Advanced Ultrasound Imaging 2024
Ultrasound Vector Velocity Imaging

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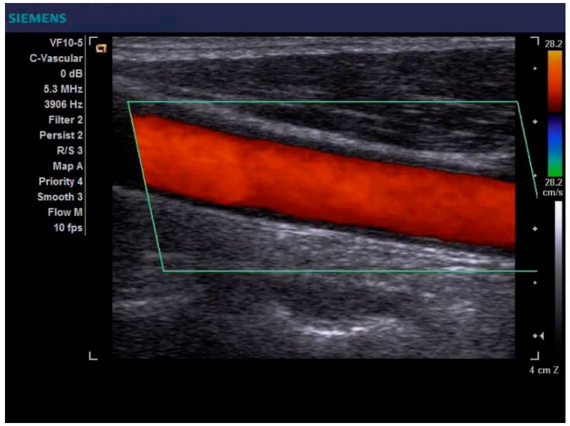
1

Modern color flow mapping



2

Ultrasound Vector Velocity Imaging

Part I:

Vector velocity imaging using transverse oscillation

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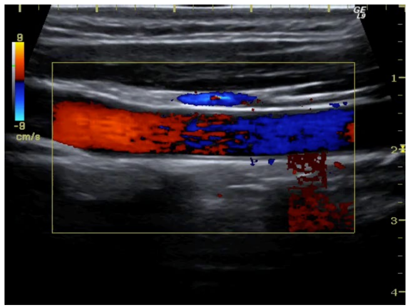
3

Conventional velocity estimation system

- Low frame rate (approx. 20 Hz)
- Angle dependent velocity estimation



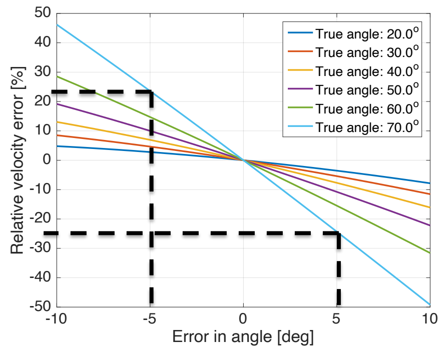
- Velocity changes direction in the image
- Determination is dependent on angle between beam and flow:

  $V_z = |v| \cos(angle)$

- At 45 degrees:
  71% of velocity
- At 60 degrees:
  50% of velocity
- At 80 degrees:
  17% (!) of velocity
- At 90 degrees
  0%

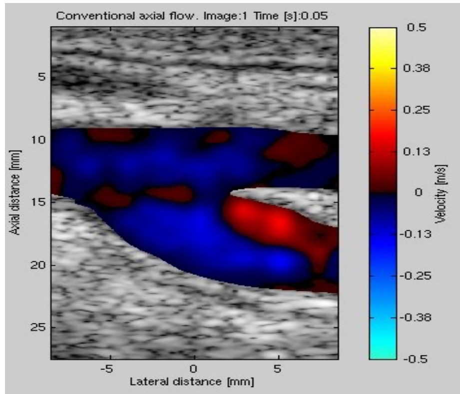
4

Sensitivity to Angle



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

Complicated flow in bifurcation

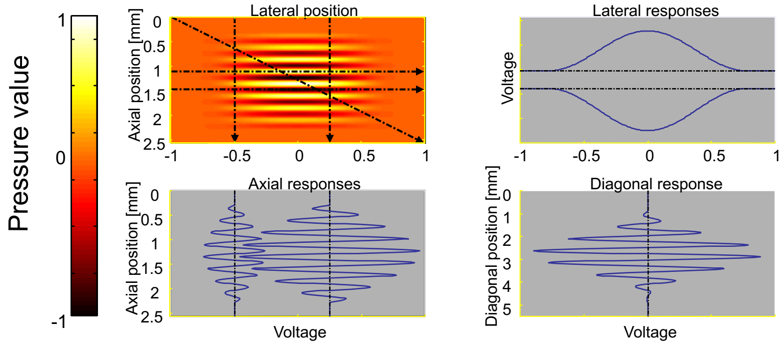


- What is the magnitude of the flow?
- What directions does it have?
- Is it normal?

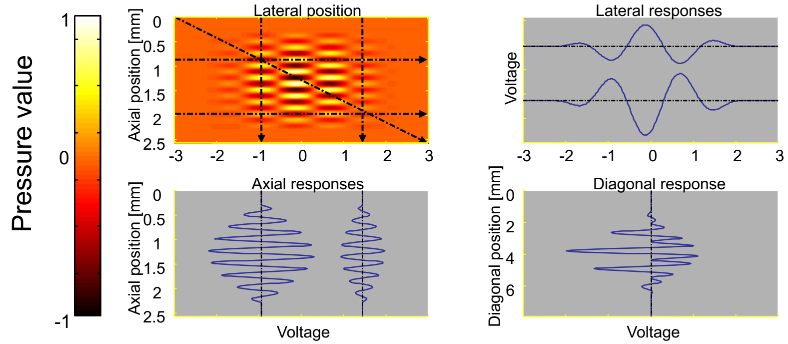
- Not possible to use one correction factor
- Angle between beam and flow changes as a function of place and time

- Full velocity vector is needed

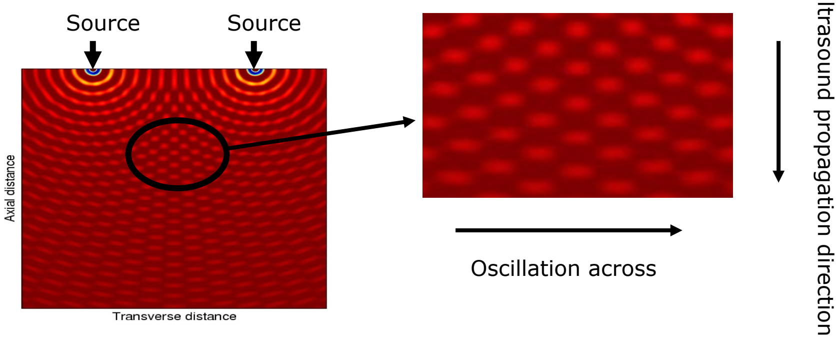
Normal velocity measurement: Sound field oscillates in ultrasound direction



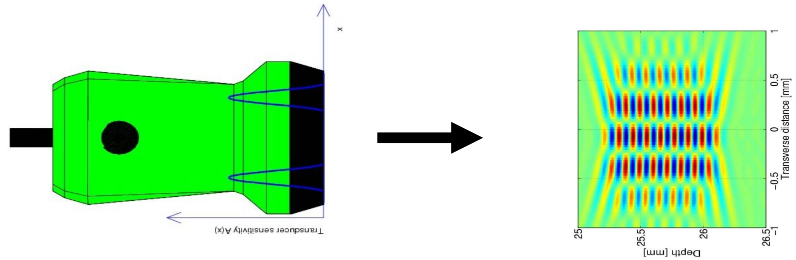
New vector velocity: Sound field also oscillates across beam



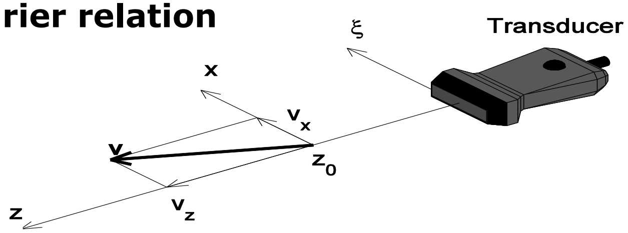
Simple generation



Generation for a transducer



Fourier relation



Fourier relation between transducer apodization function *r(ξ)* and the transverse field *R(x)* at the focus:

$$R(x) = k_1 \int_{-\infty}^{+\infty} r(\xi)\exp\left(-j\frac{2\pi}{\lambda_z z} x\xi\right) d\xi = k_1 F'\{r(\xi)\}$$

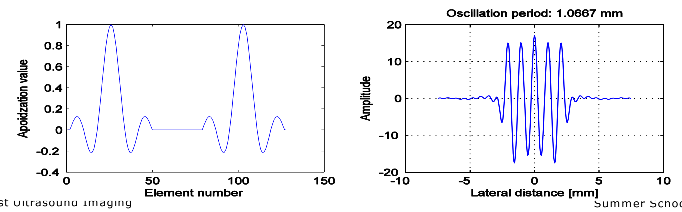
Creating a bounded lateral oscillation

Desired field: $R(x) = \mathrm{rect}(L)\cos(2\pi \frac{x}{\lambda_x})$

Apodization function:

$$r(\xi) = F^{-1}\{R(x)\} = F^{-1}\{\mathrm{rect}(L)\} * F^{-1}\{\cos(2\pi\frac{x}{\lambda_x})\}$$

$$= \frac{L}{2Z\lambda_z}\left\{\mathrm{sinc}\left(\pi\left(\frac{\xi}{z\lambda_z}+\frac{1}{\lambda_x}\right)L\right)+\mathrm{sinc}\left(\pi\left(\frac{\xi}{z\lambda_z}-\frac{1}{\lambda_x}\right)L\right)\right\}$$



Lateral oscillation period

- Peak position

$$\frac{\xi_p}{z\lambda_z} = \pm\frac{1}{\lambda_x}$$

- Distance between peaks $2\xi_p = \frac{z\lambda_z}{\lambda_x}$

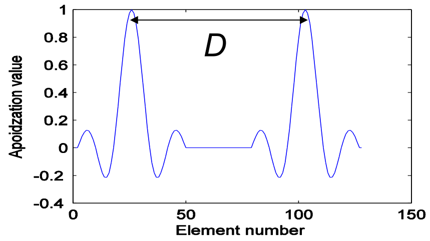
- Lateral oscillation period:

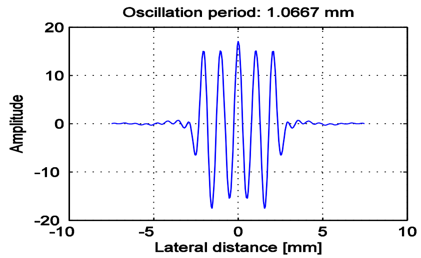
$$\boxed{\lambda_x = \frac{2z\lambda_z}{D}}$$

–*D*: distance between peaks

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

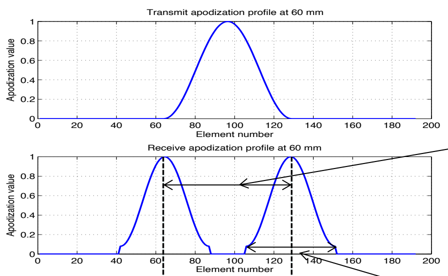
z – depth
D – distance between peaks
λ_z – axial wavelength
λ_x – Lateral oscillation period





Design of Lateral oscillation

$$\lambda_x = \frac{2\lambda z}{D} = \frac{2\lambda z}{N_d P_i}$$



Assume $\lambda_x = 4\,P_i$.
Distance between peaks:

$$N_d = \frac{2\lambda z}{4P_i^2}$$

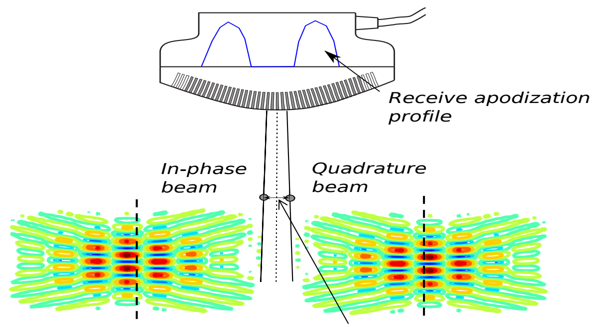
Width of peaks:

$$N_w = \frac{\lambda z}{2F_{\#TO}P_i}$$

λ – wavelength
D – distance between peaks
$F_{\#TO}$ – *F*-number for TO

z – depth
P_i – element pitch

In-phase and quadrature fields



Distance between beams is $\lambda_x/4$

Velocity estimation

- Frequency for axial velocity

$$f_z = \frac{2v_z}{c} f_0 = \frac{2v_z}{\lambda_z}$$

- Frequency for lateral velocity

$$f_x = \frac{v_x}{\lambda_x}$$

Frequency should be found from complex received signal

Pre-processing in New Estimator

Spatial quadrature signal:

$$r_{sq}(i) = \cos(2\pi f_p i T_{prf}) \exp(j 2\pi f_x i T_{prf})$$

Temporal Hilbert transform:

$$r_{sqh}(i) = \sin(2\pi f_p i T_{prf}) \exp(j 2\pi f_x i T_{prf})$$

Pre-processed signals:

$$r_1(i) = r_{sq}(i) + j r_{sqh}(i)$$

$$r_2(i) = r_{sq}(i) - j r_{sqh}(i)$$

Processed signals:

$$r_1(i) = \exp(j 2\pi i T_{prf}(f_x + f_z))$$

$$r_2(i) = \exp(j 2\pi i T_{prf}(f_x - f_z))$$

Phase differences:

$$d\theta_1 = 2\pi T_{prf}(f_x + f_z))$$

$$d\theta_2 = 2\pi T_{prf}(f_x - f_z))$$

Velocity estimates:

$$d\theta_1 + d\theta_2 = 2\pi 2 T_{prf} f_x, \quad v_x = \frac{(d\theta_1 + d\theta_2)\lambda_x}{4\pi T_{prf}}$$

Final steps in derivation

Phase estimation:

$$r(i) = x(i) + y(i)$$

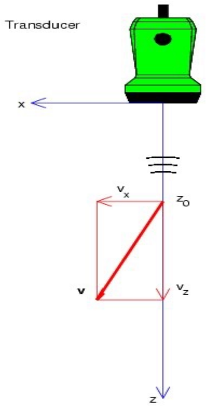
$$R(m) = \frac{1}{N-m} \sum_{i=0}^{N-m} r^*(i) r(i+m)$$

$$d\theta = \arctan\left(\frac{\Im\{R(1)\}}{\Re\{R(1)\}}\right)$$

Arctan calculation:

$$\tan(A+B) = \frac{\tan(A) + \tan(B)}{1 - \tan(A)\tan(B)}$$

Estimation of Velocity



Lateral velocity estimator:

$$v_x = \frac{d_x}{2\pi 2T_{prf}} \arctan\left(\frac{\sum_{i=1}^{N-1} \Im\{R_1(1)\}\Re\{R_2(1)\} + \Im\{R_2(1)\}\Re\{R_1(1)\}}{\sum_{i=1}^{N-1} \Re\{R_1(1)\}\Re\{R_2(1)\} - \Im\{R_1(1)\}\Im\{R_2(1)\}} \right)$$

Axial velocity estimator:

$$v_z = \frac{c}{2\pi f_0 4T_{prf}} \arctan\left(\frac{\sum_{i=1}^{N-1} \Im\{R_1(1)\}\Re\{R_2(1)\} - \Im\{R_2(1)\}\Re\{R_1(1)\}}{\sum_{i=1}^{N-1} \Re\{R_1(1)\}\Re\{R_2(1)\} + \Im\{R_1(1)\}\Im\{R_2(1)\}} \right)$$

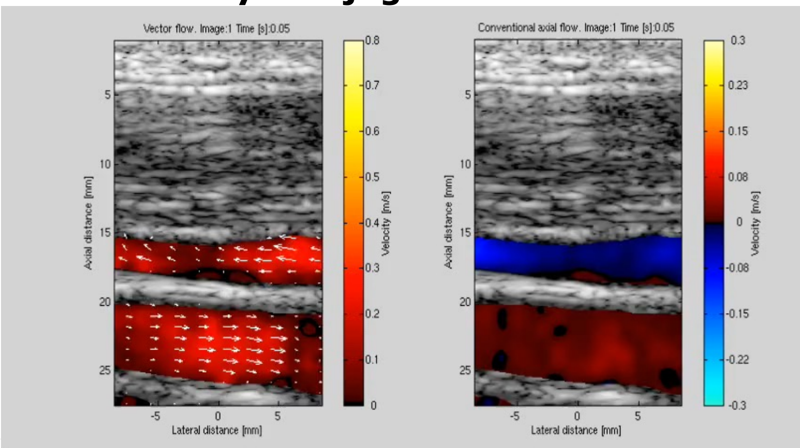
21

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

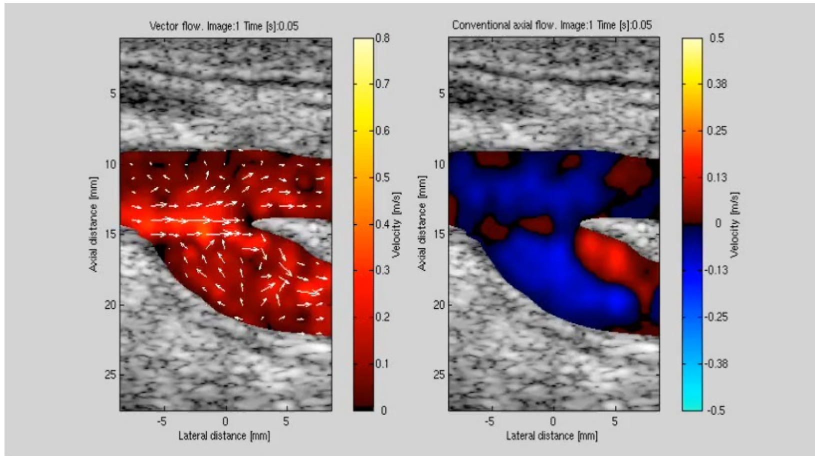
22

In-vivo vector velocity for carotid artery and jugular vein



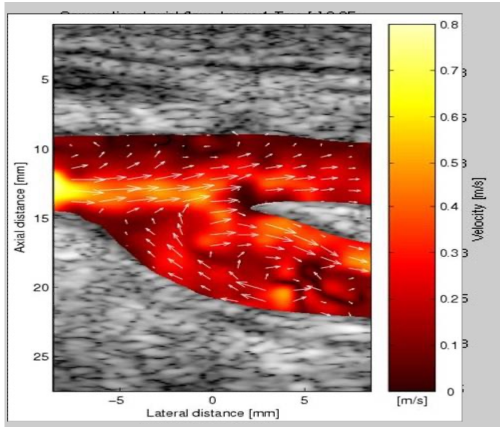
23

Velocity in carotid bifurcation



24

Complicated flow in bifurcation



New Transverse Estimator

$$v_x = \frac{\lambda_x}{2\pi 2T_{prf}} \arctan\left(\frac{\Im\{R_1(1)\}\Re\{R_2(1)\} + \Im\{R_2(1)\}\Re\{R_1(1)\}}{\Re\{R_1(1)\}\Re\{R_2(1)\} - \Im\{R_1(1)\}\Im\{R_2(1)\}}\right)$$

$$v_z = \frac{\lambda}{2\pi 4T_{prf}} \arctan\left(\frac{\Im\{R_1(1)\}\Re\{R_2(1)\} - \Im\{R_2(1)\}\Re\{R_1(1)\}}{\Re\{R_1(1)\}\Re\{R_2(1)\} + \Im\{R_1(1)\}\Im\{R_2(1)\}}\right)$$

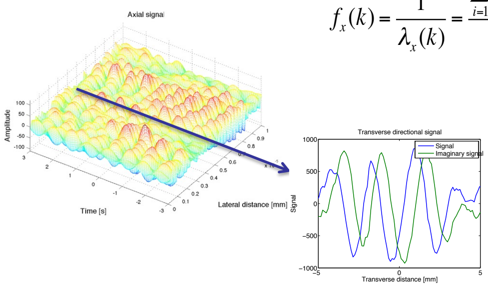
$$R_1(l) = \frac{1}{(N-1)N_d N_s} \sum_{i=1}^{N-1} \sum_{n=1}^{N_d} \sum_{k=-N_s/2}^{N_s/2} r_1^*(k+N_z,n,i) r_1(k+N_z,n,i+l)$$

$$R_2(l) = \frac{1}{(N-1)N_d N_s} \sum_{i=1}^{N-1} \sum_{n=1}^{N_d} \sum_{k=-N_s/2}^{N_s/2} r_2^*(k+N_z,n,i) r_2(k+N_z,n,i+l)$$

R_1 - Complex autocorrelation of signal one averaged over directional signal and depth
R_2 - Complex autocorrelation of signal two
N_z – *RF sample depth for velocity estimate*

Calculation of Mean Lateral Oscillation Wavelength

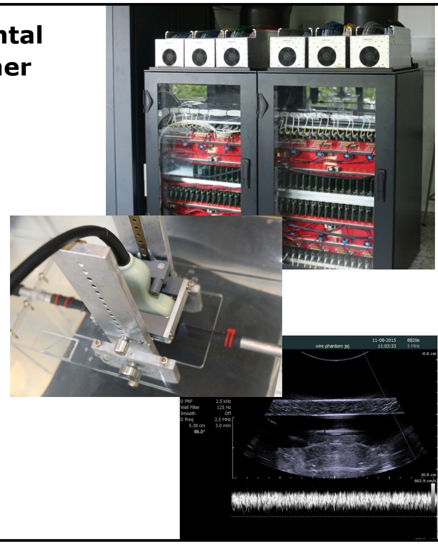
$$f_x(k) = \frac{1}{\lambda_x(k)} = \frac{\sum_{i=1}^{N_c} \sum_{m=-N/2}^{N/2} \frac{m}{N\Delta x} R_{sq}(k,m,i)}{\sum_{i=1}^{N_c} \sum_{m=-N/2}^{N/2} R_{sq}(k,m,i)}$$



$R_{sq}(k,m,i)$ – Fourier transform of lateral signal at sample *k* and emission *i*

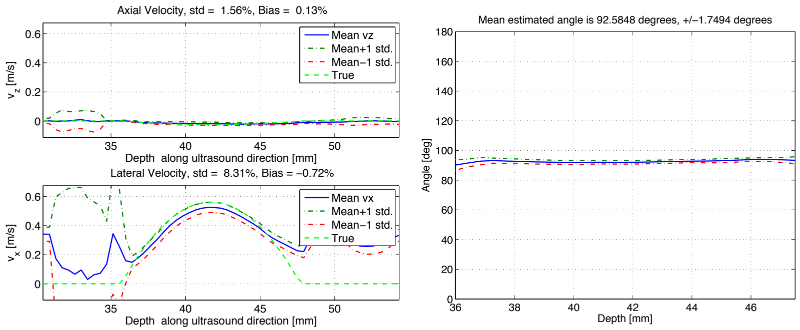
SARUS Experimental Ultrasound Scanner

- 192 channels sampled at 17.5 MHz/12 bits
- 129 B-mode emissions
- Interspaced with VFI emissions focused at 105 mm
- f_{prf}=5 kHz
- BK Medical 8820e 3 MHz convex array probe used
- Data acquired for 30 frames
- Acquired on rig with parabolic flow



Velocity Profiles at 40 mm using 16 Emissions at 90º Beam-to-flow Angle

DTU



V_x std: 8.31%, bias -0.72%, angle std: 1.75 degrees

Is it Accurate? Clinical study

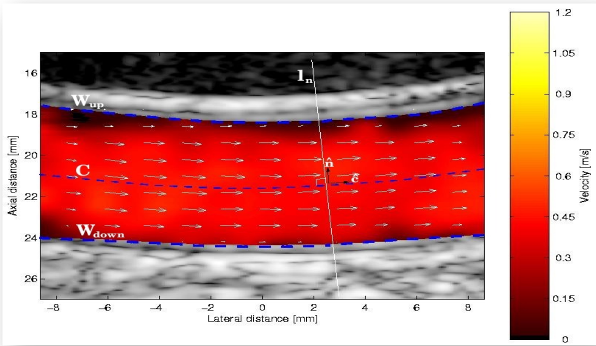
DTU

- 11 healthy volunteers
  - seven males and four females,
  - 24 – 44 years old, mean age: 32 years)
- Each person was scanned by US and MRI

  - Examination for every person were performed at two separate occasions with no more than a week in between.
  - The volunteer rested supine 15 minutes prior to both examinations.
  - All scans were carried out by an experienced radiologist.

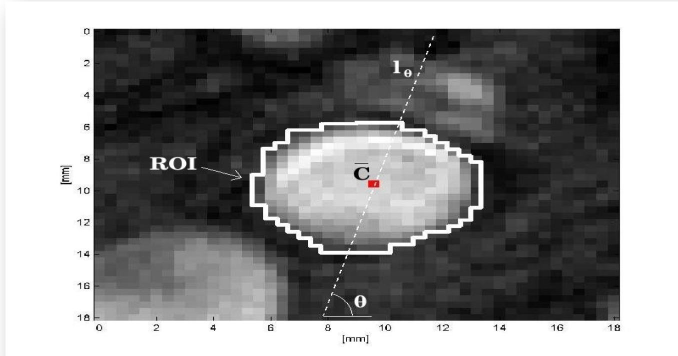
Vector Velocity Image of Stroke Volume

DTU

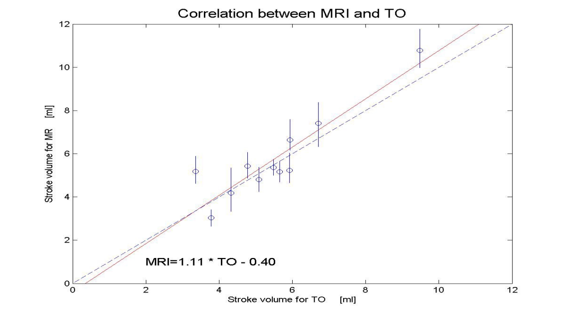


MR Measurement of Volume Flow

DTU



Clinical Validation of Vector Flow against MR



R = 0.91, P<0.01

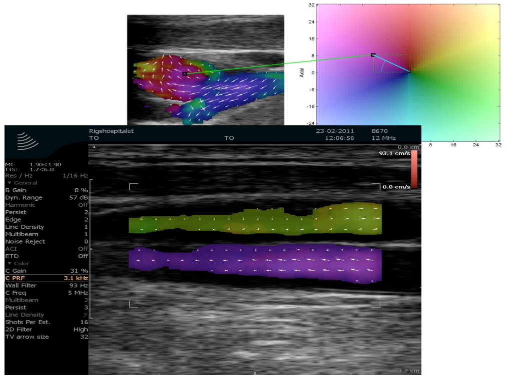
95% CI for R: 0.69 to 0.98

Regression line:

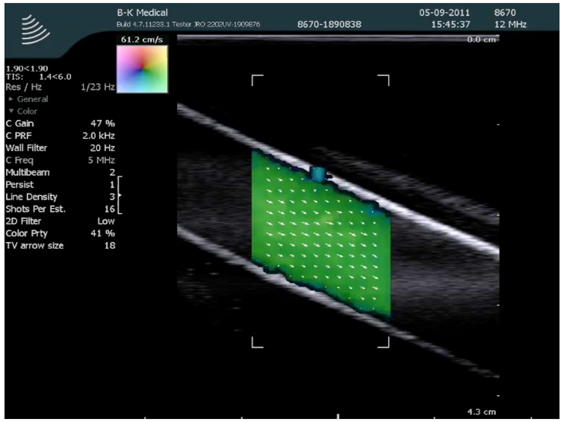
MRI = 1.1 * TO – 0.4 ml

Vertical bars indicate range for rotational symmetry assumption.

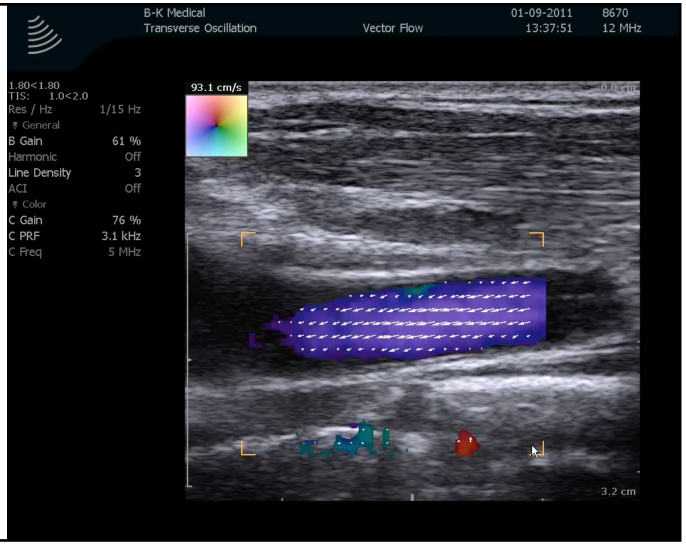
Commercial implementation: BK Medical ProFocus scanner FDA approved January, 2012



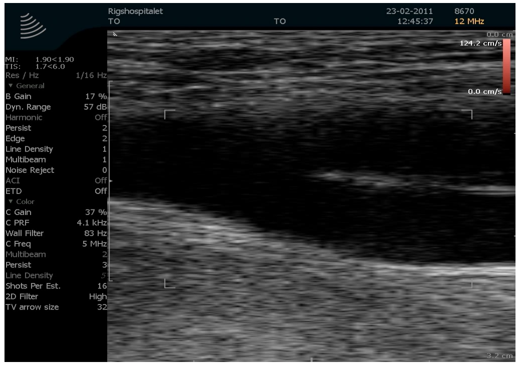
Display of velocity



Scanning of the carotid artery

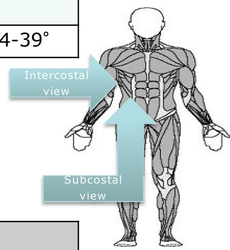


Bifurcation in Femoral Artery

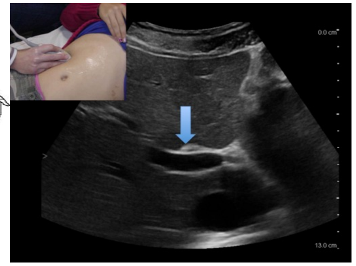


Influence of Beam-to-flow Angle

TO	SDU
10-61°	4-39°

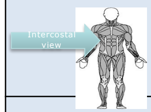
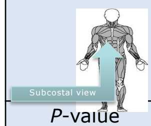


TO	SDU
53-130°	57-99°

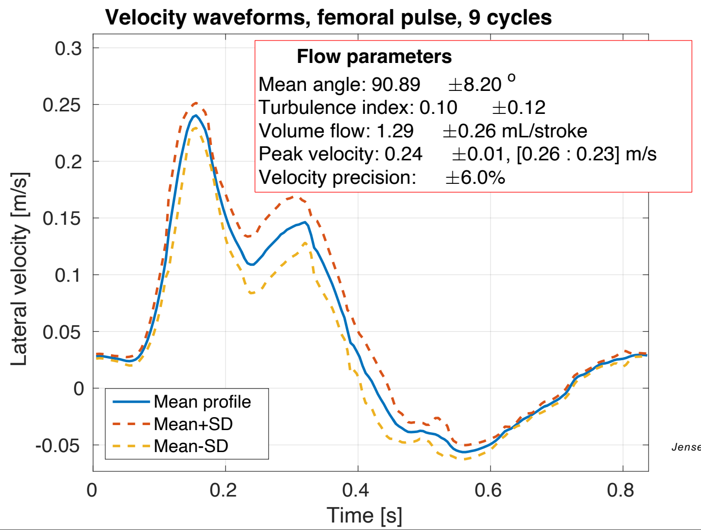


From Brandt et al., IEEE IUS, 2015

Estimated Peak Velocities

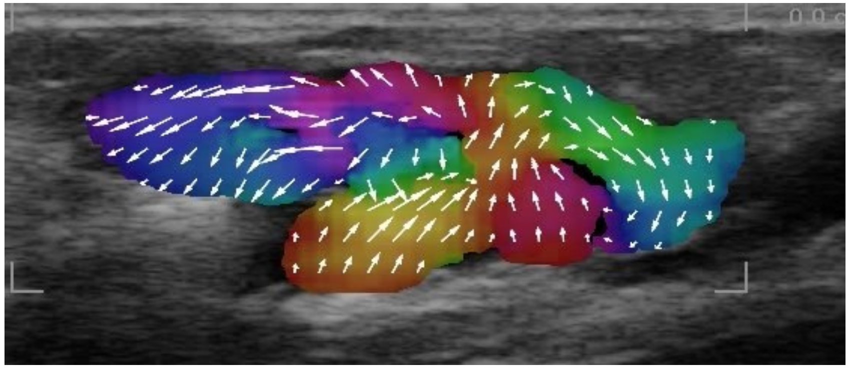
	Mean TO (SD)	Mean SDU (SD)	*P*-value
	0.203±(0.038) m/s	0.202±(0.029) m/s	0.94
	0.180±(0.034) m/s	0.320±(0.060) m/s	0.001
P-value	0.26	0.001	

From Brandt et al., IEEE IUS, 2015



Jensen, IEEE UFFC, 2017, 64(8), pp. 1194-1204

Vein-artery connection for kidney hemodialysis patient



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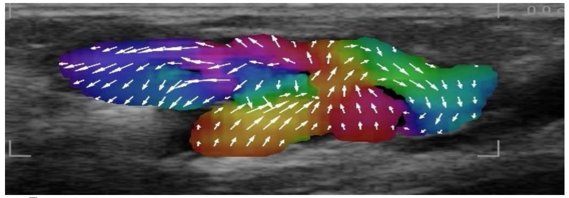
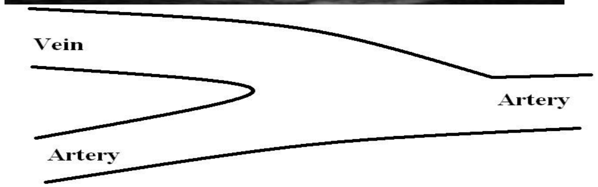
41

Anatomy of vein-artery graft





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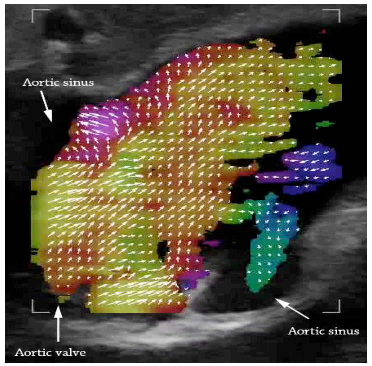
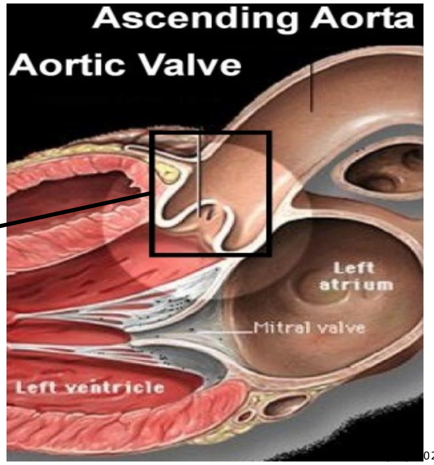
42

Anatomy of Intercardiac Scan of Right Atrium





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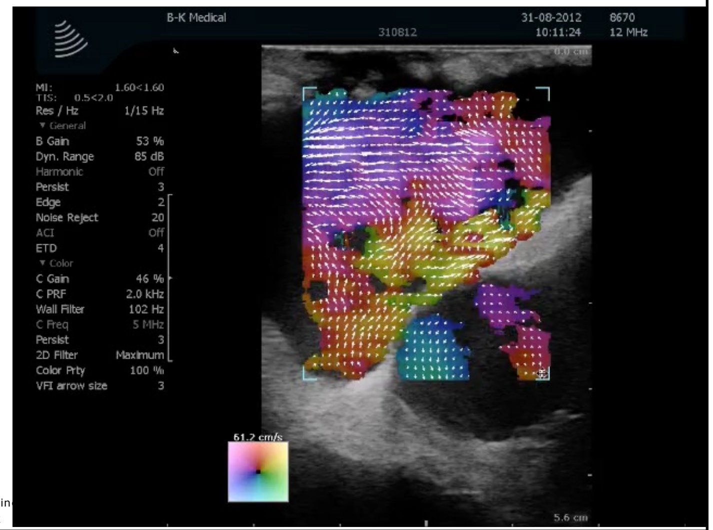
43

Intercardiac scan Right Atrium



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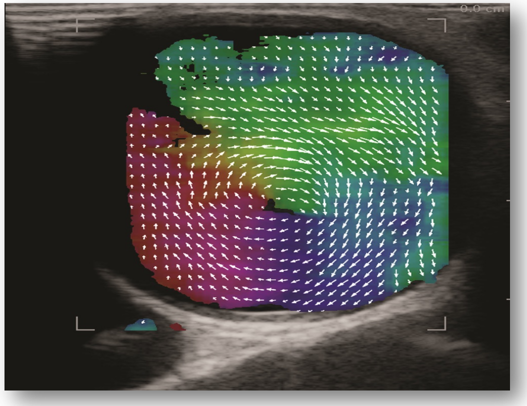
44

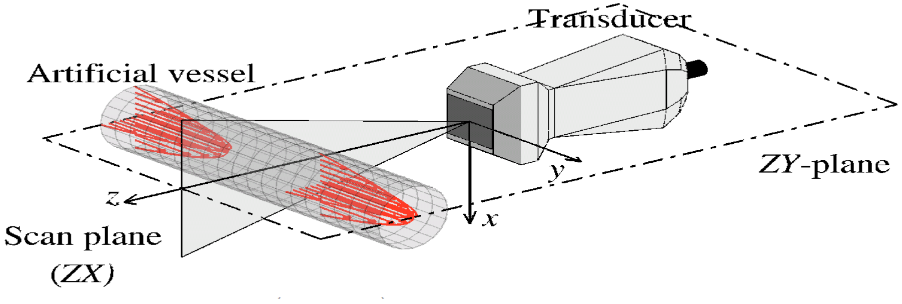
Systolic blood flow in ascending aorta of a patient with aortic valve stenosis (short axis view)



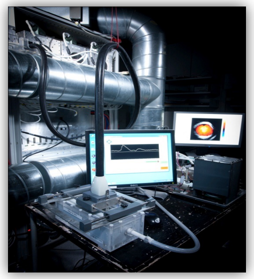
Hansen et al. Ultrasonic Imaging, Vol. 35, No. 4, 2013

3D Measurement situation

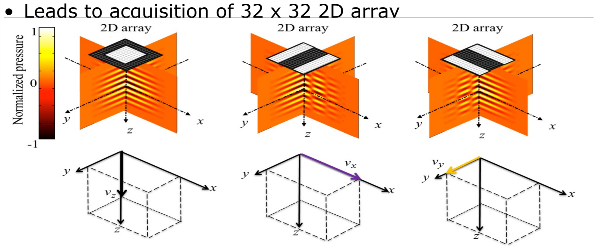
- Cross-sectional scan of vessel:



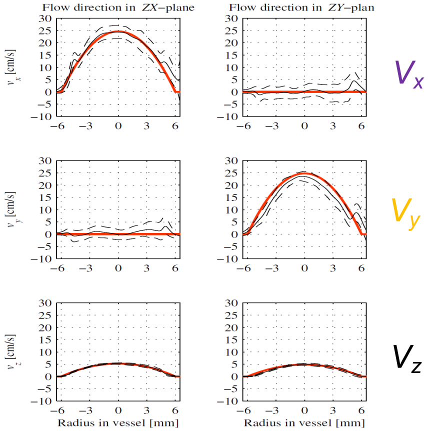
Requirements for 3D velocity estimation

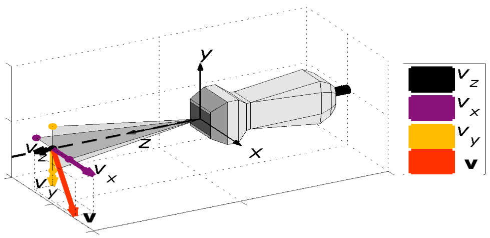


- 2D array transducer
  - 32 x 32 = 1024 elements
- Reception on all 1024 elements
- Beamforming of 5 beams in parallel from received data
- Three different apodization patterns should be employed
- Leads to acquisition of 32 x 32 2D array

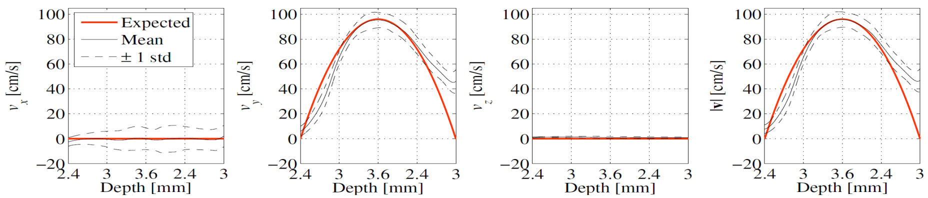


Measurement of all three velocity components





3D flow profiles



$$\bar{\mathbf{v}} = \begin{pmatrix}\bar{v}_x\\ \bar{v}_y\\ \bar{v}_z\end{pmatrix} = \begin{pmatrix}-0.03\\ 95.\\ 1.0\end{pmatrix} \pm \begin{pmatrix}9.\\ 6.\\ 0.8\end{pmatrix} \text{ cm/s}, \quad \mathbf{v}_{\text{exp}} = \begin{pmatrix}0.\\ 96.\\ 0.\end{pmatrix} \text{ cm/s}, \quad \text{and} \quad \mathbf{B}_{\mathbf{v}} = \begin{pmatrix}-0.03\\ -0.8\\ -1.\end{pmatrix} \text{ cm/s.}$$

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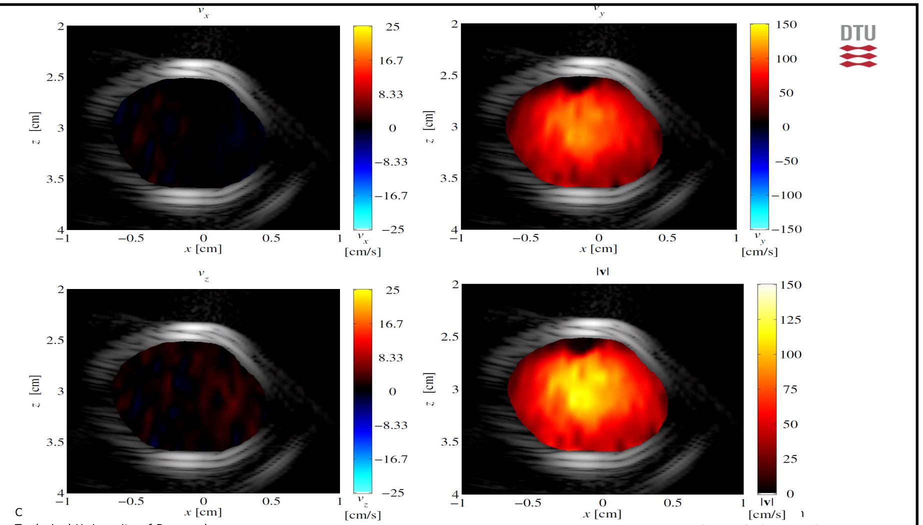
49



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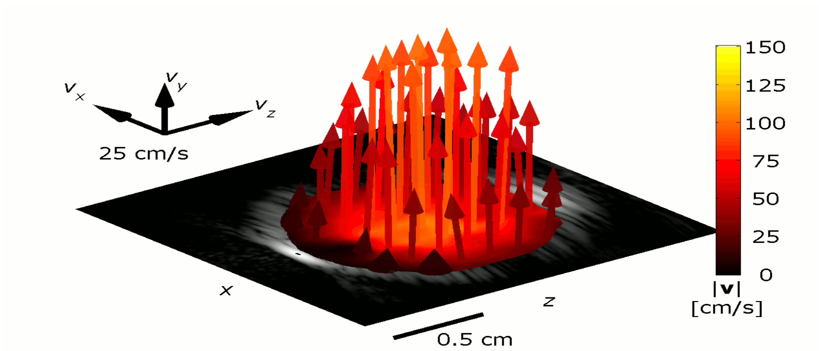
50

3D vector flow image



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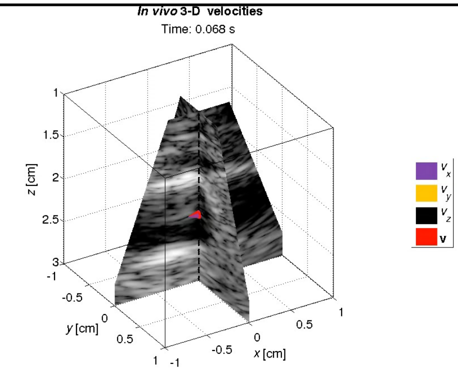
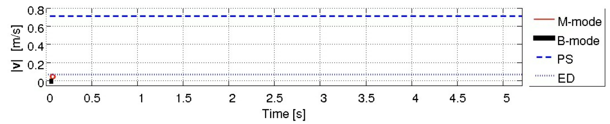
51

In-vivo 3D vector velocity imaging





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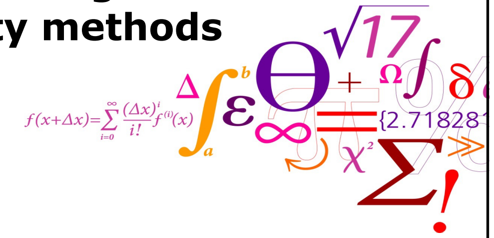
52

Ultrasound Vector Velocity Imaging

Part II:

Directional beamforming and other vector velocity methods



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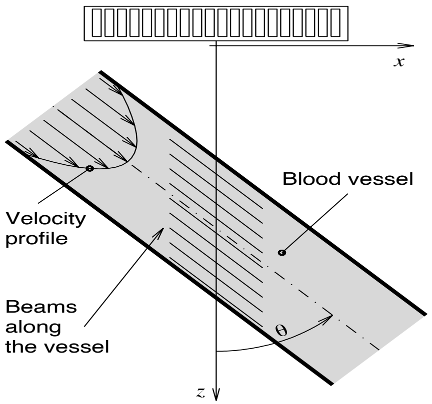
53

Outline

- Directional beamforming
  - Beamformation
  - Angle estimation
- Crossed beams velocity estimation
- Speckle tracking
- Finding the angle from the spectral display

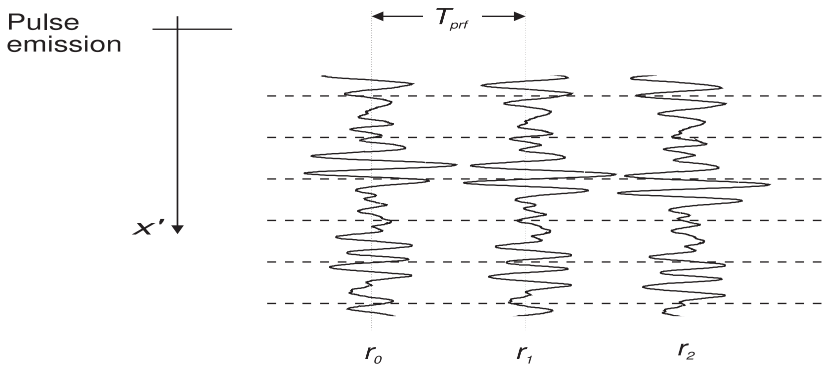
54

Directional beamforming



55

Cross-correlation of directional lines



56

Cross-Correlation to Find Velocity

$$R_{12}(n) = \frac{1}{M}\sum_{j=0}^{M-1} r_1(j) r_2(j+n)$$

$$= \frac{1}{M}\sum_{j=0}^{M-1} r_1(j) r_1(j+n-n_s)$$

$$R_{12}(n) = R_{11}(n-n_s)$$

Velocity estimate is:

$$v_{mag} = \frac{n_s \Delta x'}{T_{prf}}$$

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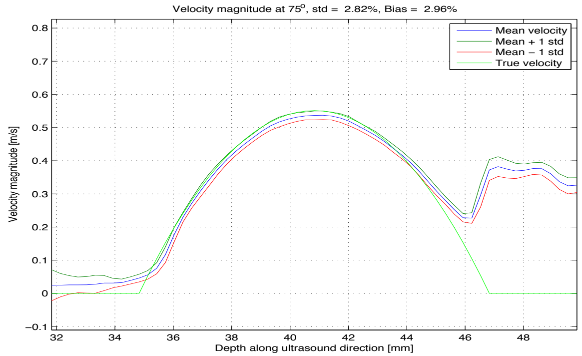
57

Velocity profiles for directional beamforming

75° flow angle, 16 emissions/estimate, line length: 20 λ



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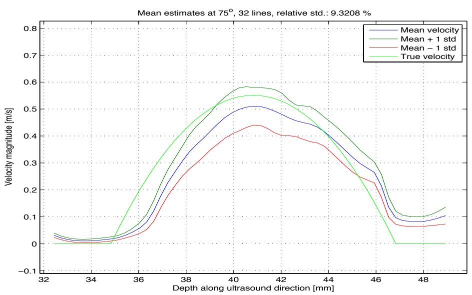
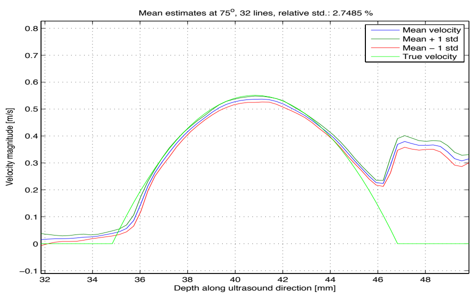
58

Performance using the same data



Transverse oscillation
9.3%



Directional beamforming
2.7%

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59

Number of calculations

Transverse oscillation

$$N_{TO} = (4 \cdot 28 N_s)\frac{f_s}{N_s} F_f$$

Directional beamforming

$$N_d = (N_l^2 + N_l)\frac{f_s}{N_s} F_f$$

Ratio:

$$R_c = \frac{N_d}{N_{TO}} = \frac{(N_l^2 + N_l)}{4 \cdot 28 N_s}$$

Typical values: N_l =100, N_s = 8 gives ***R_c = 11.3***

Neglects finding the velocity direction

N_l – Number samples in directional line
f_s – Sampling frequency

N_s – Number of RF samples in estimate
F_f – Fraction of time for flow

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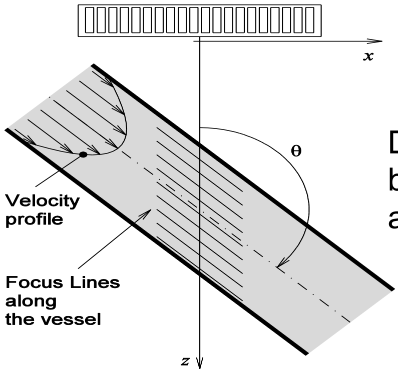
60

Determination at Different Angles



Directional lines are beamformed at different angles

61

Determination of Velocity Angle

$$R_{12n}(\theta) = \frac{\max\{R_{12}(k,\theta)\}}{R_{12}(0,\theta)}$$

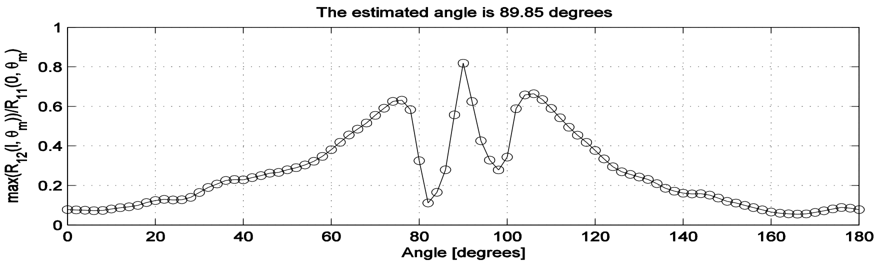
$$\theta_m = ArgMax(R_{12n}(\theta))$$

Angle is found from maximum in normalized peak value of cross-correlation function.

Value is interpolated using a second order polynomial to increase the accuracy.

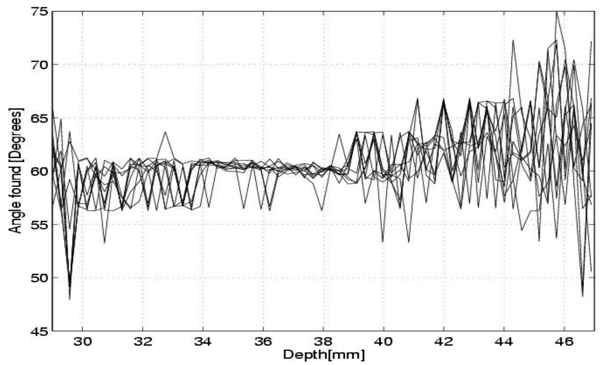
62

Angle Determination at 90 deg



63

Estimated Velocity Angles at 60 deg



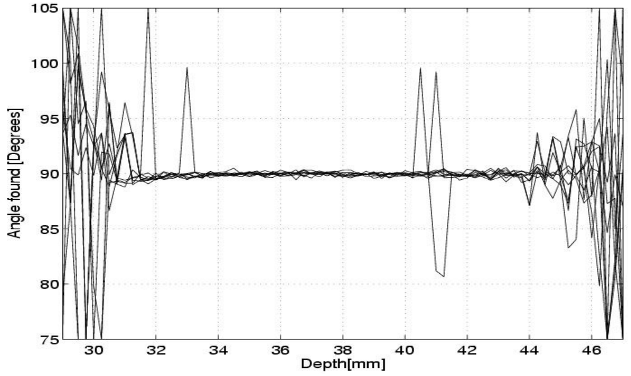
For all estimates:

Mean: 60.54 deg

Std. 2.1 deg

64

Estimated Velocity Angles at 90 deg



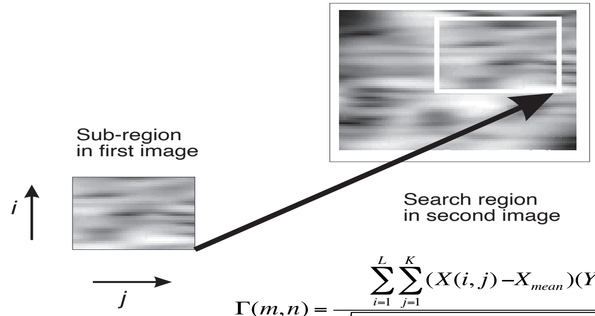
For all estimates:

Mean: 90.0003 deg

Std. 1.32 deg

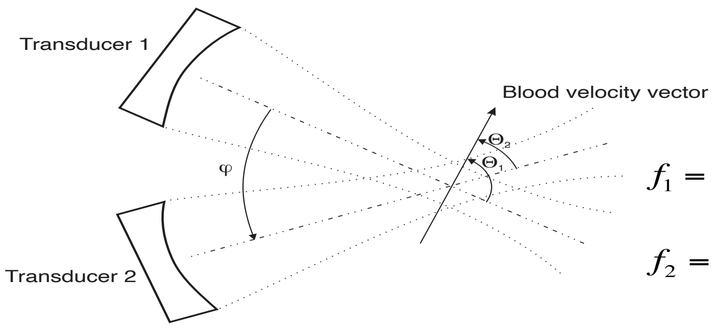
Speckle tracking

Search to find motion



$$\Gamma(m,n) = \frac{\sum_{i=1}^{L}\sum_{j=1}^{K}(X(i,j)-X_{mean})(Y(i+m,j+n)-Y_{mean})}{\sqrt{\sum_{i=1}^{L}\sum_{j=1}^{K}(X(i,j)-X_{mean})^2 \sum_{i=1}^{L}(Y(i+m,j+n)-Y_{mean})^2}}$$

Crossed beams velocity estimation



$$f_1 = \frac{2|\vec{v}|}{c} f_0 \cos\theta_1$$

$$f_2 = \frac{2|\vec{v}|}{c} f_0 \cos\theta_2$$

Finding the velocity vector

- Calculation of the velocity components:

$$v_z = |\vec{v}|\cos\theta_1 = \frac{c}{2}\frac{f_1}{f_2}$$

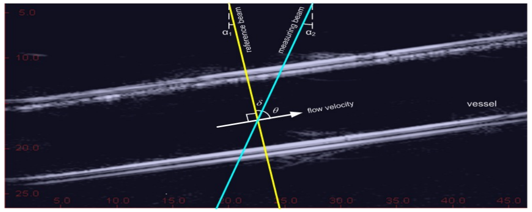
$$v_x = |\vec{v}|\sin\theta_1 = \frac{c}{2}\frac{f_2 - f_1\cos\varphi}{f_2\sin\varphi}$$

$$\varphi = \theta_1 - \theta_2$$

$$\varphi = \arcsin\left(\frac{D_y/2}{\sqrt{(D_y/2)^2 + D_z^2}}\right)$$

- Note how it is dependent on the angle difference

Dual beam method



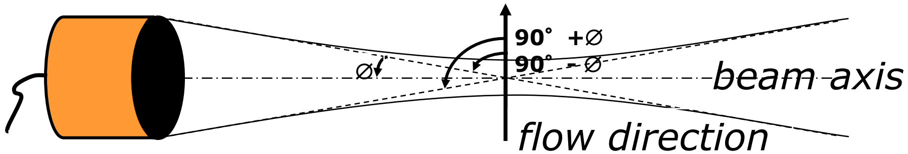
<u>Assumption</u>:

A reference beam can be <u>transversely</u> <u>oriented</u> to the flow direction

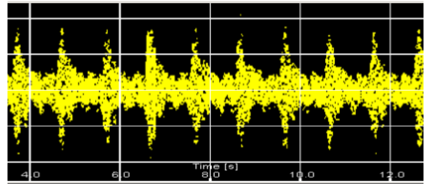
Angle estimation is based on inspection of the (transverse) Doppler spectrum

Slide courtesy of Piero Tortoli, University of Florence

Transverse Doppler spectrum



The flow is interrogated by a range of angles around the nominal 90° Doppler angle

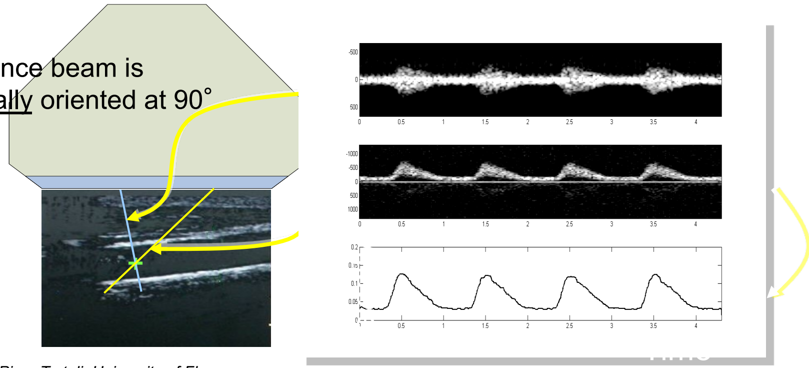


Slide courtesy of Piero Tortoli, University of Florence

Corresponding spectrum is symmetrical around zero frequency

Automatic transverse angle tracking

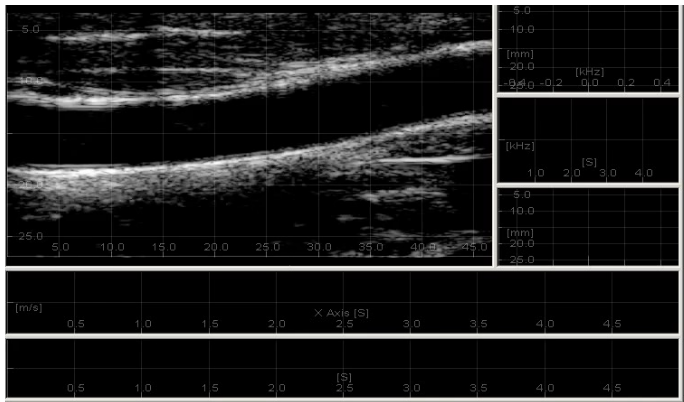
The reference beam is <u>automatically</u> oriented at 90° to the flow



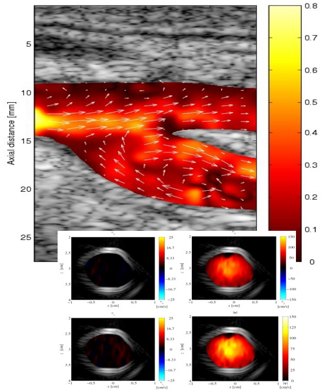
Slide courtesy of Piero Tortoli, University of Florence

In vivo Test

Slide courtesy of Piero Tortoli, University of Florence



Perspective on vector velocity imaging



- **Velocity imaging:**
  - Velocity magnitude correctly identified
  - No angle correction – correct magnitude and direction for all times and places
  - Velocity is independent of transducer placement, which improves on workflow and accuracy
  - Disturbed and turbulent flow can