Advanced Ultrasound Imaging 2023

Synthetic Aperture Velocity Imaging

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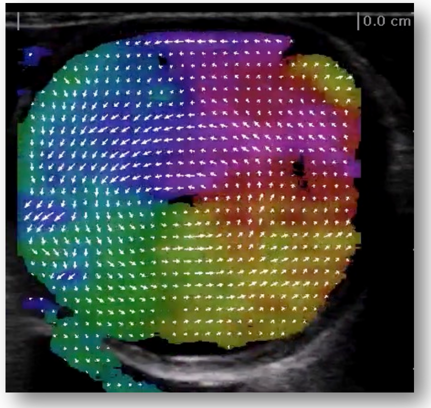
1

Outline

- Limitations of current ultrasound system
- Potentials and problems of synthetic aperture flow imaging
- Solving the problems with vector flow and motion
- Application in practice – pre-clinical test
- Can we make quantitative 2-D images for all image types?
  - Non-linear/linear
  - Vector Flow fast-slow
  - Super resolution imaging
- Quantification and slow flow possibilities
- What about 3-D Tensor Velocity Imaging?

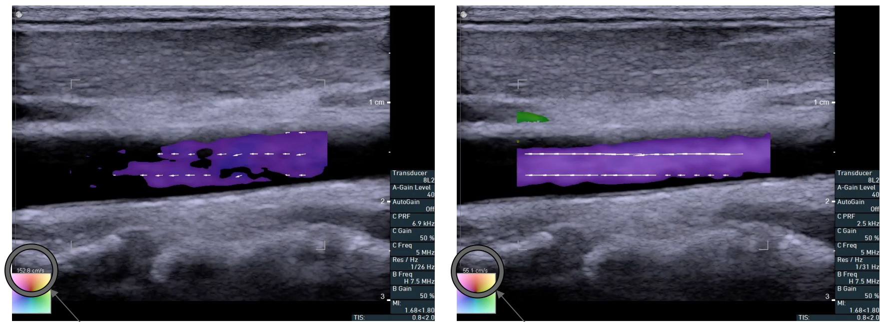


Pulsating rotational flow in the Aorta

2

Frame Rate problem:

Limited Dynamic Range in VFI and CFM



V_{max} = 152.8 cm/s

V_{max} = 55.1 cm/s

3

Limitations of current ultrasound systems

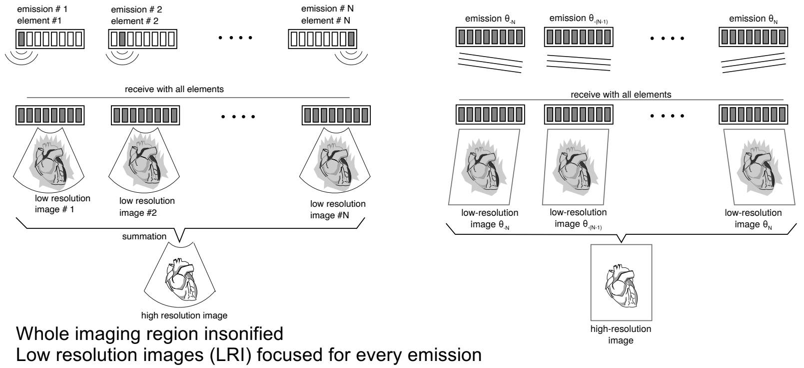
- Only one transmit focus
- Frame rate is limited especially for blood flow and 3D imaging

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

- Velocity estimation is poor due to few data samples
- Impossible to see perfusion
- Images are diffraction limited
- 3-D data rates are a major problem

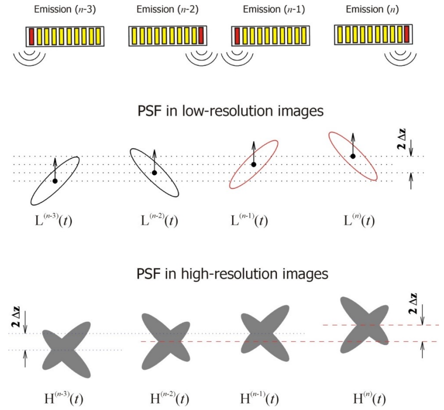
4

Synthetic Aperture and UltraFast Imaging



- Whole imaging region insonified
- Low resolution images (LRI) focused for every emission
- All LRIs combined to High Resolution Image (HRI)
- Dynamic focusing in both transmit and receive everywhere

Synthetic Aperture Flow Imaging

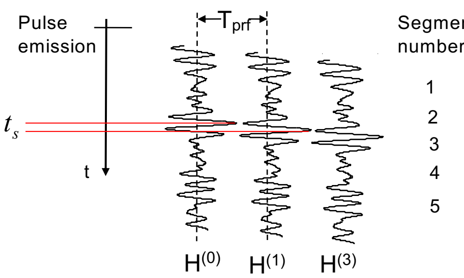


- HRI(1) = LRI(1)+LRI(2) equal to HRI(3) = LRI(3)+LRI(4) apart from displacement
- Correlation can yield displacement and, thus, velocity
- Continuous data everywhere
- Ideal for low velocity flow
- Contrast depends on length *N* of sequence
- Maximum detectable velocity given by:

$$v_{\max} \approx \frac{\lambda/4}{NT_{prf}} = \frac{cf_{prf}}{4Nf_0}$$

Nikolov & Jensen: IEEE UFFC, 2003, 50(7), pp. 848-856

Cross-correlation Velocity Estimator



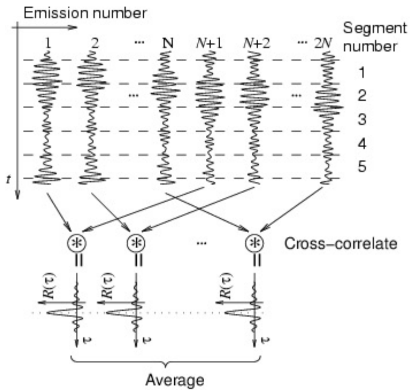
1. Cross-correlate segments from two consecutive high-resolution images

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

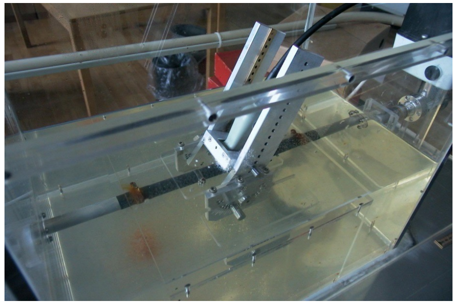
$$t_s = \frac{2|\vec{v}|\cos\Theta}{c} T_{prf}$$

The estimated axial velocity V_n is: $$\hat{v}_n = \frac{c\hat{t}_s}{2T_{prf}}$$

Recursive Cross-correlation

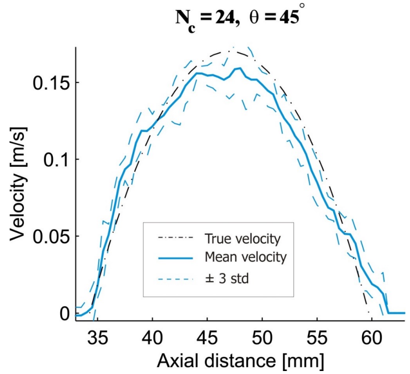


Flow Measured in Flow Rig



- 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

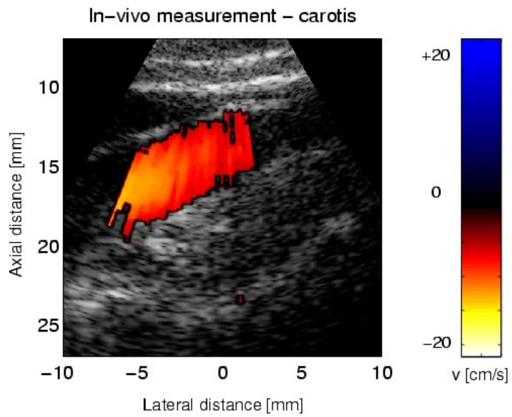
First SA Velocity Image from Flow Rig



- Parabolic velocity profile
- Standard deviation relative to maximum: 3%
- 4 LRI for one HRI
  6 HRIs/estimate
- 6,000 images/s at f_{prf}=25 kHz

Nikolov & Jensen: IEEE UFFC, 2003, 50(7), pp. 848-856 and IUS 2001

In-vivo SA Flow Image

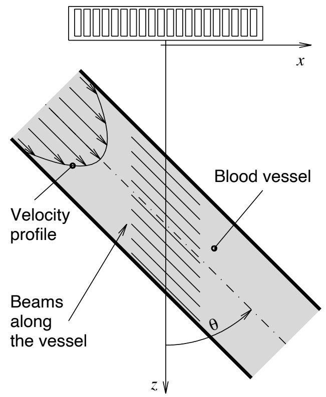


24 emissions used
500 used in traditional systems
-> ***20 times faster***

More than
200 images/sec
to 15 cm depth

900 images/sec
at 4 cm

Directional beamforming



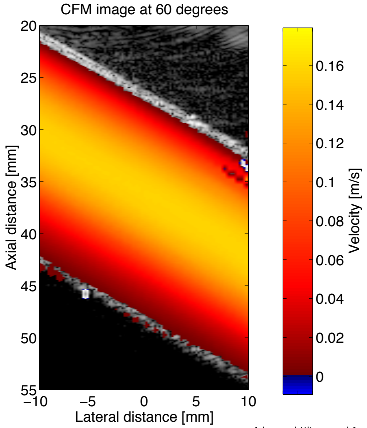
- Beamform along flow direction
- Cross-correlation to find velocity magnitude

- Minimizes de-correlation from velocity gradient
- Yields very precise estimates
- Possible to estimate high velocities

Jensen and Nikolov, IEEE UFFC, 2004, 51(9), pp. 1107-1118

Directional SA Flow Imaging

- 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

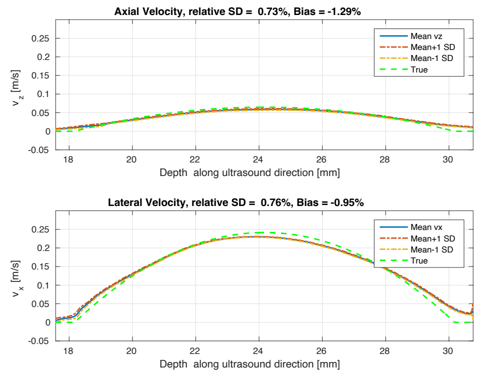


Jensen and Nikolov, IEEE UFFC, 2004, 51(9), pp. 1107-1118

13

Velocity profiles in flow rig at 75 degrees

Directional Transverse Oscillation, cross-correlation estimator



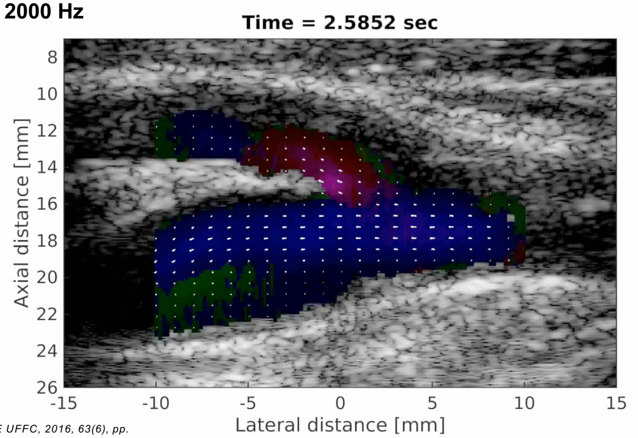
- Measured data
- Fully quantified vector flow:
  - 0.76% SD
  - -1.29% bias
- Hundred to thousands of frames can be presented per second

Jensen: IEEE UFFC, 2019, 66(6), pp. 1024-1031 & 1032-1038

14

SA Vector Flow Imaging in Carotid bifurcation

Frame Rate: 2000 Hz

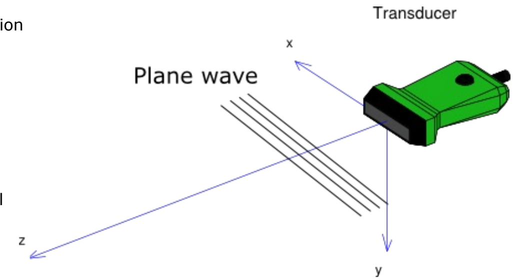


Villagomez-Hoyos et al., IEEE UFFC, 2016, 63(6), pp. 842-853

15

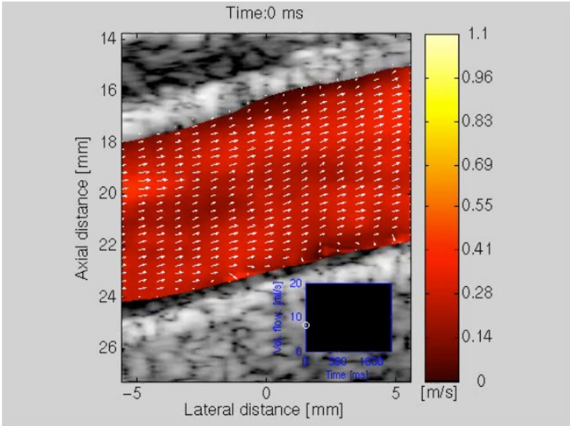
Fast plane wave imaging

- 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



16

Frame rate : 100 Hz, Common carotid artery



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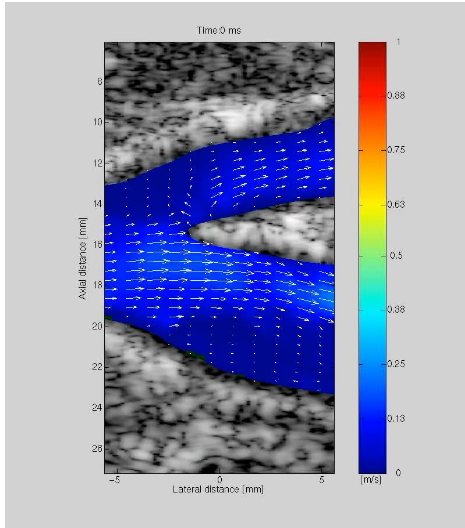
17



Carotid bifurcation

100 frames/sec

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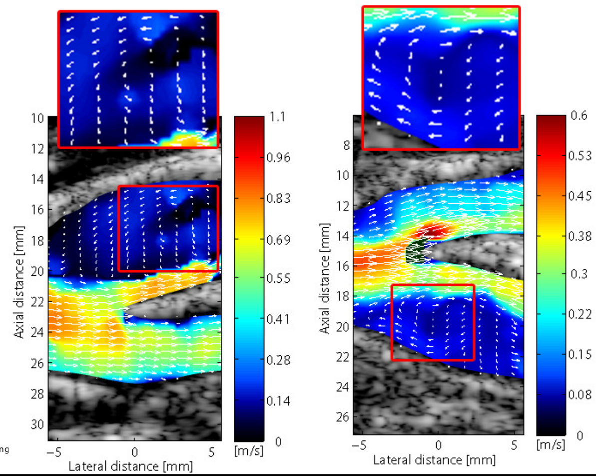
Carotid bifurcation



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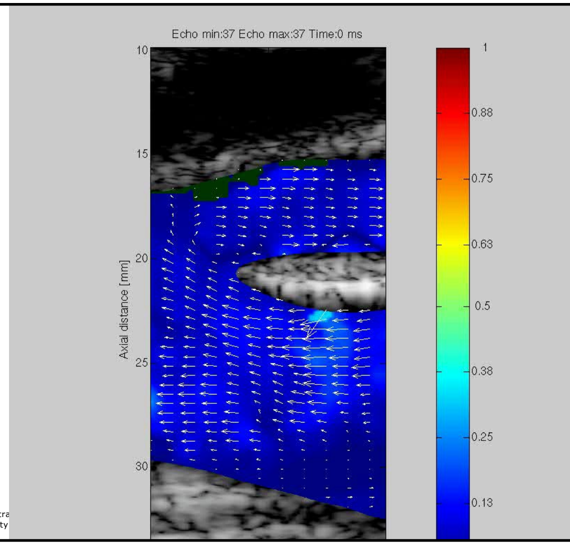
19



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

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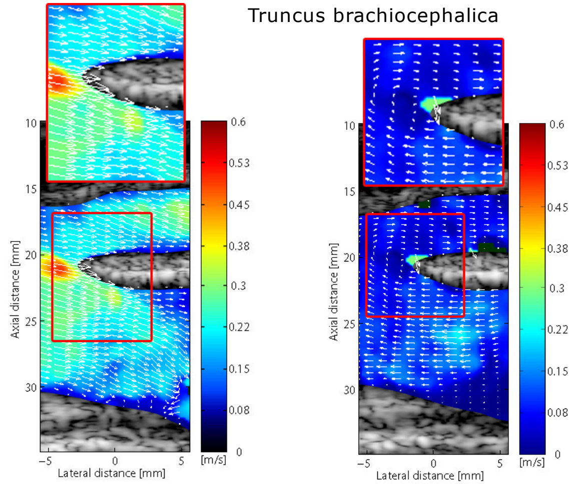
20

Truncus brachiocephalica

DTU



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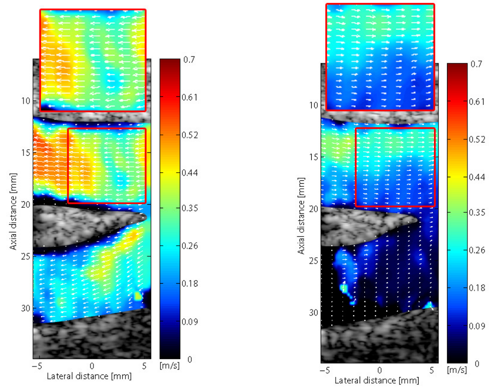
21

Femoral bifurcation

DTU



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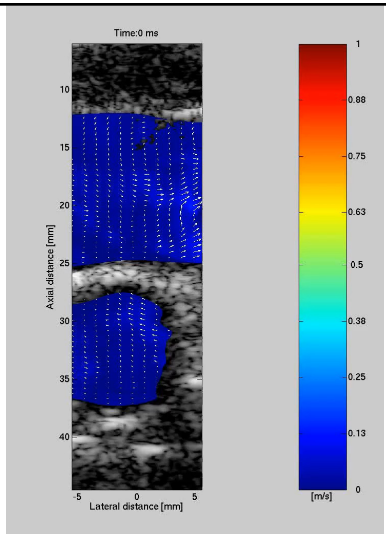
22

Jugular Vein and Carotid Artery With Ultrafast Plane Wave Imaging



DTU

Hansen et al., UMS, 2009, 30, pp. 471-476

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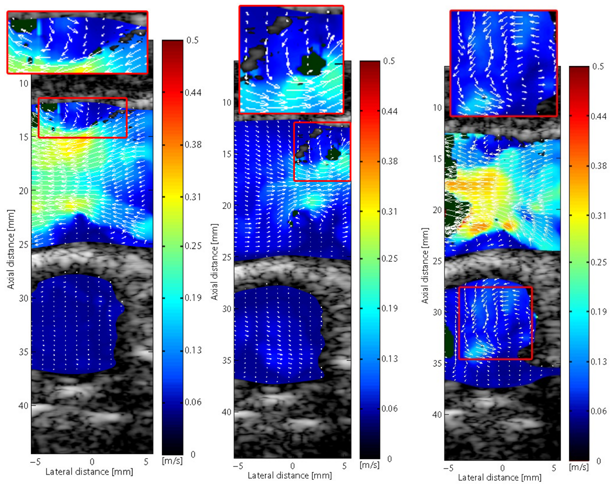
23

DTU



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Jugular vein and carotid artery

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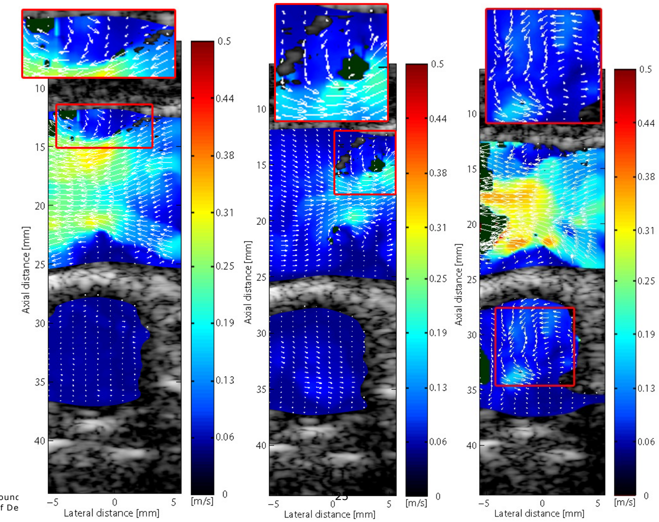
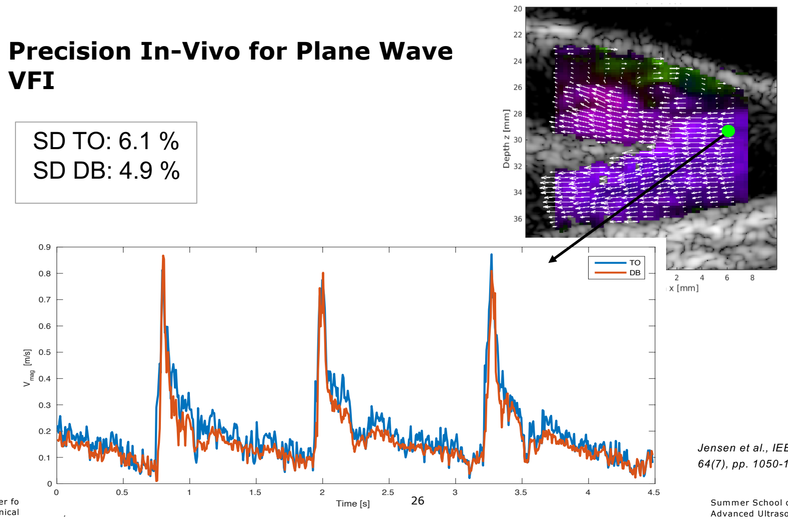
24



Hansen et al., UMS, 2009, 30, pp. 471-476

Precision In-Vivo for Plane Wave VFI

SD TO: 6.1 %
SD DB: 4.9 %

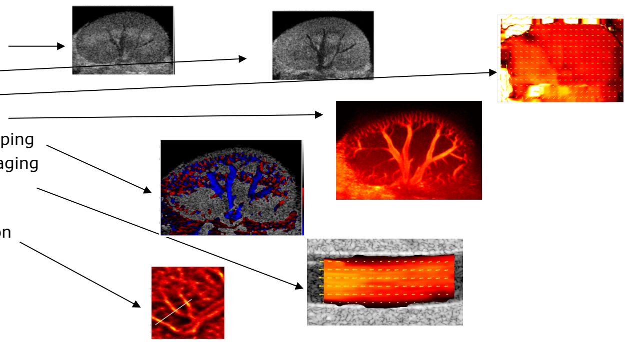


Jensen et al., IEEE UFFC, 2017, 64(7), pp. 1050-1062

Demands on Ideal Synthetic Aperture 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

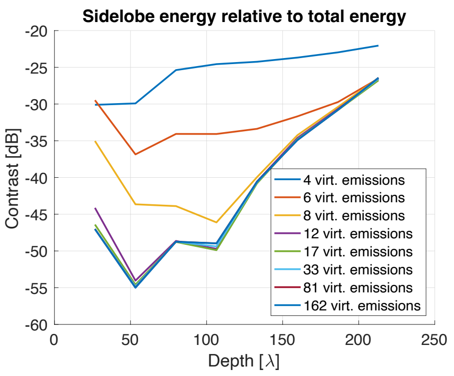


- Would enable retrospective diagnostics involving all the above images

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
  - Long acquisition times ➡ Continuous imaging

B-mode Optimization



- Resolution:
  - Spread out virtual source as much as possible
  - 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

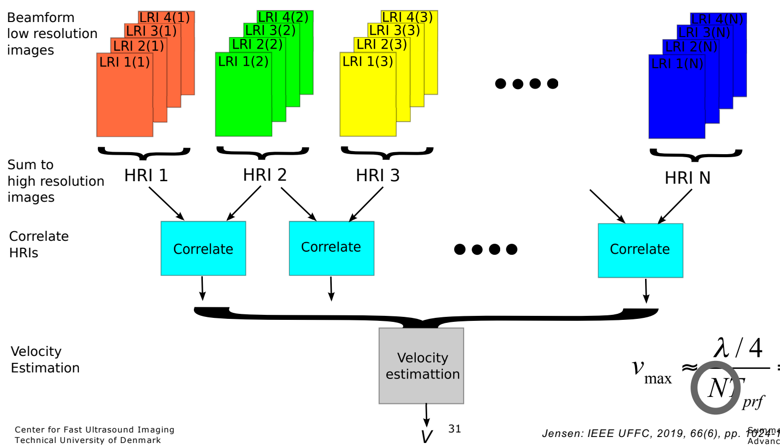
- High velocities:
  - Maximum detectable velocity v_{max}:

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

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

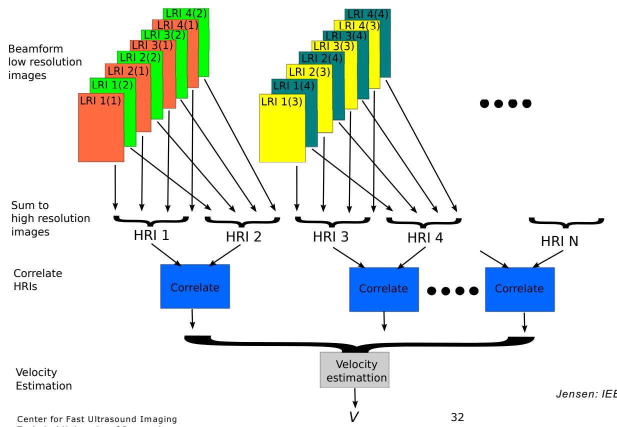
Drawback of SA Velocity Imaging



$$v_{max} \approx \frac{\lambda/4}{N T_{prf}} = \frac{c f_{prf}}{4 N f_0}$$

Jensen: IEEE UFFC, 2019, 66(6), pp. 1024-1031 & 1032-1038

SA VFI Interleaved Sequence

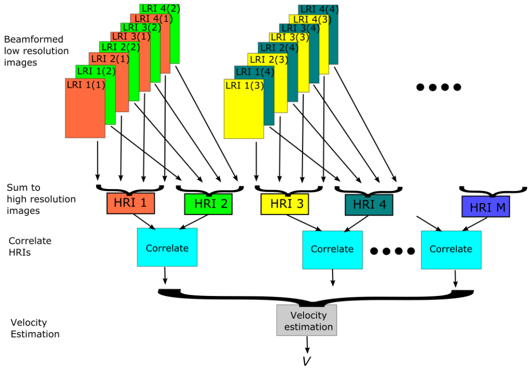


- 5 Virtual sources
- Interleaved with + - + for each virtual source – Pulse Inversion (5x3=15 LRI sequence)
- Data acquired using SARUS
- Phased array 3 MHz, 128 elements

$$v_{max} \approx \frac{\lambda/4}{T_{prf}} = \frac{c f_{prf}}{4 f_0}$$

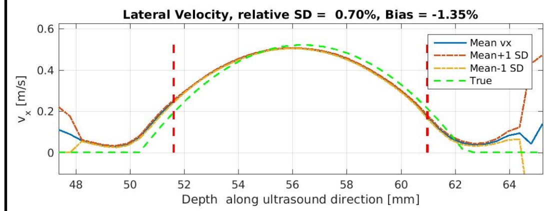
Jensen: IEEE UFFC, 2019, 66(6), pp. 1024-1031 & 1032-1038

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

Estimates for Measured, Interleaved Data



Mean velocity profile at 75 degrees,
f_{prf}=450 Hz & directional beamforming

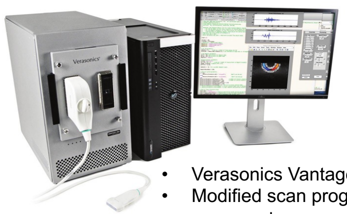
- Directional beamforming and interleaved sequence
- SARUS measurements in flow rig
- f_{prf} = 450 Hz
- Effective f_{prf} = 450/15=30 Hz
- Bias: -1.35%, SD=0.70%

- V_{max}=10 m/s for f_{prf}=9 kHz
- Even possible at f_{prf}=225 Hz @ 90°

Corresponds to V_{max} = 23.1 m/s @ f_{prf} = 10 kHz

Jensen: IEEE UFFC, 2019, 66(6), pp. 1024-1031 & 1032-1038

Verasonics Scanning Setup



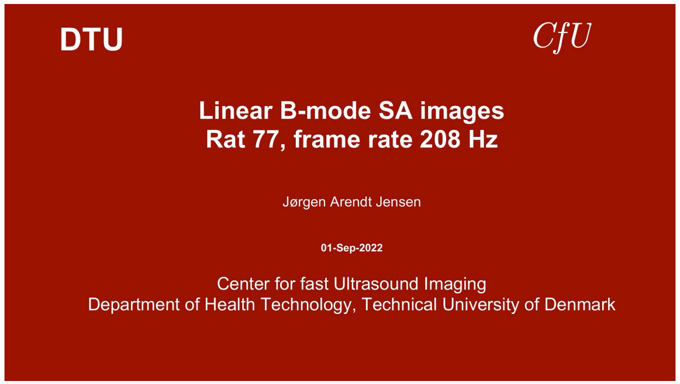
- Verasonics Vantage 256 scanner
- Modified scan program with SARUS commands
- Real time GPU preview
- Continuous streaming to RAM at 3 Gbytes/s
- GPU beamforming and processing after acquisition
- SA PI sequence with 2 x 12 emissions
- HRI frame rate of 208 Hz

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

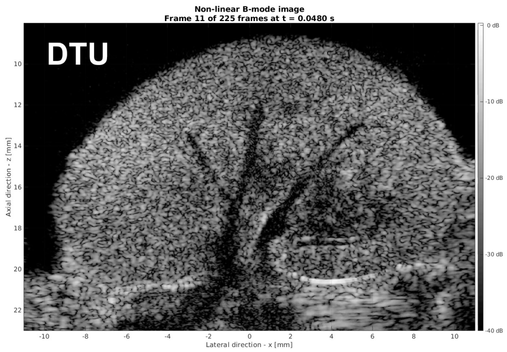
B-mode Image of Rat Kidney

Frame rate 208 Hz



Non-linear B-mode Image of Rat Kidney

Frame rate 208 Hz



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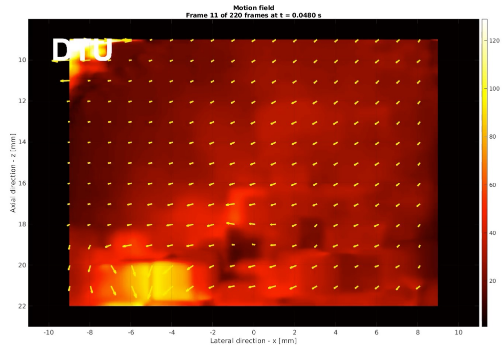
Tissue Motion of Rat Kidney

Frame rate 208 Hz



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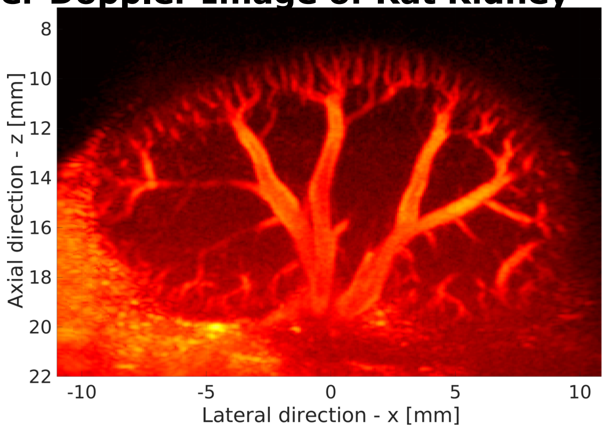
Power Doppler Image of Rat Kidney



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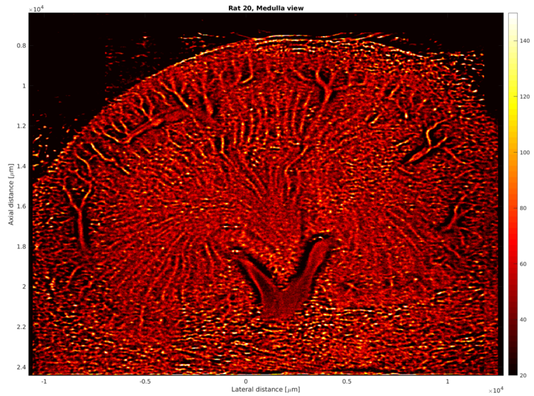
Super Resolution Image of Rat Kidney

SURE – SUper **R**esolution using **E**rythrocytes



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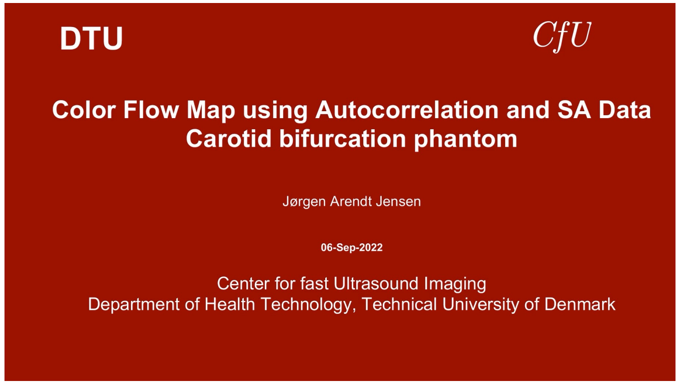
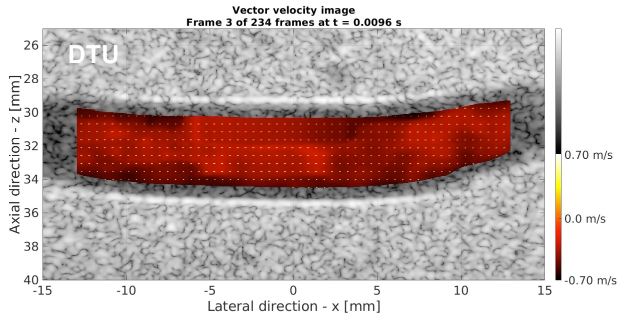
Color Flow Map of Bifurcation Phantom

Frame rate 208 Hz

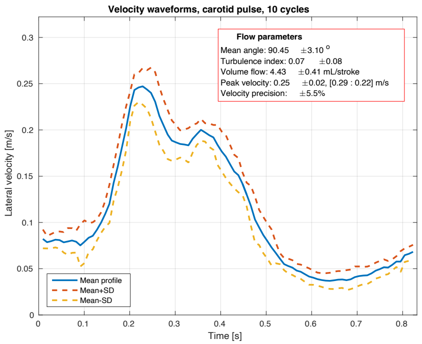


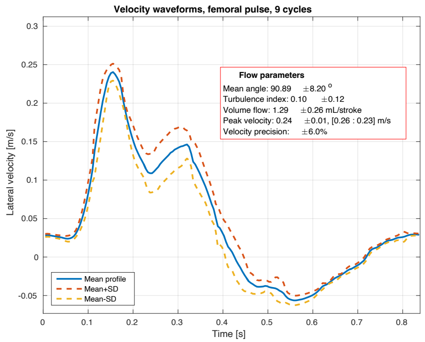
Vector Flow Image, Bifurcation Phantom

Frame rate 208 Hz

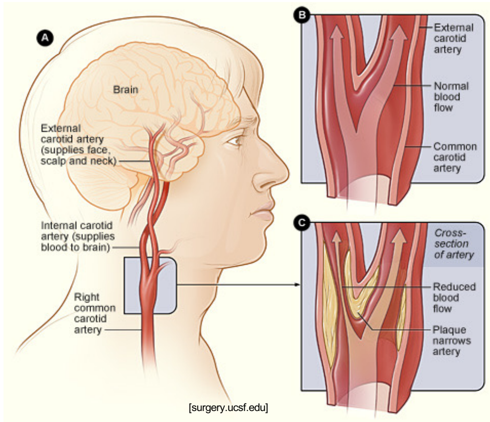


Quantification from multiple heart beats





Pressure Gradient Measurements



Estimating pressure gradients from Navier-Stokes equation

Temporal acceleration

Pressure gradient

Neglect gravitation as patient lies down

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

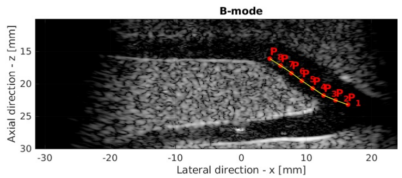
$$m \cdot a = F$$

Spatial acceleration

Neglect viscosity due to large vessels

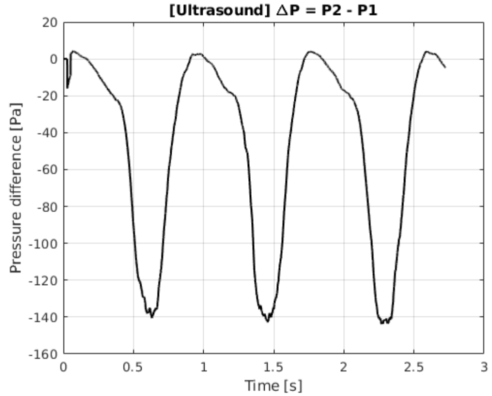
VFI can estimate both spatial and temporal accelerations

Pressure gradients in carotid bifurcation



Standard deviation of a 2.2 Pa to 3.2 Pa

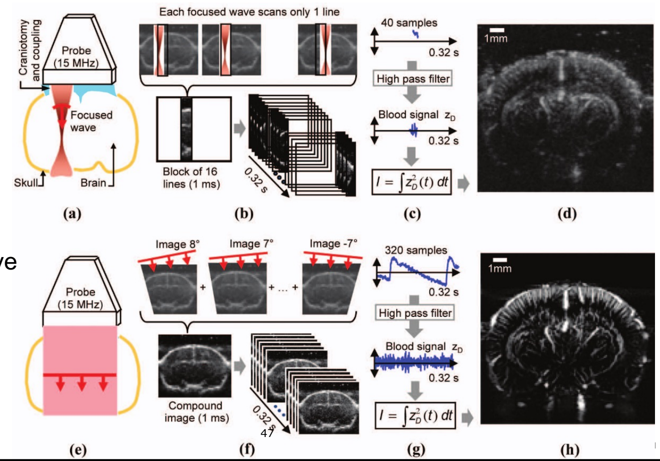
An order of magnitude more precise that pressure wires and catheters



SA Low Velocity Flow

Conventional Imaging

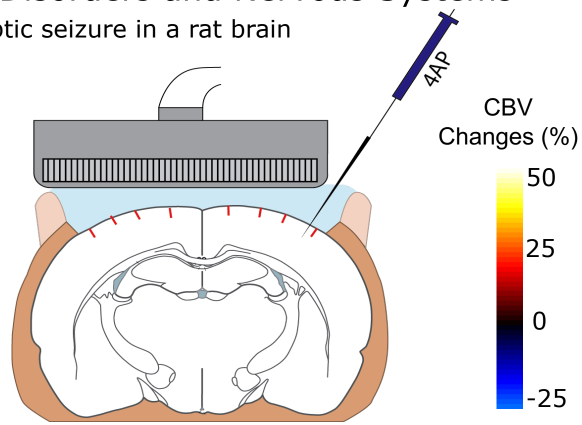
SA Plane Wave Imaging



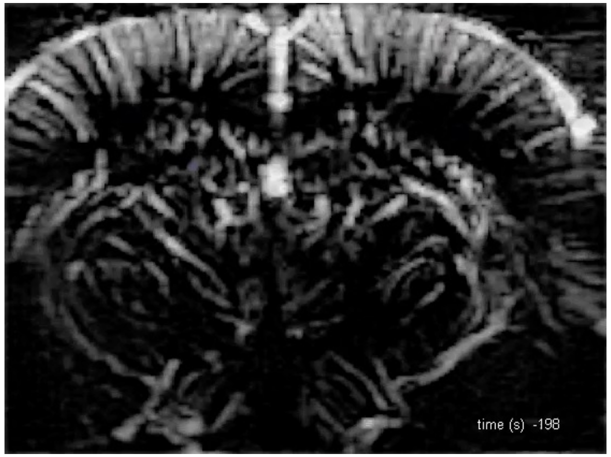
Mace et al., Nature Methods, 2011(8) pp. 662-664
Mace et al., IEEE UFFC, 2013, 60(3), pp. 492-506

Brain Disorders and Nervous Systems

Epileptic seizure in a rat brain

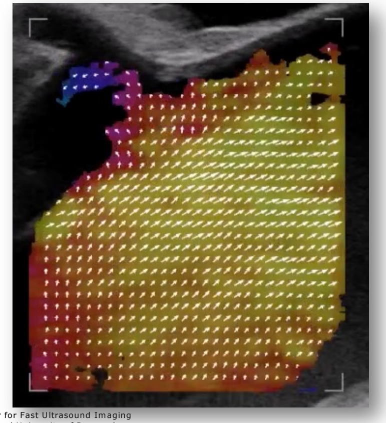


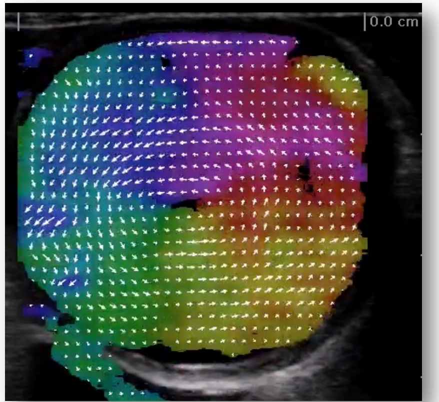
Courtesy of: E. Macé, G. Montaldo, I. Cohen, M. Baulac, M. Fink, M. Tanter, *Nature Methods*, July 2011



Mace et al., Nature Methods, 2011(8) pp. 662-664
Mace et al., IEEE UFFC, 2013, 60(3), pp. 492-506

The 3-D Problem

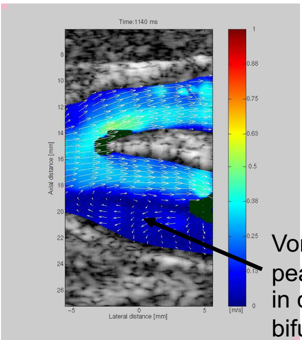




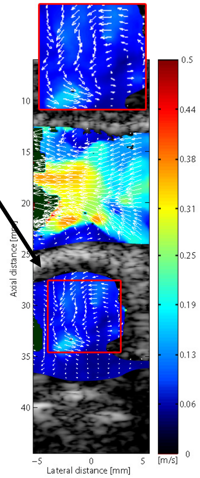
Hansen et al. UMB, 2016, 42(10), pp. 2414-2422

3D flow

Rotational flow
in the carotid artery

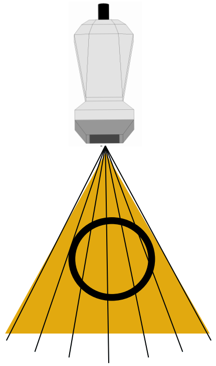


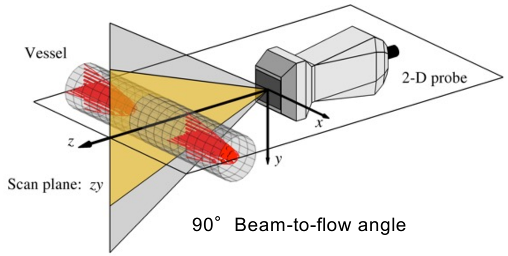
Vortices after
peak systole
in carotid
bifurcation



Measurement Setup

Cross-sectional view

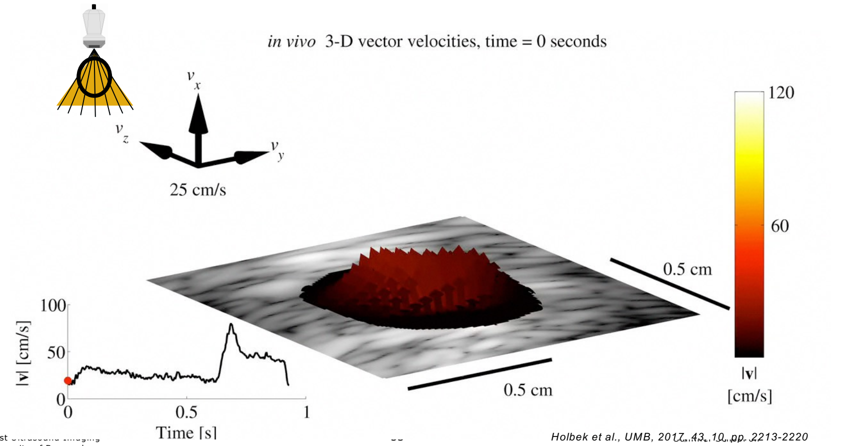




90° Beam-to-flow angle

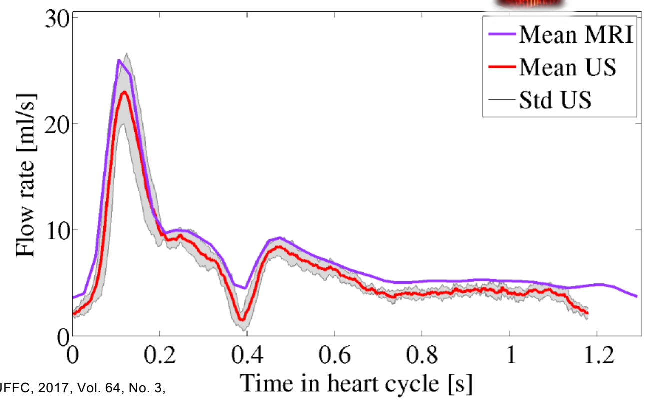
Pihl et al., IEEE UFFC, 2014, 61, pp. 1599-1607 & 1608-1618,

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



Holbek et al., UMB, 2017, 43, 10, pp. 2213-2220

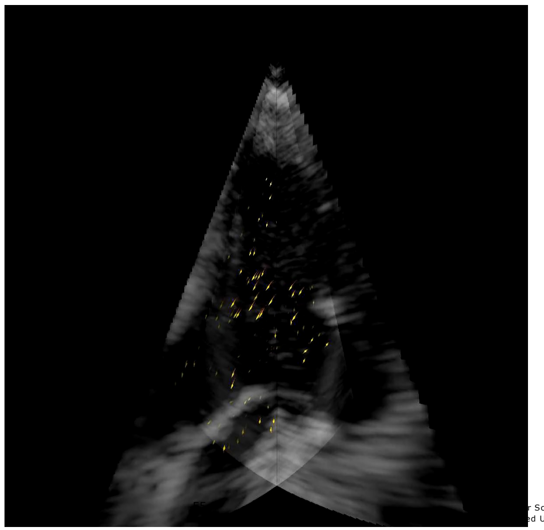
Clinical validation



Holbek et al., IEEE UFFC, 2017, Vol. 64, No. 3, 2017, p. 544-554.

Holbek et al., UMB, 2017, 43, 10, pp. 2213-2220

3-D Cardiac Flow from NTNU



Wigen et al., IEEE MI, 2018, 37(12), pp. 2619-2629

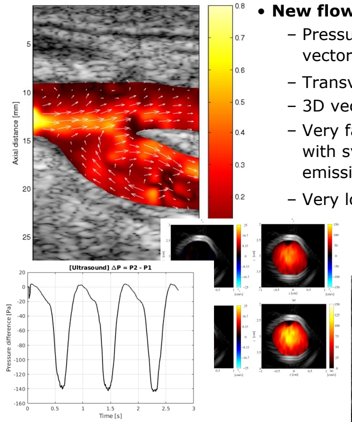
Fully Populated versus Row-Column Arrays

- *Vermon 3MHz 2D full array with 1024 channels*
- *6 transducer plugs, 3 cm thick cable*
- *Transducer footprint: 16 λ x 16 λ = 9.6 mm x 9.6 mm*

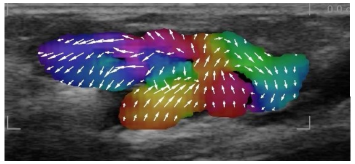
- *Row-Column Array prototype with 62 + 62 elements*
- *124 channels, one transducer plug, thin, normal cable*
- *Transducer footprint: 32 λ x 32 λ = 16.7 mm x 16.7 mm*

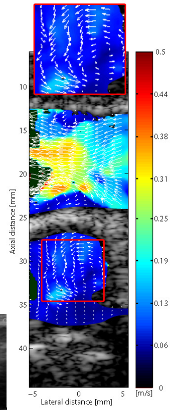
Engholm et al., Sens. Actuators A: Phys., 2018, 273, pp. 121-133,

Perspective on vector velocity imaging

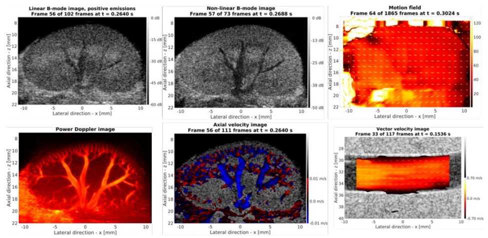


- **New flow methods:**
  - Pressure gradients can be deduced from the vector flow
  - Transverse spectral velocity estimation
  - 3D vector velocity imaging possible
  - Very fast vector flow imaging can be made with synthetic aperture and plane wave emission with complete sequences
  - Very low velocity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





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