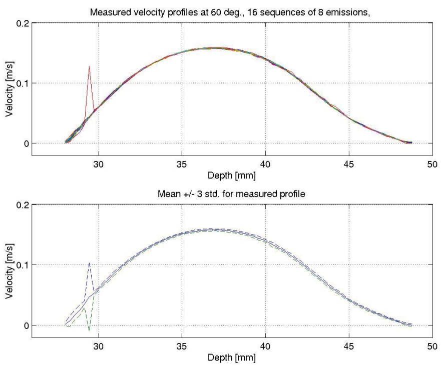


Flow Measured in Flow Rig



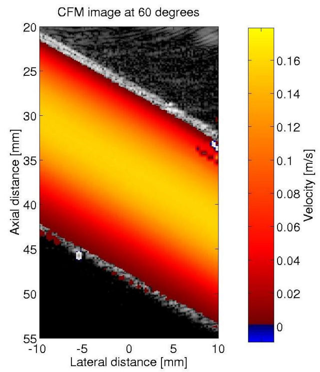
- Re-circulating flow rig
- 128 elements, 7 MHz linear array transducer
- 60 degrees flow angle
- 8 emission centers using 11 elements and 20 μs chirp
- Data from closets 64 elements acquired by RASMUS
- 16 x 8 emissions used in estimates
- f_{prf} = 3 kHz

Velocity Profiles at 60 degrees



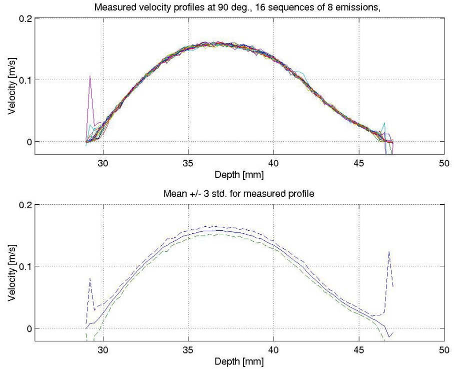
Relative std: 0.36 % (0.65 mm/s)

60 Degrees Flow Image



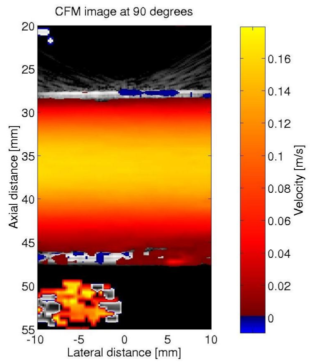
- Full image acquired in 128 emissions
- 60 independent images to a depth of 10 cm can be shown per second
- Relative standard deviation of 0.36 %
- Correct velocity magnitude can be followed everywhere simultaneously at all times

Velocity Profiles at 90 degrees



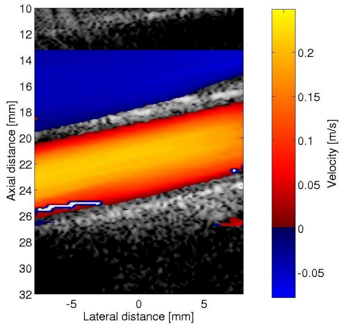
Relative
std: 1.2 %
(2.1 mm/s)

90 Degrees Flow Image

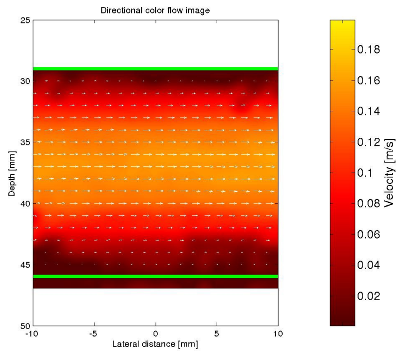


- Full transverse flow
- Relative standard deviation of 1.2 %
- 8 emission centers using 11 elements and 20 μs chirp
- Data from closets 64 elements acquired by RASMUS
- 16 x 8 emissions used in estimates

In-vivo SA Image of Carotis



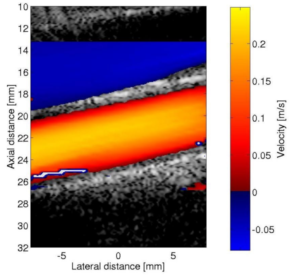
Measured Directional SA Flow Image



Transverse flow, arrows indicate estimated direction and magnitude

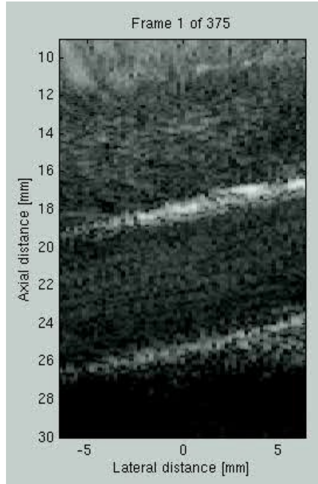
Potential Benefits of SA flow

- Frame rate can be made very high
- Data is available all time at all spatial positions
- Estimates can be averaged over many emissions to give quantitative values
- Stationary echo canceling without initialization and limited filter length
- Flow can be followed any place for all time



B-flow

- The data sets are complete and can be used for other purposes
- B-flow imaging can be made
  - Shows the image after echo canceling
  - Filters out stationary tissue
  - A flow detection techniques



Frame rate: 375 frames/sec,
slowed by a factor of 12

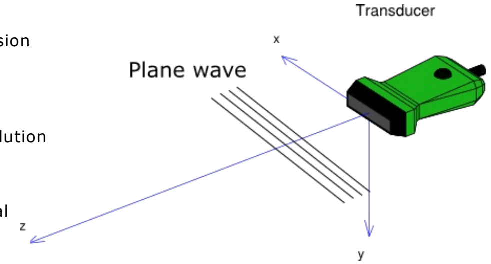
Fast plane wave imaging (Ultrafast imaging)

- Single plane wave emitted
- Full image reconstructed from single emission
- Very fast imaging can be attained with thousand of image per second

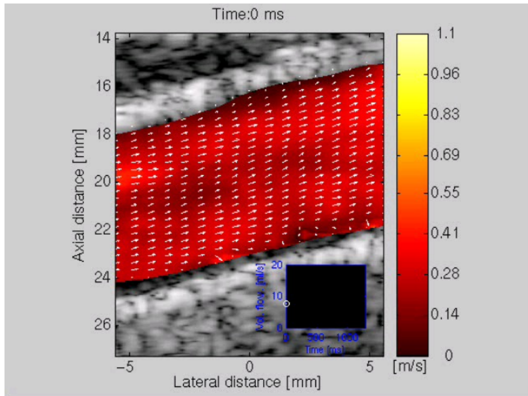
- Flow imaging with excellent temporal resolution
- Vector flow imaging possible

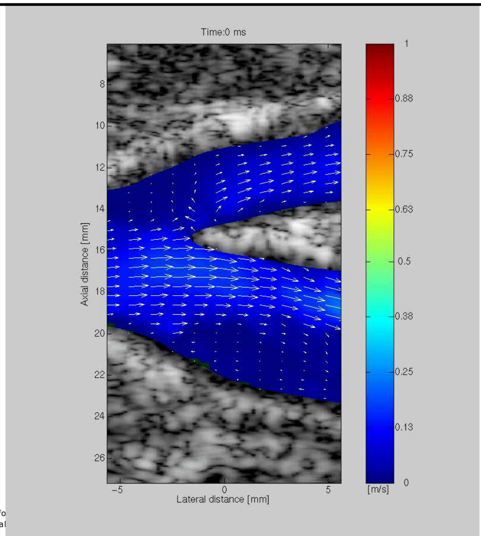
- Implemented on the RASMUS experimental scanner
- Frame rate of more than 100 Hz

- Speckle tracking used for velocity estimation



Frame rate : 100 Hz, Common carotid artery

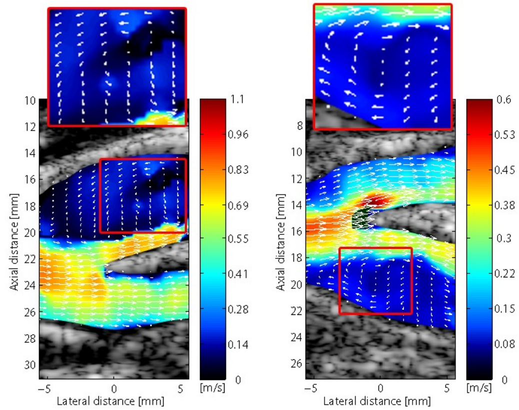


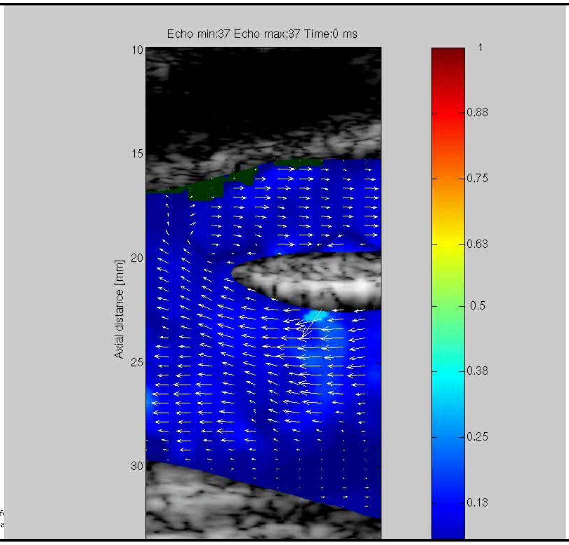


Carotid bifurcation

100 frames/sec

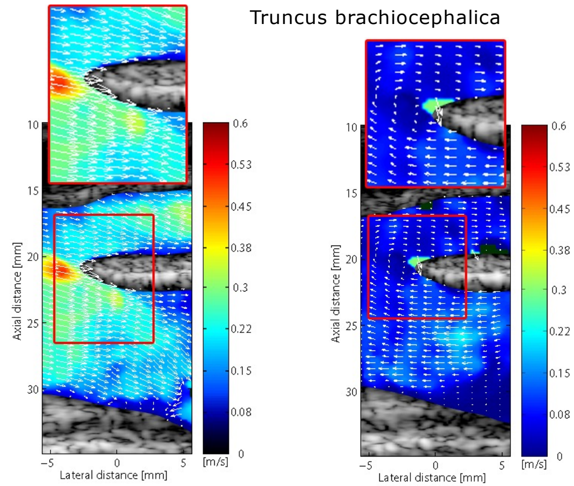
Carotid bifurcations



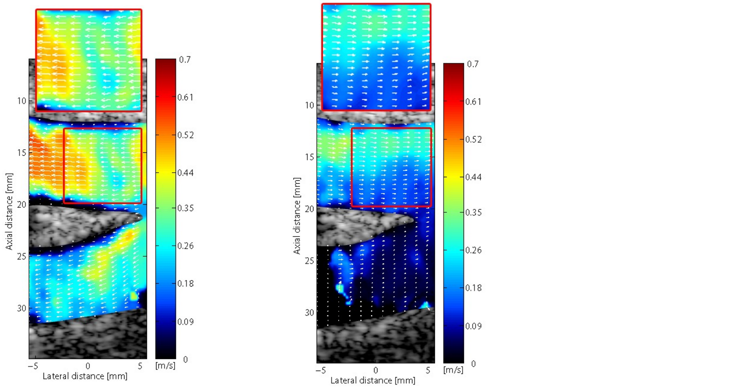


Truncus brachiocephalica, a. subclavia and a. carotis com.

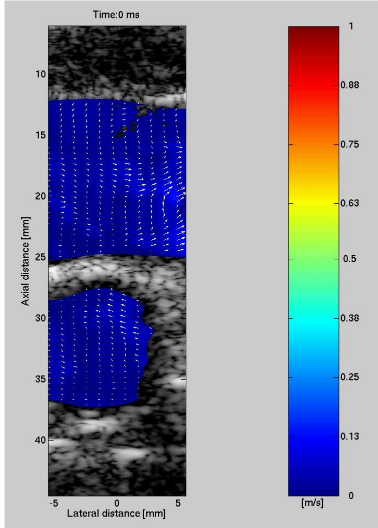
Truncus brachiocephalica



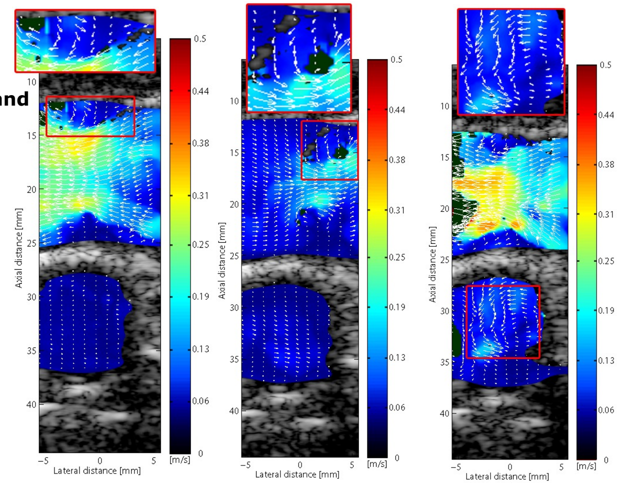
Femoral bifurcation



Jugular vein and carotid artery



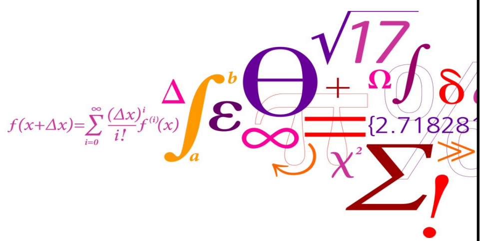
Jugular vein and carotid artery



SA Velocity Imaging

Part II:

What lies ahead?



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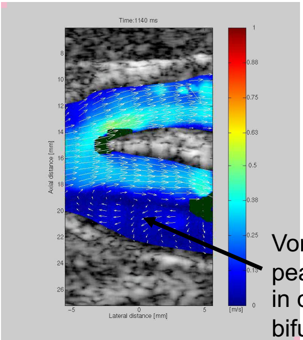
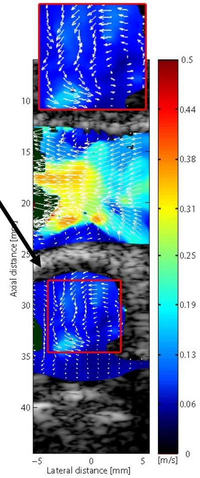
Department of Health technology

3D flow

Rotational flow
in the carotid artery



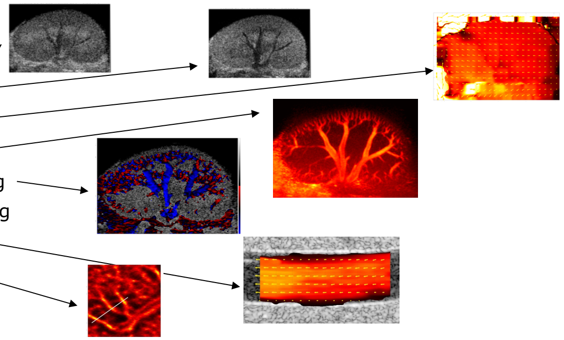


Vortices after
peak systole
in carotid
bifurcation

Demands on ideal imaging sequence

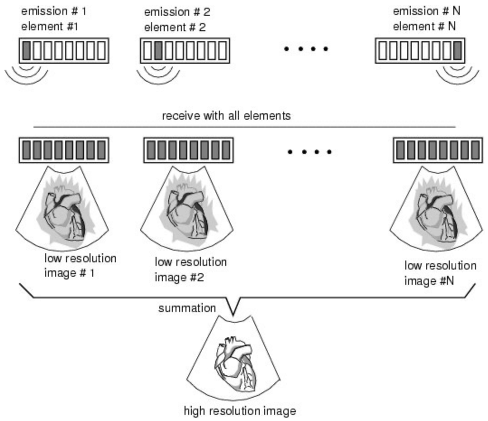
Can we design a single nearly optimal synthetic aperture (SA) acquisition sequences for all imaging modes?

1. B-mode image
2. Non-linear
3. Tissue motion
4. Power Doppler
5. Color flow mapping
6. Vector flow imaging
   - Fast flow
   - Slow flow
7. Super resolution



Would enable retrospective diagnostics involving all the above images

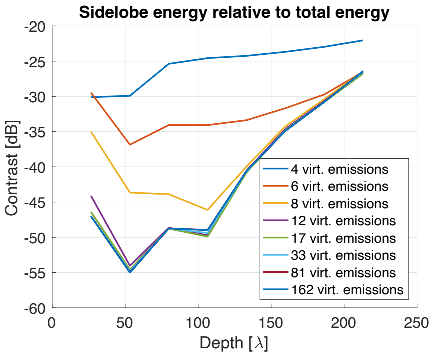
Synthetic Aperture Imaging



Demands

- B-mode
  - High resolution ➡ Wide coverage of aperture
  - High contrast ➡ Many receiving elements and many emissions
- Non-linear imaging
  - Isolation of non-linear component ➡ Repeated emissions (PI or AM)
- Motion estimation
  - Correlation of frames ➡ Repetition of high-resolution images
- Fast motion
  - Short distance between HRI ➡ High f_{prf} and/or short sequences
- Slow flow & super resolution
  - Long acquisition times ➡ Continuous imaging

B-mode Optimization for Linear Array



- Resolution:
  - Spread out virtual source in transmit
  - Use all elements in receive
- Contrast
  - 12 virtual source give near optimal contrast
  - Hanning apodization in transmit and receive processing
- Signal-to-noise ratio:
  - Use 32 elements in transmit
- Non-linear imaging
  - Repeat virtual source with positive and negative emission (pulse inversion)

Motion Estimation Optimization

- High velocities:
  - Maximum detectable velocity v_{max}:

$$v_{max} \propto \lambda f_{prf}$$

λ – Wavelength (c/f_0)
f_{prf} – Pulse repetition frequency

- Solution:
  - Shortest possible time distance between high resolution images
  - Interleaved sequence, repetition of emissions

- Low velocities:
  - Minimum detectable velocity proportional to observation time

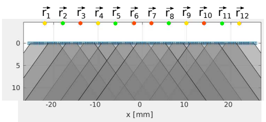
$$N/(f_{prf} N_{emis})$$

  - Observation time limited by tissue motion in the image

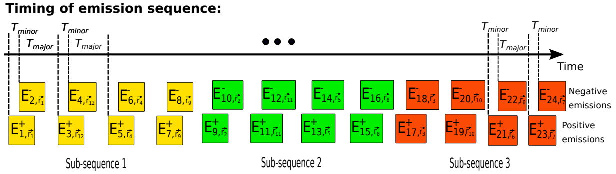
- Solution
  - Motion estimation and correction
  - Continuous data sequence for unlimited observation time

Synthetic Aperture Scan Sequence
Interleaved, Permutated

Position of virtual sources in transmit:

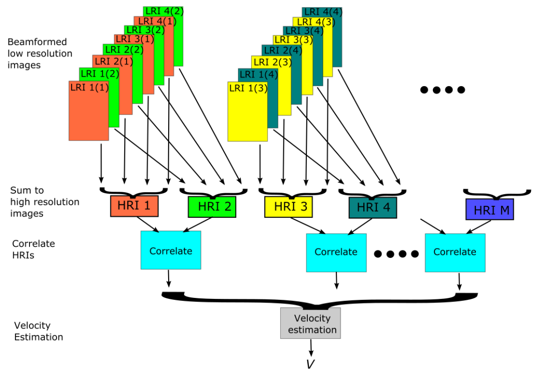


Timing of emission sequence:



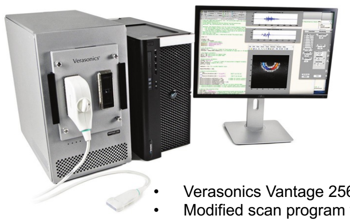
- 12 virtual sources:
  - Good contrast
  - Optimal resolution
- Interleaving:
  - Estimates highest possible velocities
  - Permutation improves high velocity estimation
- Pulse inversion:
  - Non-linear imaging possible
- Continuous data:
  - Low velocity estimation

Synthetic Aperture Sequence



- Synthetic aperture sequence with interleaved emissions
- Positive and negative emissions for PI imaging
- 12 virtual emissions using 32 elements and F# = -0.7
- Virtual sources evenly spread over the aperture
- Continuous data acquisition for *2 x 12* emissions
- Applicable for any linear or phased array probe

Verasonics Scanning Setup



- Verasonics Vantage 256 scanner
- Modified scan program with SARUS commands
- Real time GPU preview
- Continuous streaming to RAM at 3 Gbytes/s
- GPU beamforming and processing after acquisition
- SA PI sequence with 2 x 12 emissions
- HRI frame rate of 208 Hz, f_{prf}=5 kHz

GE L8-18i Hockey stick probe

- Operated at 10 MHz
- In vivo scanning of exposed kidney of Sprague-Dawley rat

GE L3-12D linear array probe

- Operated at 6 MHz
- Scanning of carotid bifurcation phantom with pulsating flow

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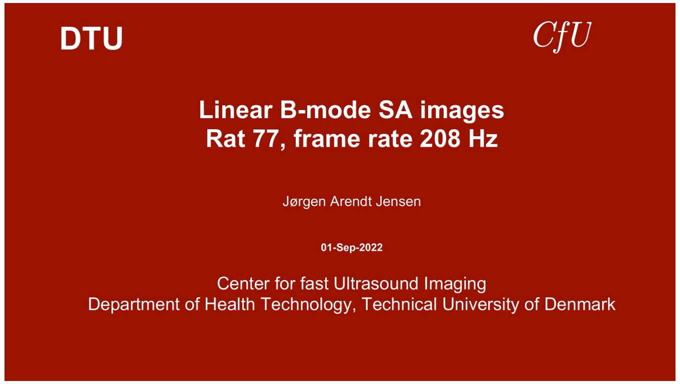
B-mode Image of Rat Kidney

Frame rate 208 Hz



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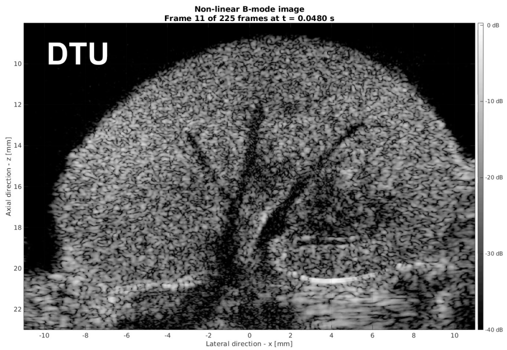
Non-linear B-mode Image of Rat Kidney

Frame rate 208 Hz



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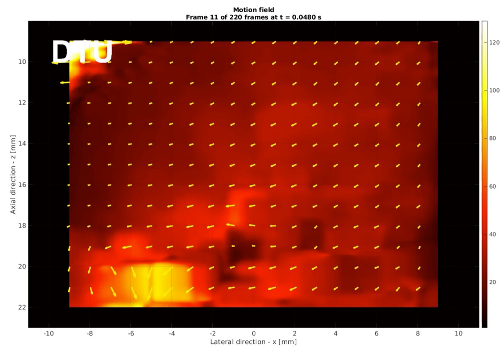
Tissue Motion of Rat Kidney

Frame rate 208 Hz



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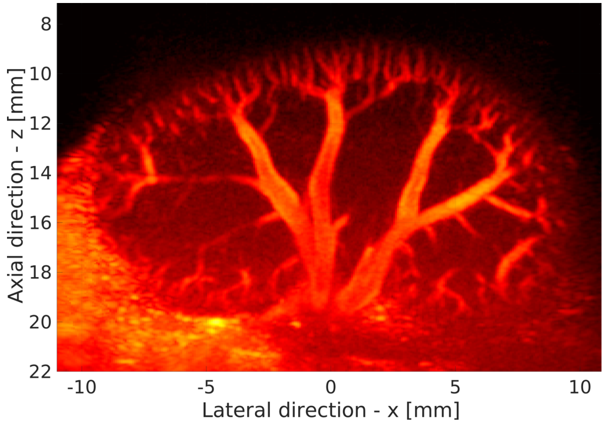
Power Doppler Image of Rat Kidney



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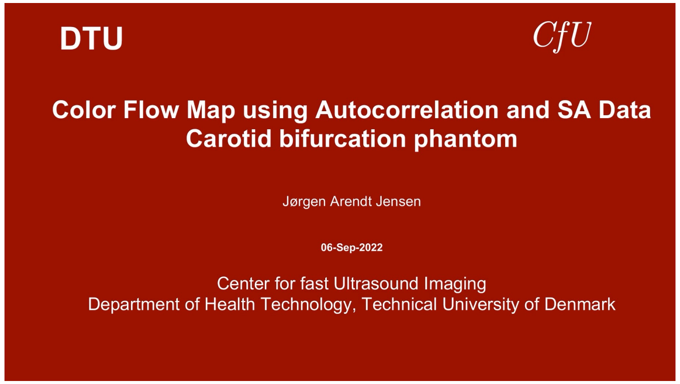
Color Flow Map of Bifurcation Phantom

Frame rate 208 Hz



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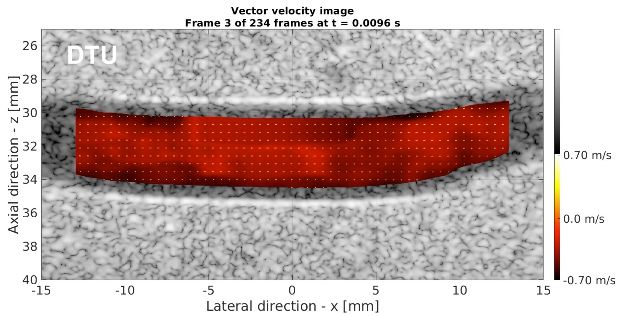
Vector Flow Image, Bifurcation Phantom

Frame rate 208 Hz



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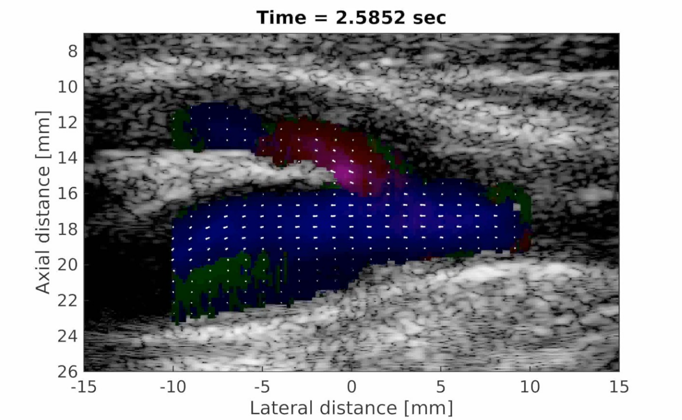
SA Vector Flow Imaging in Carotid bifurcation
Frame Rate: 2000 Hz



Villagomez et al, IUS 2015

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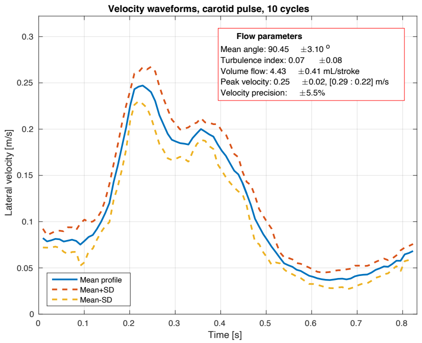
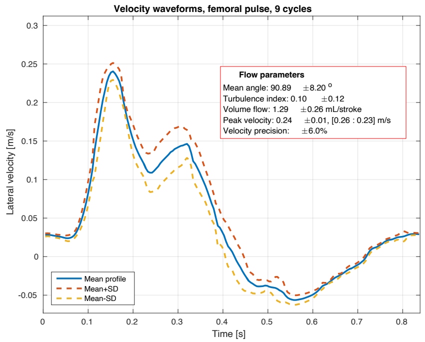
Quantification from multiple heart beats





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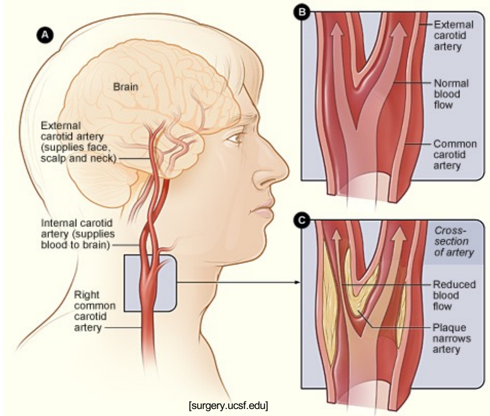
Pressure Gradient Measurements



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Estimating pressure gradients from Navier-Stokes equation

Temporal acceleration

Pressure gradient

Neglect gravitation as patient lies down

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

$$m\cdot a = F$$

Spatial acceleration

Neglect viscosity due to large vessels

VFI can estimate both spatial and temporal accelerations

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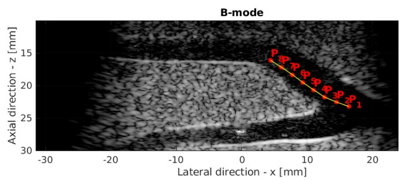
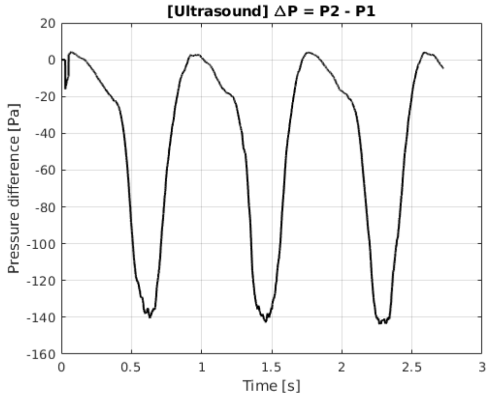
Pressure Gradients in Carotid Bifurcation Phantom



Standard deviation of a 2.2 Pa to 3.2 Pa

An order of magnitude more precise that pressure wires and catheters



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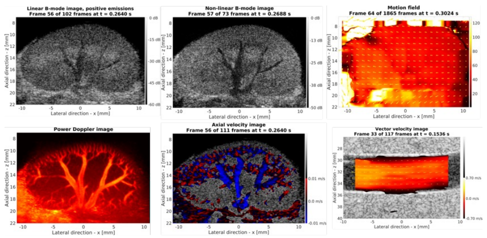
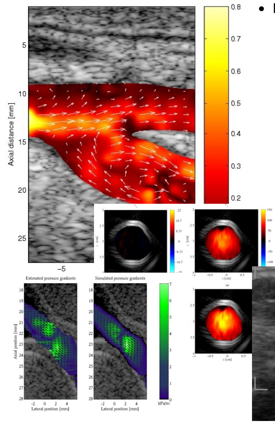
Synthetic Aperture Imaging can give a Paradigm Shift in Ultrasound



- Universal SA sequence can be made
- Near optimal performance with 12 virtual sources
- Pulse inversion and interleaving yields
  - Non-linear images
  - Fast motion estimation
- Continuous data gives
  - Precise velocity estimates
  - Low velocity
  - Pressure gradients and quantification
  - Super resolution
- Images can be made retrospectively from the complete data set for precise diagnosis

Perspective on vector velocity imaging



- **New flow methods:**
  - Pressure gradients can be deduced from the vector flow
  - Transverse spectral velocity estimation
  - 3D vector velocity imaging possible
  - Very fast vector flow imaging can be made with synthetic aperture and plane wave emission
  - Very low velocity flow can be visualized