Can we measure turbulence in the body using ultrasound?

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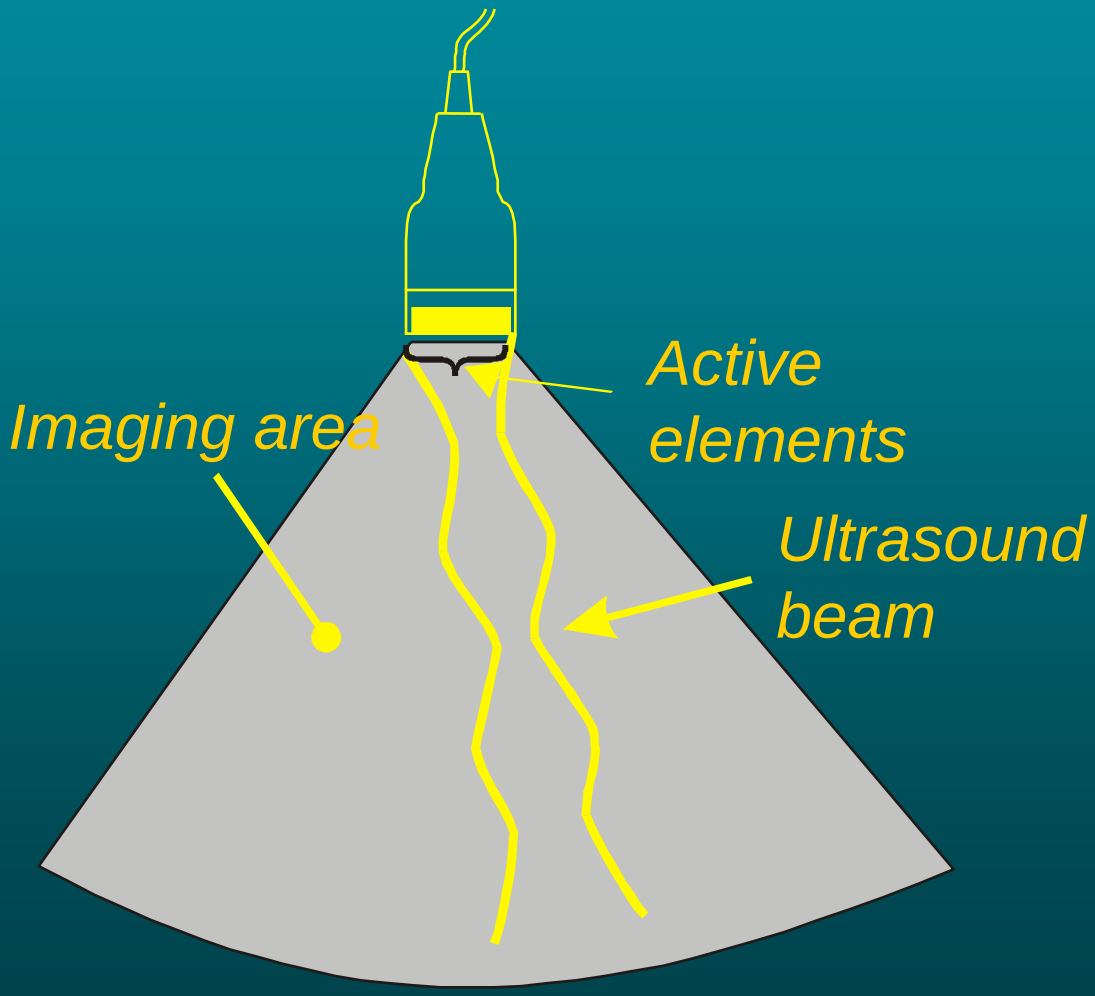
Outline

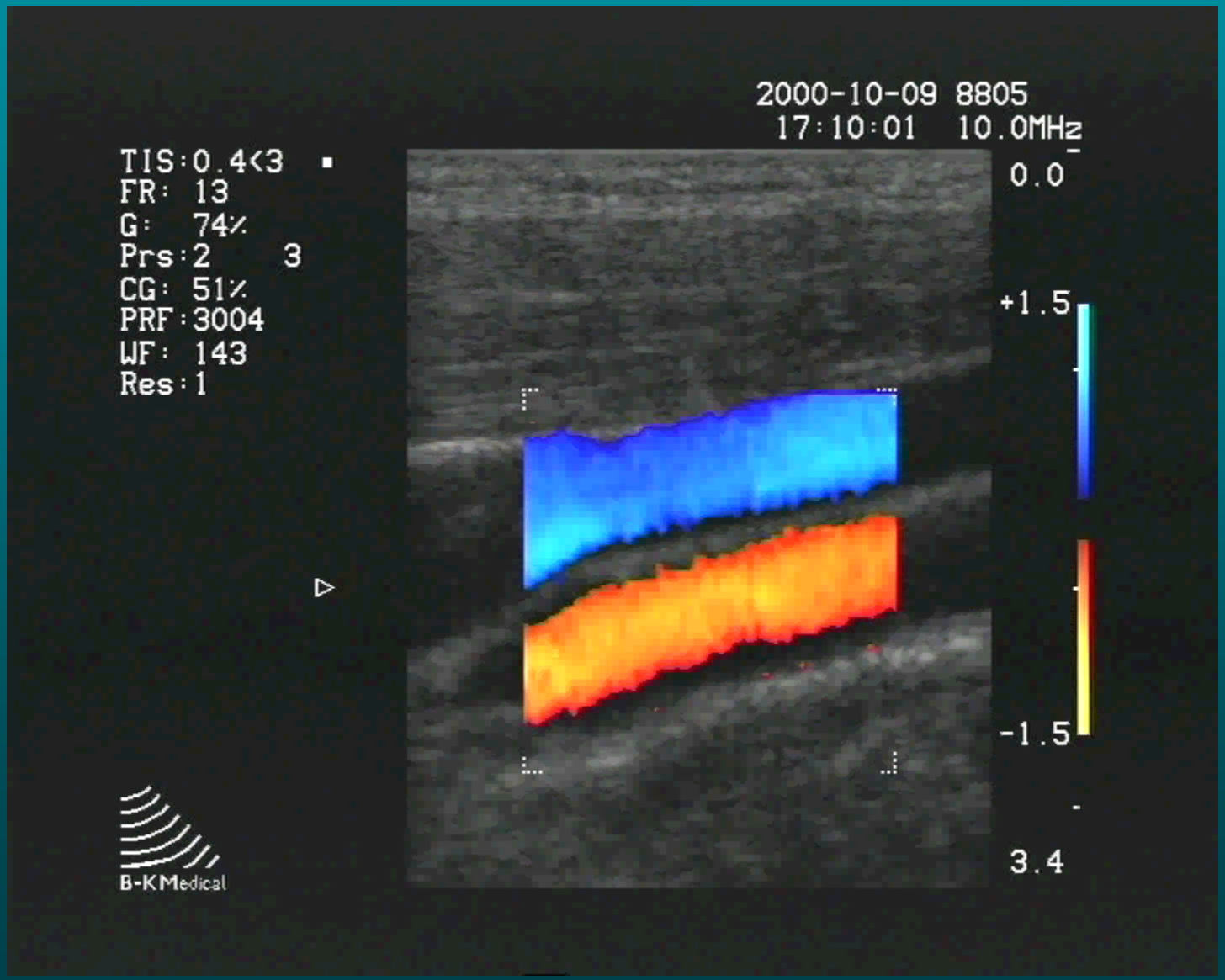
- Limitations of current ultrasound system
- A method for vector flow imaging
  - Transverse oscillation principle
  - Estimator
  - Results from use
- Clinical study comparing with MR
- Turbulence in the body
- Conclusion

Normal Imaging

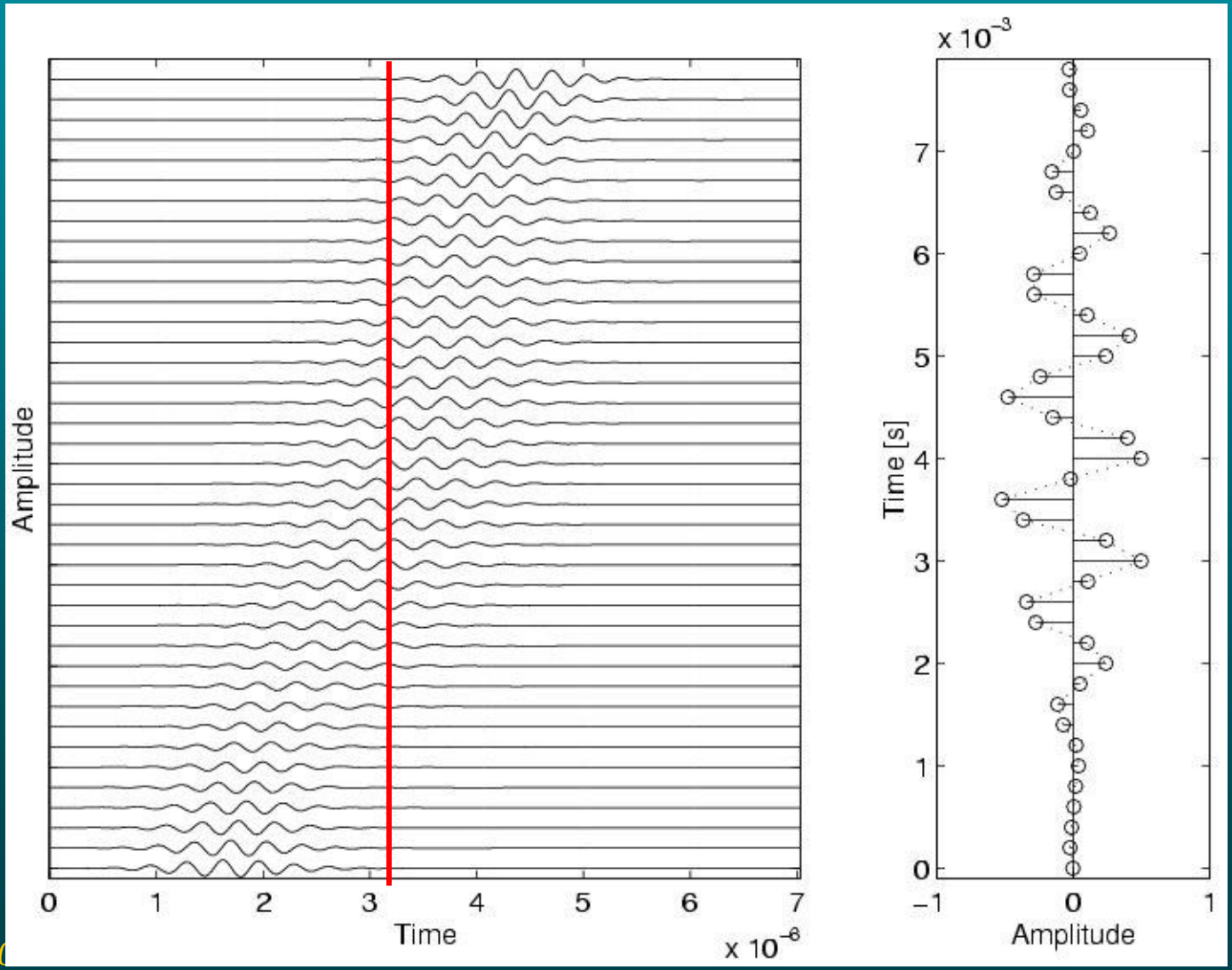


- Beam in one direction at a time
- Only one emit focus
- 8-16 emissions per direction
- Velocity found as a function of depth

Blood flow to and from the brain



Measurement of velocity



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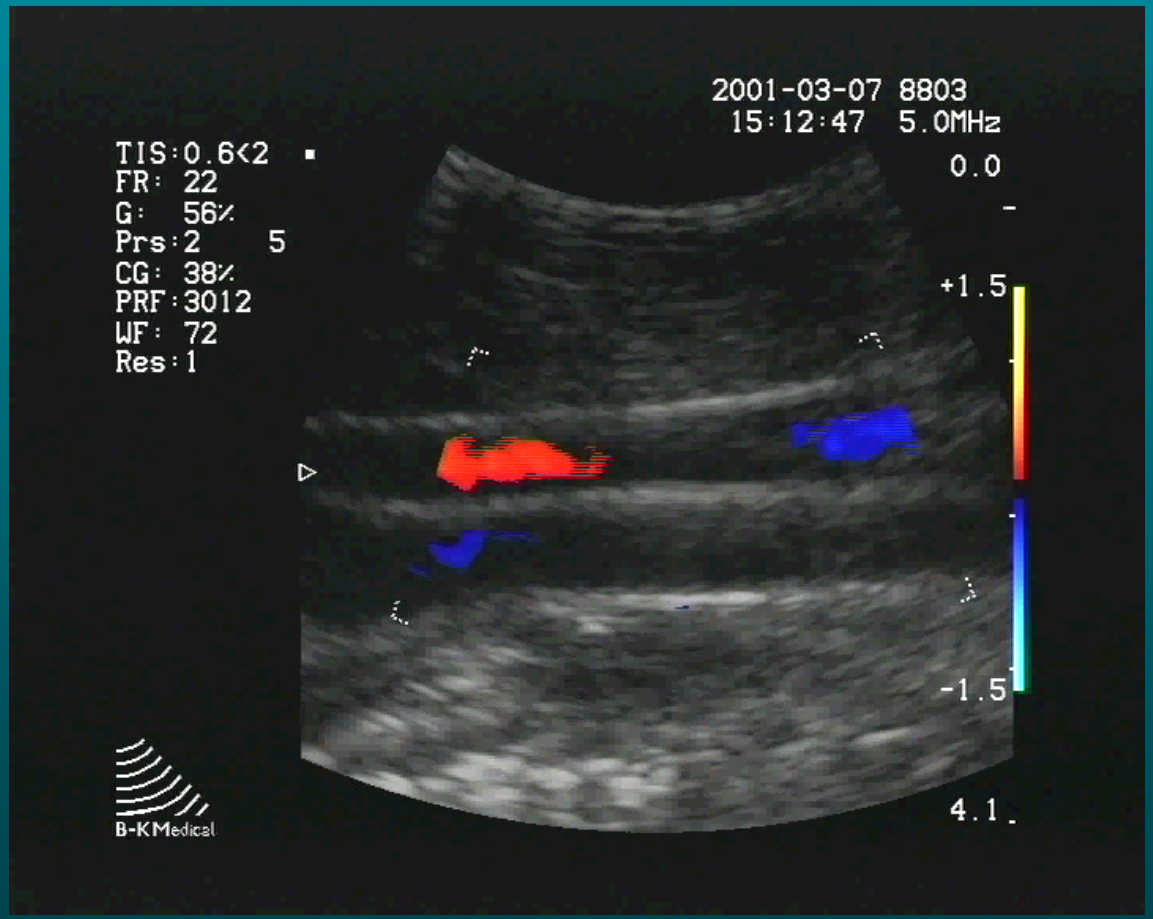
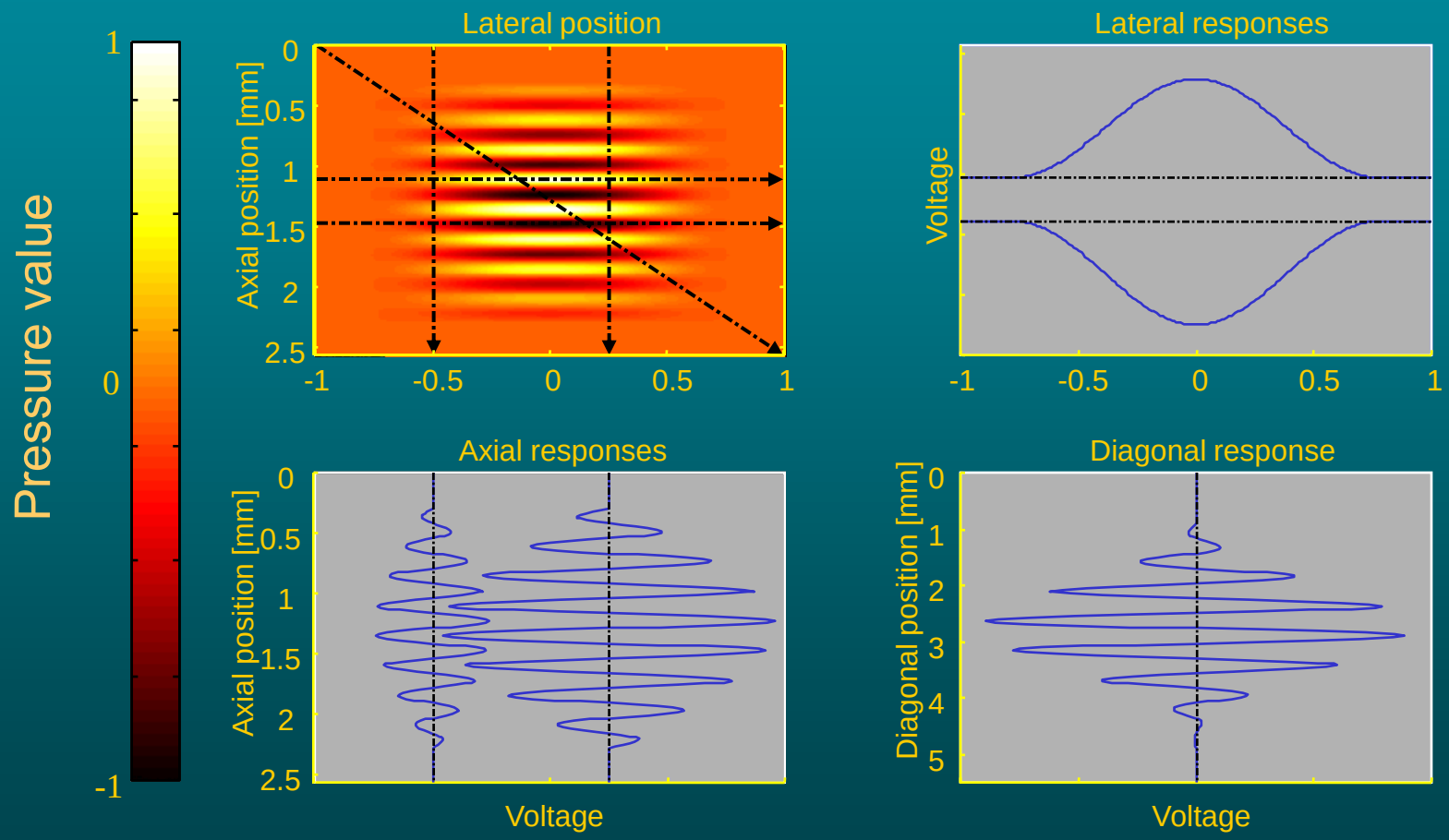
CFM with Angle Problem

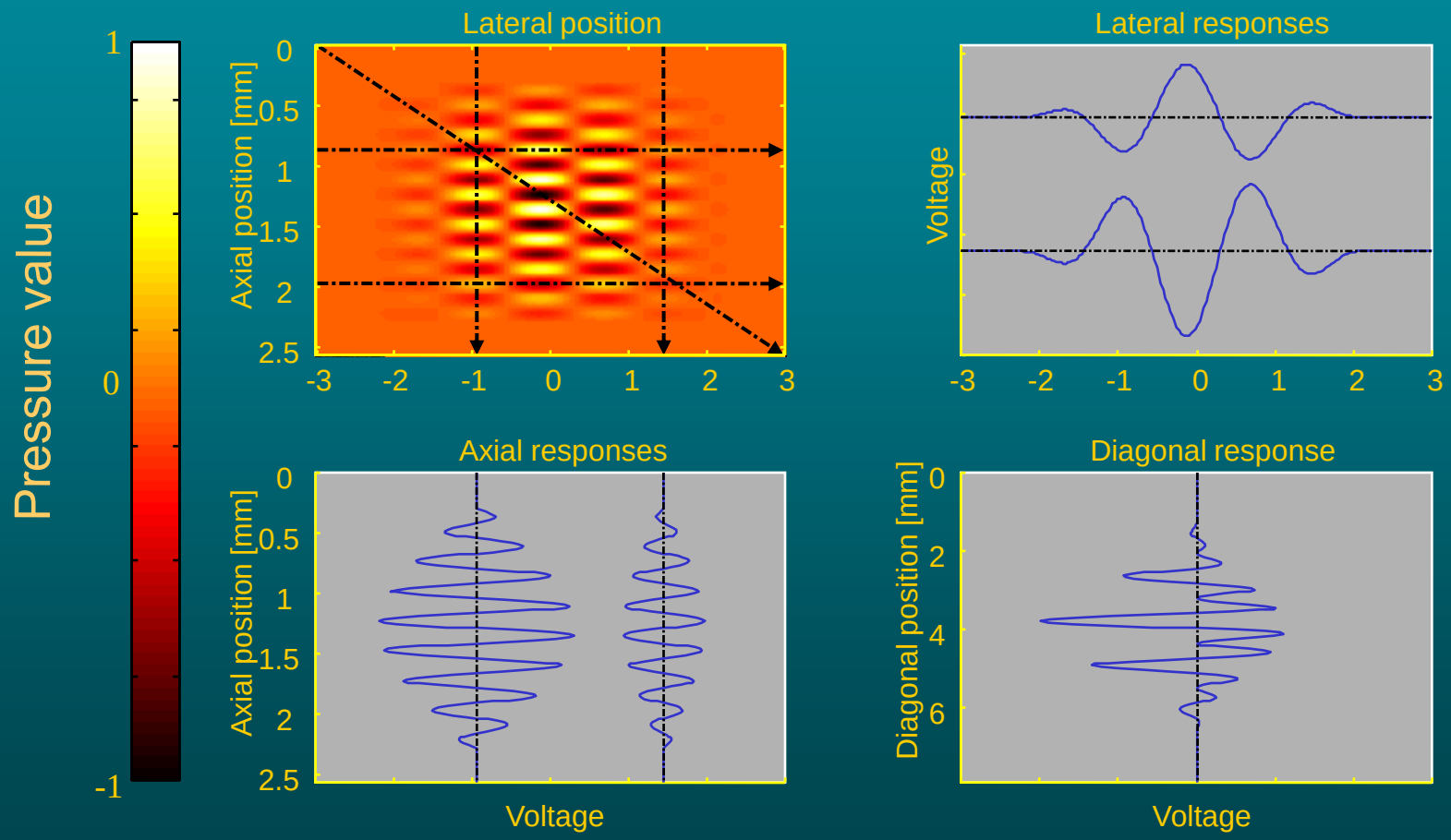


- Velocity changes direction in the image
- Determination is dependent on angle between beam and flow

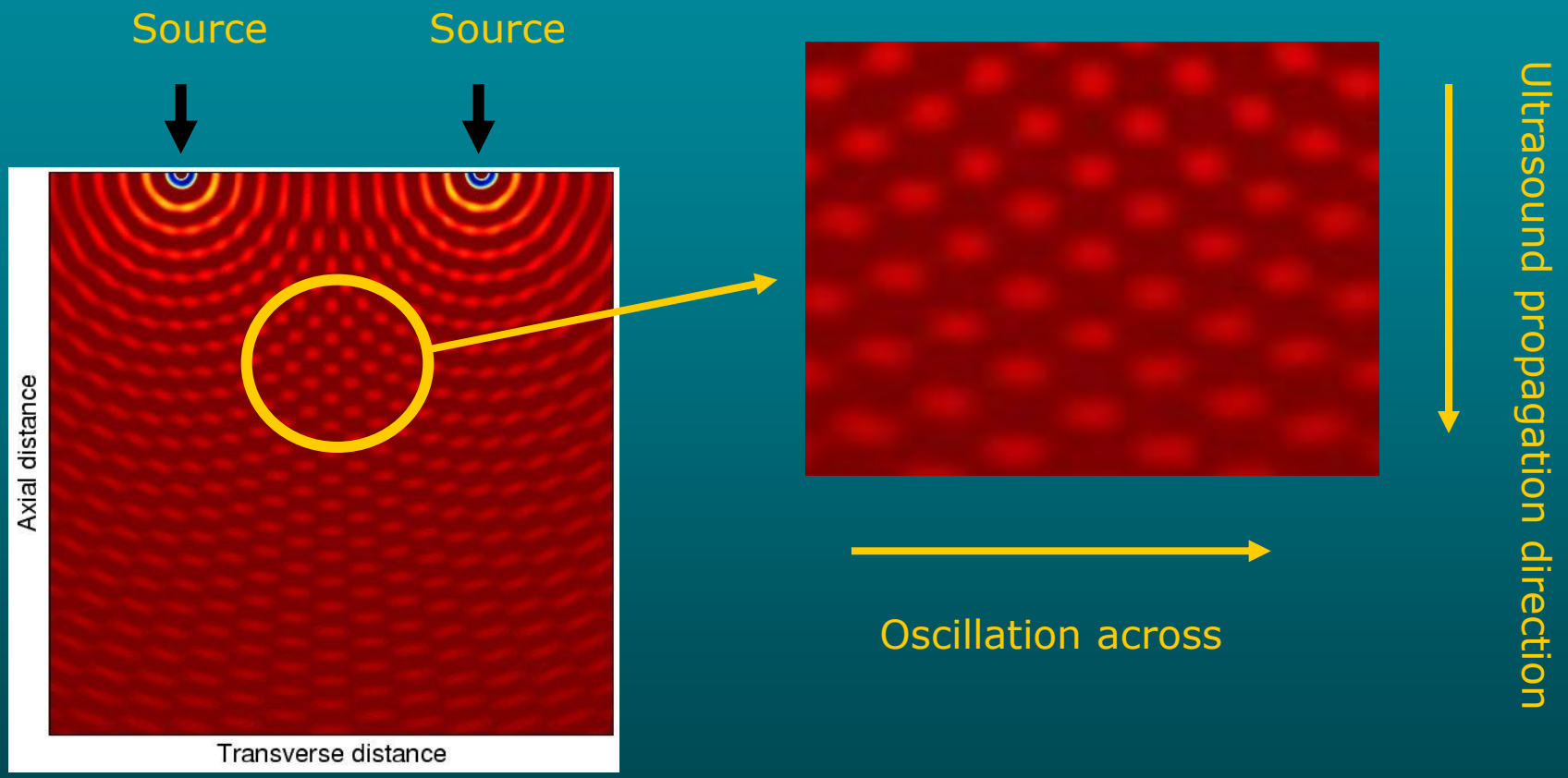
Normal velocity measurement



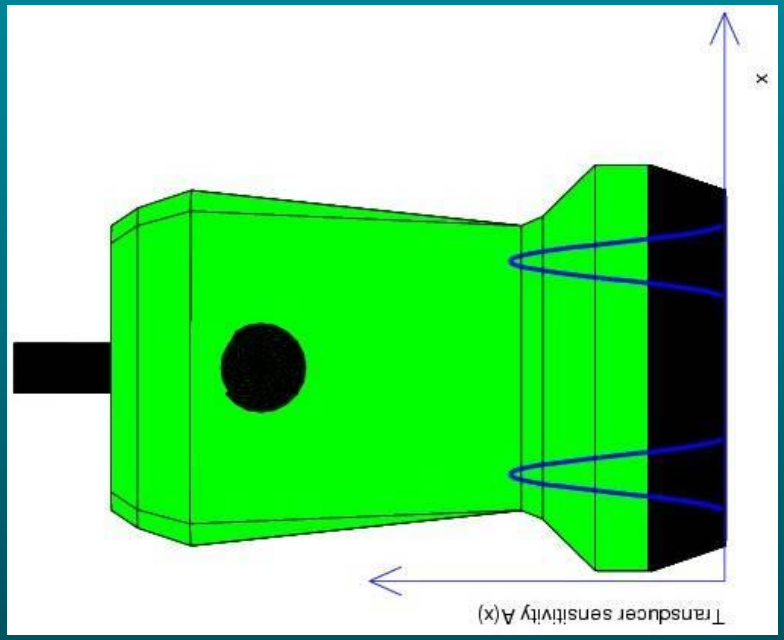
New double oscillating field

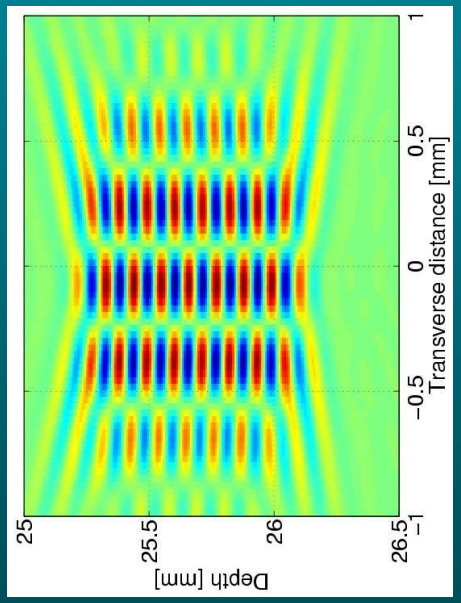


Simple generation

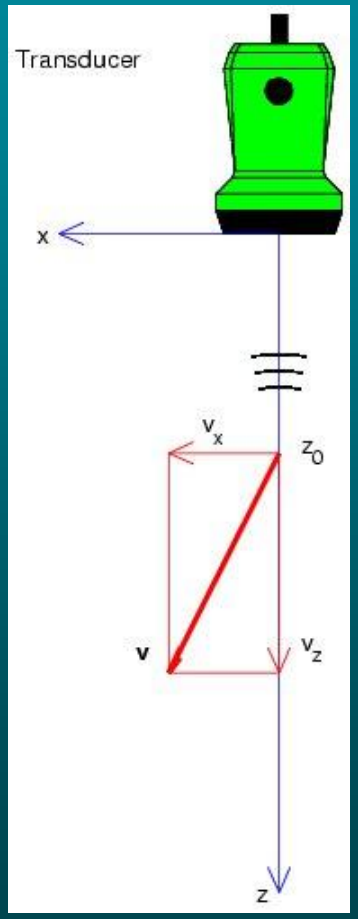


Generation for a transducer





Estimation of velocity vector



Fourth order estimator:

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

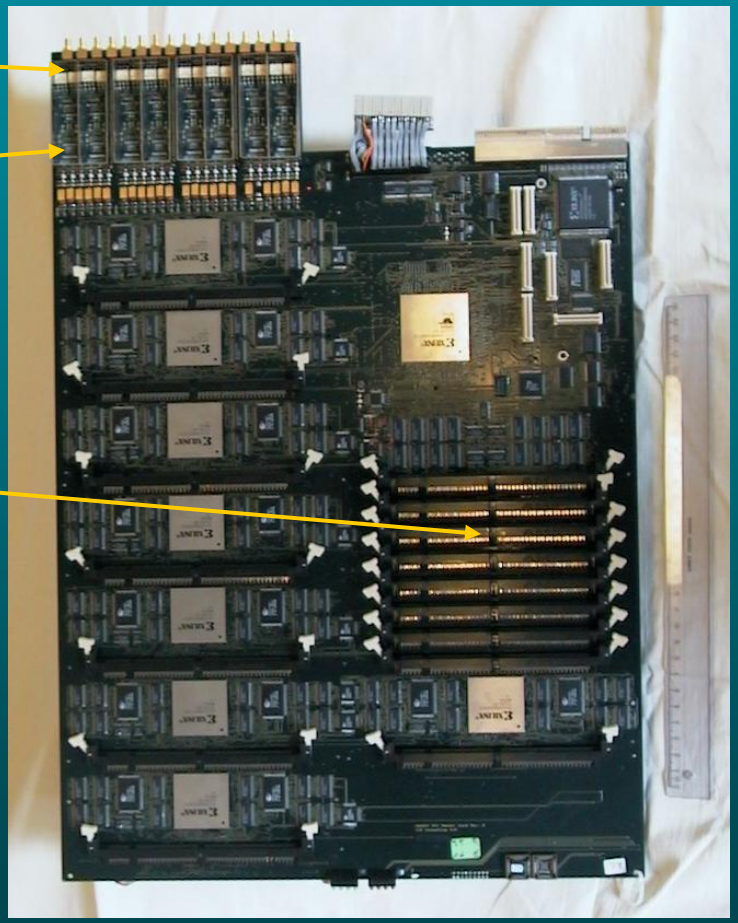
$$v_z = \frac{c}{2\pi f_0 4T_{prf}} \arctan\left(\frac{\sum_{i=1}^{N-1} \Im\{R_1(1)\}\Re\{R_2(1)\} - \Im\{R_2(1)\}\Re\{R_1(1)\}}{\sum_{i=1}^{N-1} \Re\{R_1(1)\}\Re\{R_2(1)\} + \Im\{R_1(1)\}\Im\{R_2(1)\}} \right)$$

RASMUS

- Remotely Accessible Software programmable Multi-channel Ultrasound System
- Can be used for synthetic aperture, real-time, *in-vivo* data acquisition (5 Gbytes/s)
- Made solely for research purposes

Receiver, measurement

- 2-to-1 multiplexing
- 8 channels per board
- Samples at 40 MHz and 12 bits
- 256 MBytes of storage per channel (3 seconds of real time data, 2 GBytes)
- 8 boards, 128 channels sampled

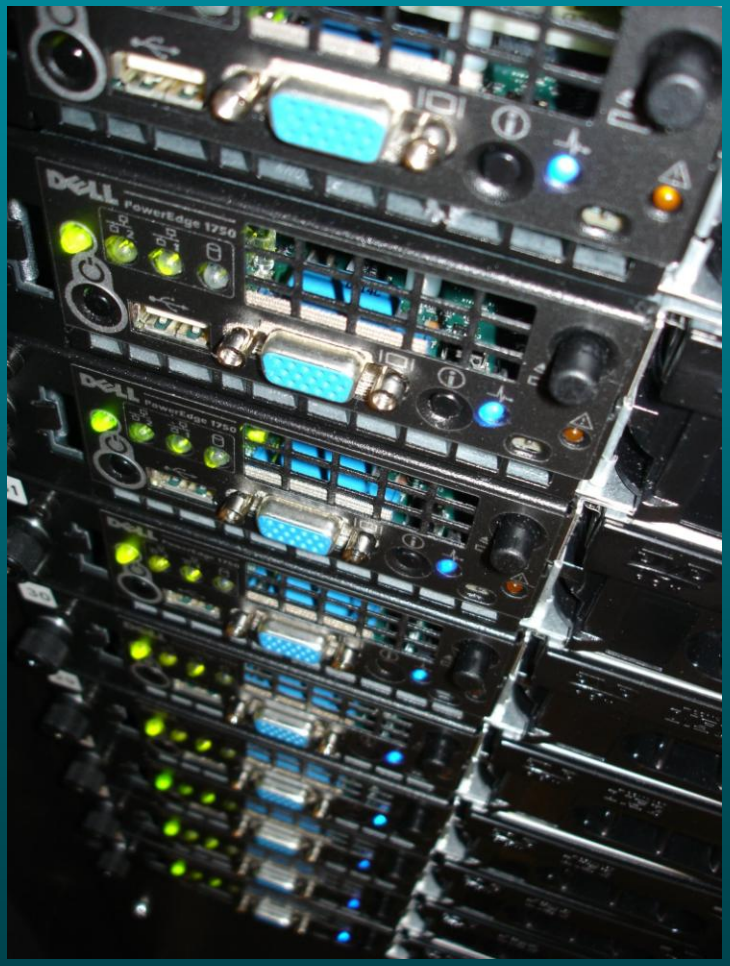


RASMUS

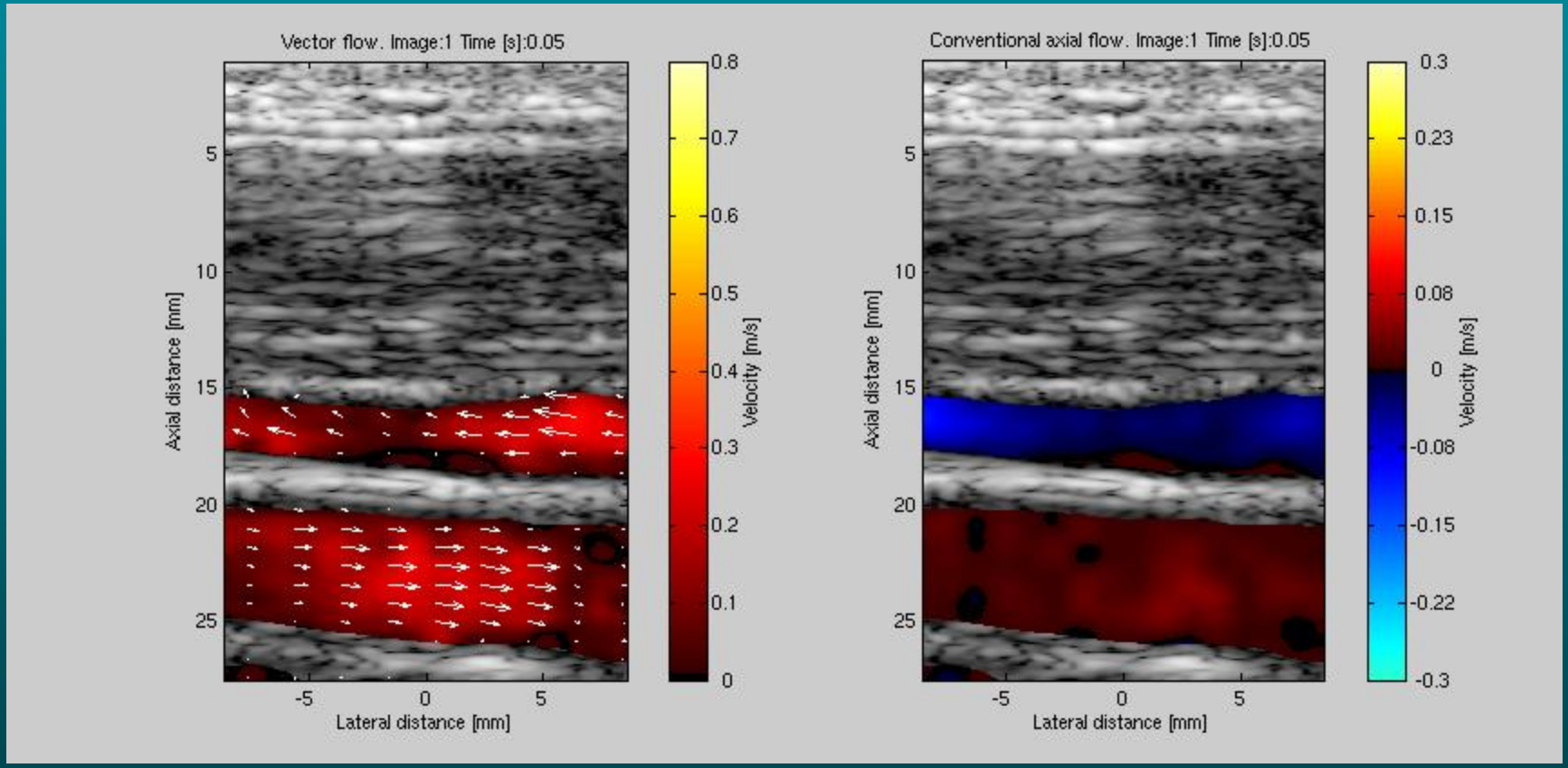
- Generates 5.1 GBytes/sec
- 24 GBytes RAM
- 72 FPGAs for processing (20 billion calculations per second)
- Controlled by 3 Linux PCs
- Remote control under Matlab
- Commands like in *Field II*
- Any FPGA can be accessed
- Data can be transferred from any memory in the system
- Connected through a SHARC DSP for display

The CFU Linux Cluster

- 100 Dell PCs, 3 GHz Xenon, 1 Gbytes RAM each
- 150 billion calculations per second
- Network: 50 Gbits/second (1 DVD film/second)
- 7 Tbytes data storage ($7 \cdot 10^{12}$ bytes)
- 100 Gbytes RAM
- 2.2 million times faster than our first workstation (1 year of work in 14 seconds)



In-vivo vector velocity for carotid artery and jugular vein

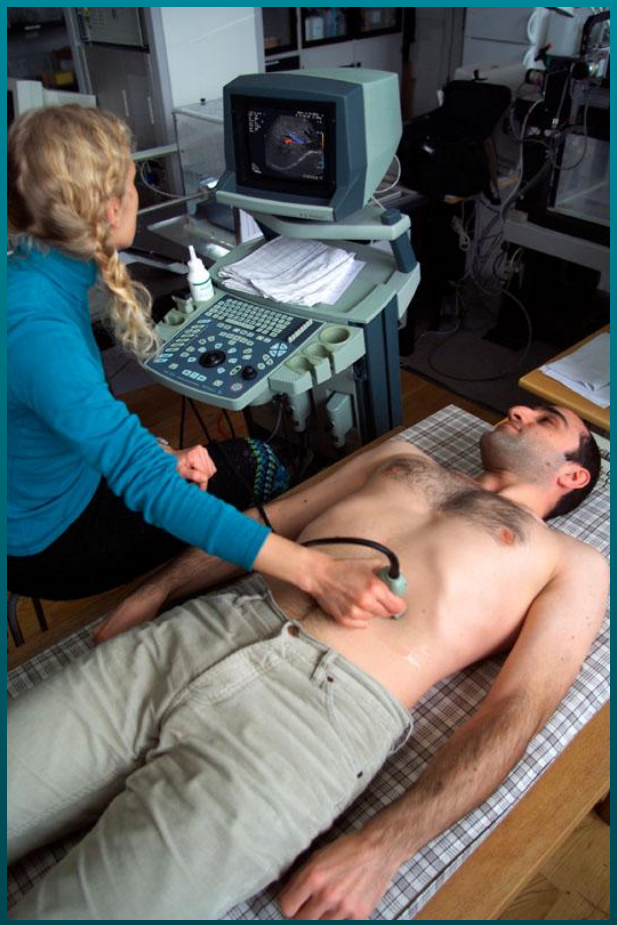


New method

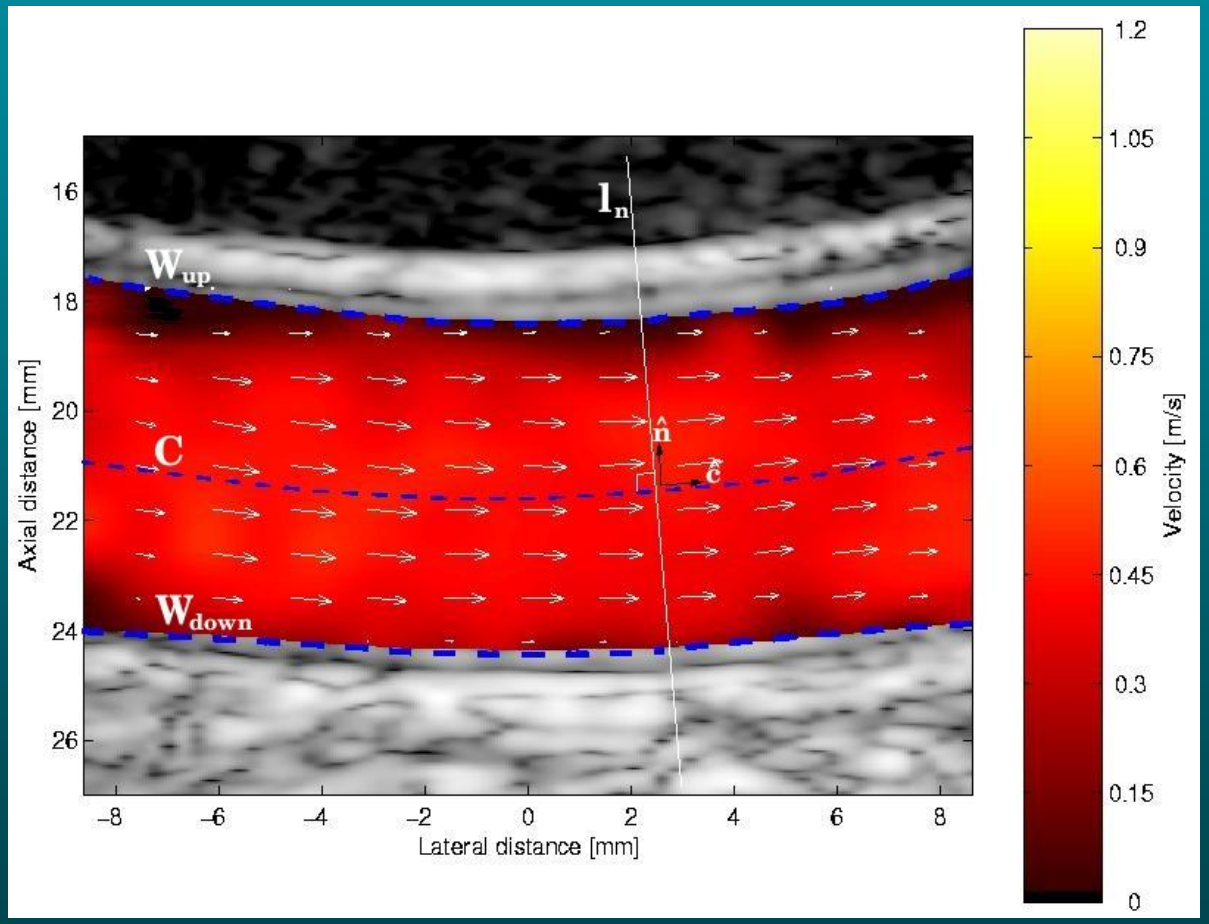
Conventional method

Clinical study

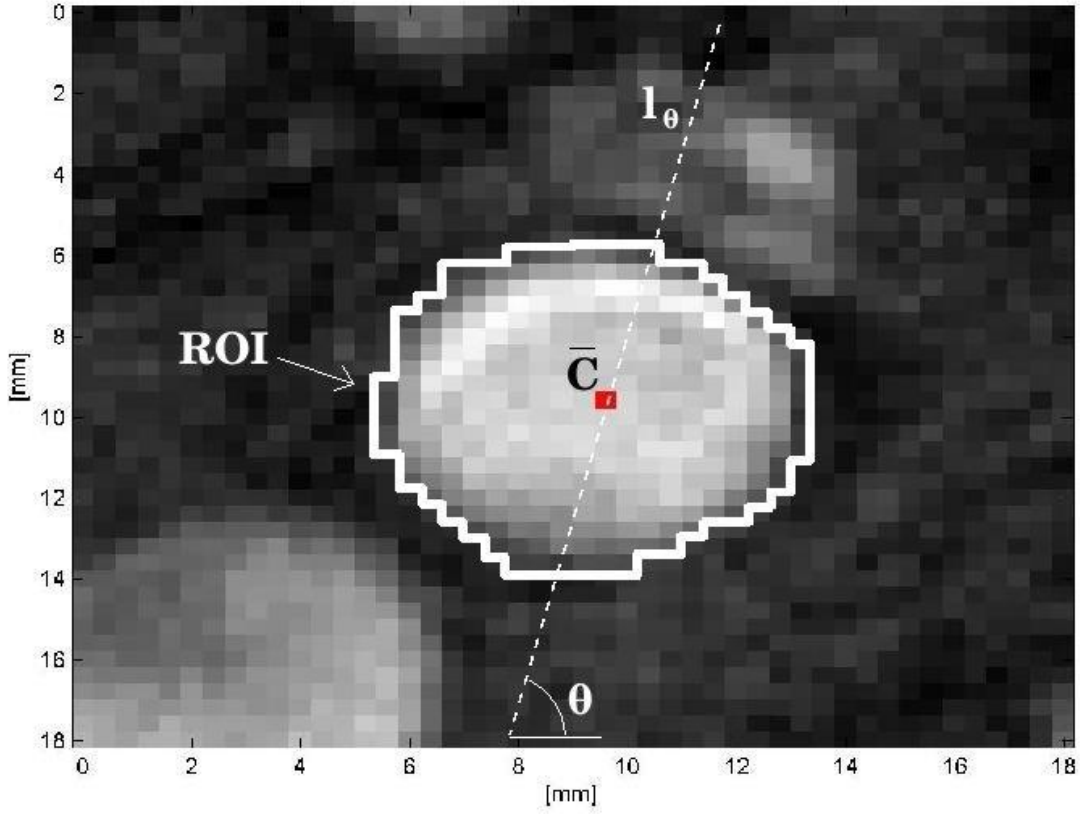
- 11 healthy volunteers
  - seven males and four females,
  - 24 – 44 years old, mean age: 32 years)
- Each person was scanned by US and MRI.
  - Examination for every person were performed at two separate occasions with no more than a week in between.
  - The volunteer rested supine 15 minutes prior to both examinations.
  - All scans were carried out by an experienced radiologist.

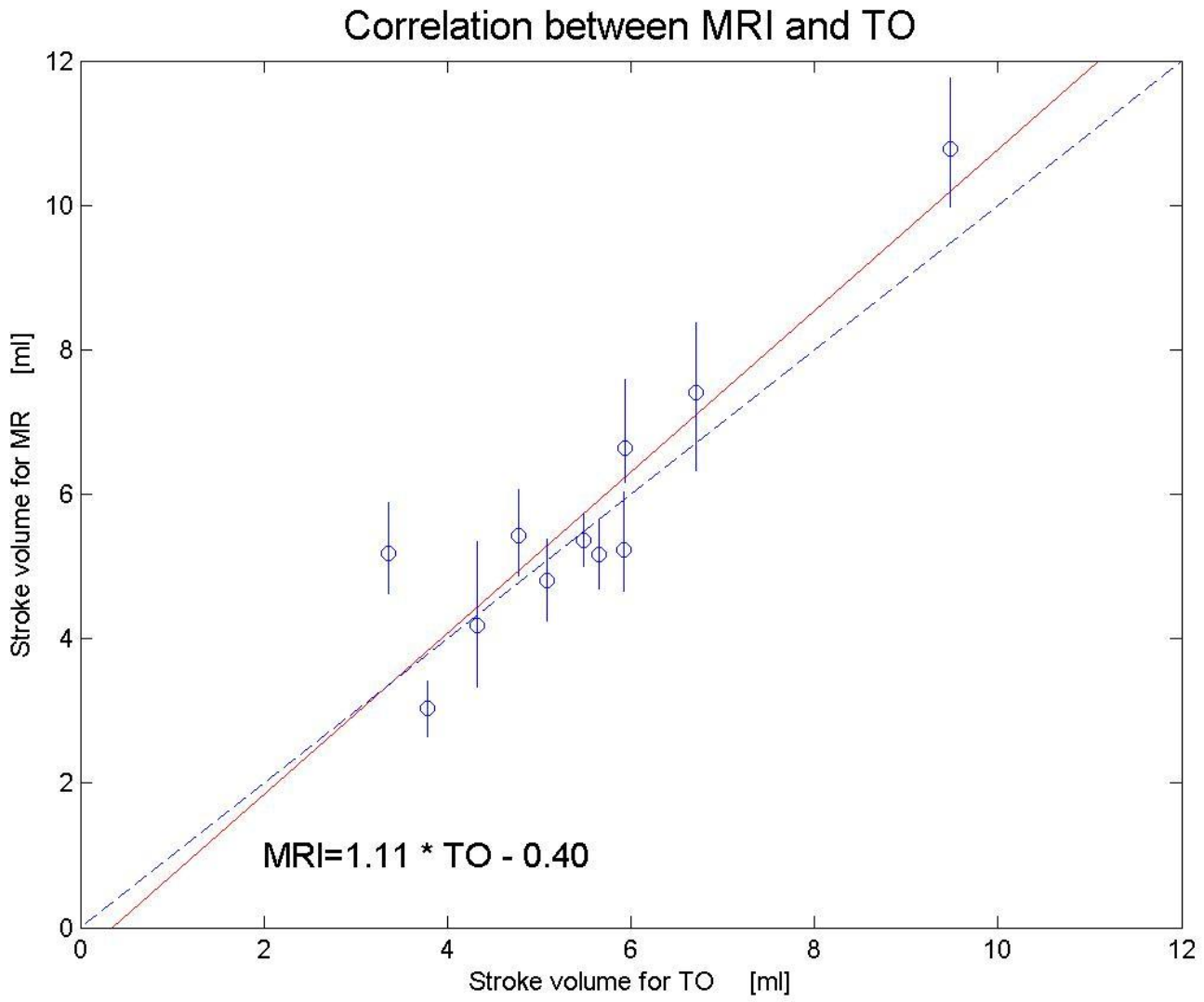


Vector velocity image of volume flow

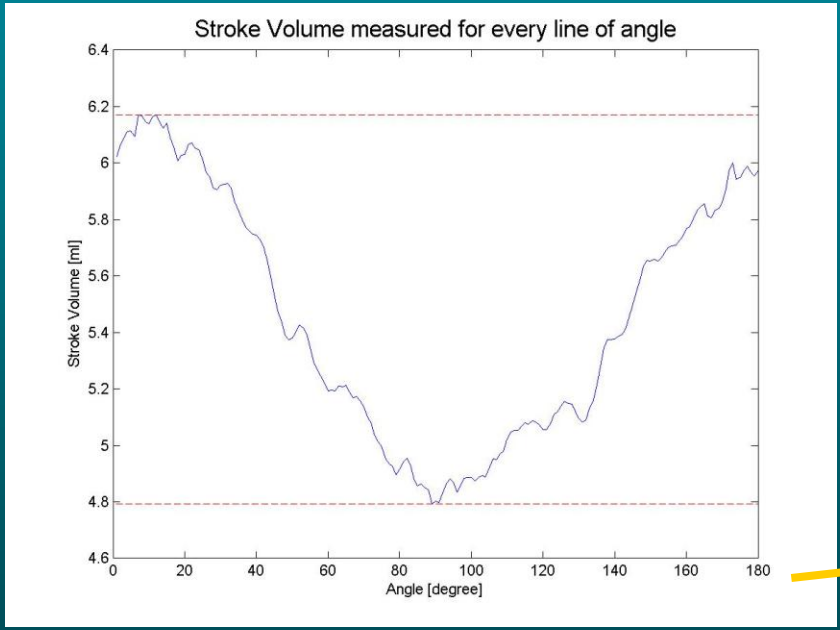


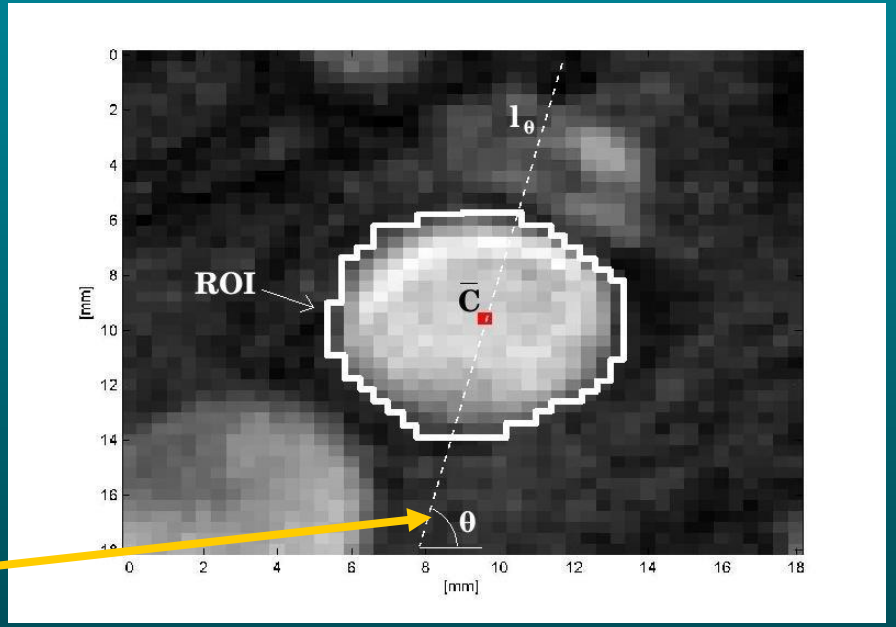
MR measurement of volume flow




Correlation between MRI and TO
Stroke volume for MR [ml]
Stroke volume for TO [ml]
MRI=1.11 * TO - 0.40
0
2
4
6
8
10
12

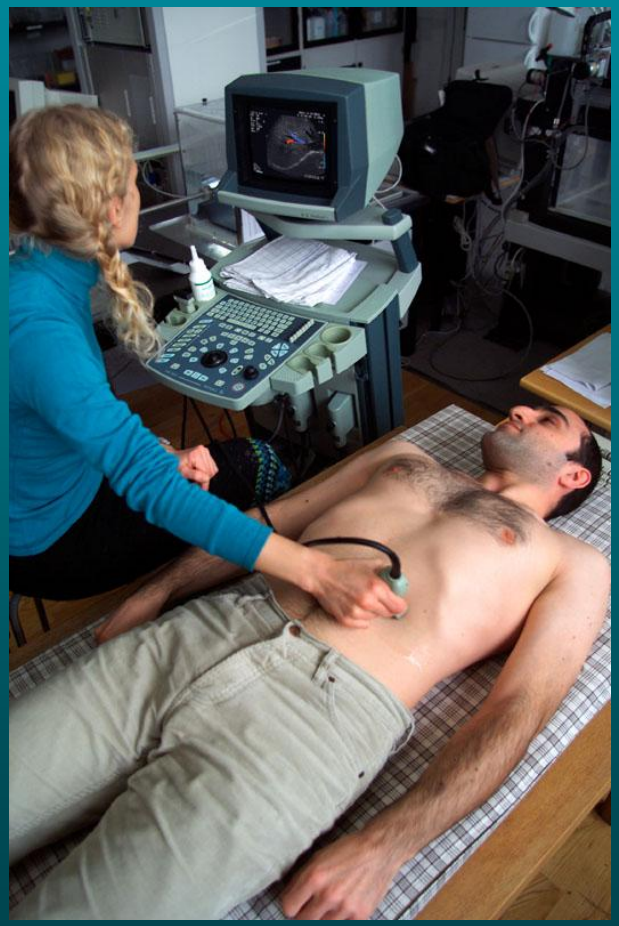
Sources of error





MR stroke volume as function of line angle

Result of clinical study

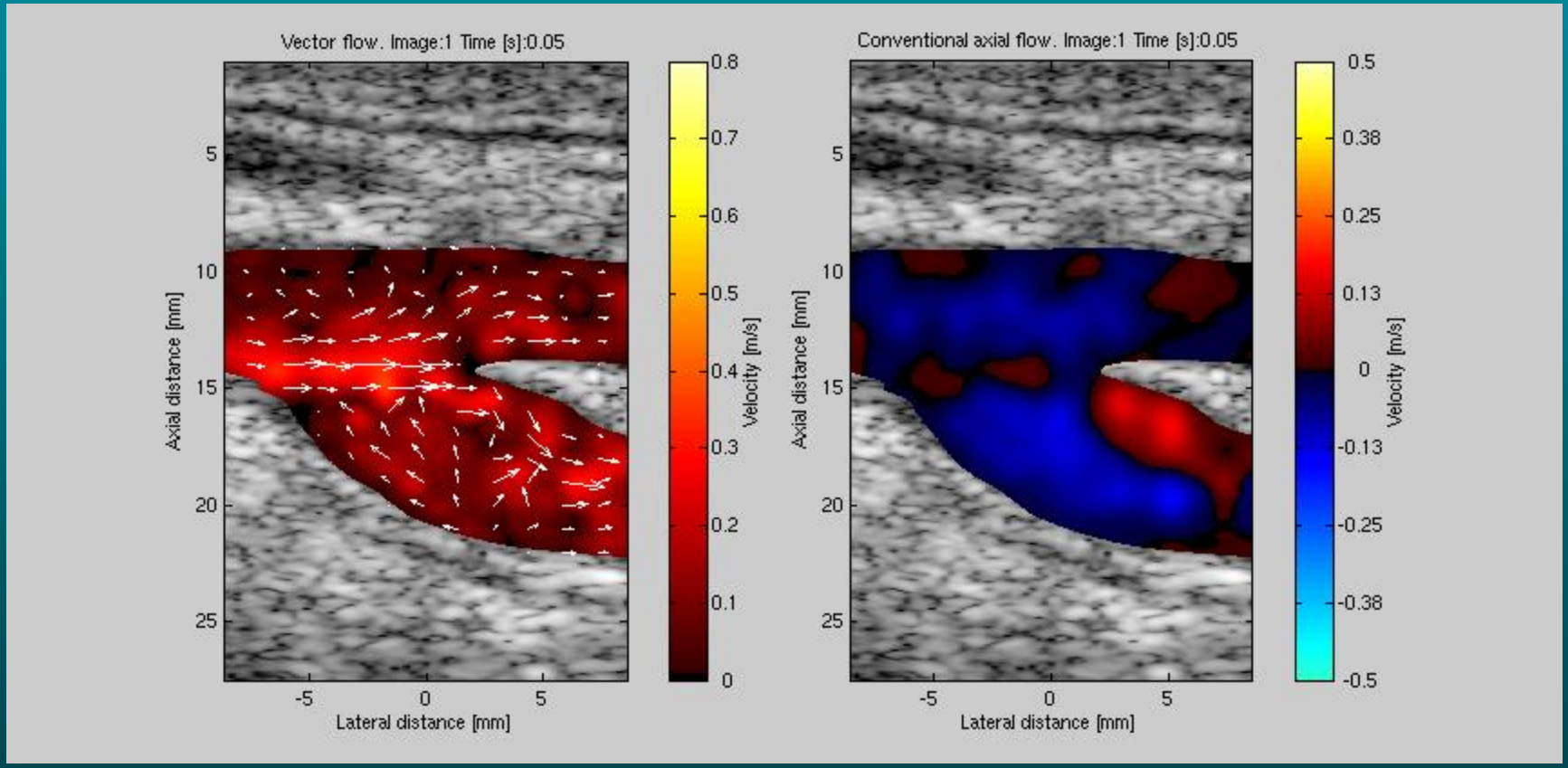


- Stroke volume in the right common carotid artery of 11 healthy volunteers compared
- Strong linear correlation (0.91, $p<0.01$) found between MR and Ultrasound
- TO ultrasound underestimated stroke volume
  by 0.24 ml/stroke compared to MRI
  - Underestimation illustrated by the slope of the regression equation (MRI=1.11*TO-0.40).
  - Is consistent with earlier results which showed an underestimation of less than 10% for all angles between 50° to 90°

Flow in the body

- Vessels in the human body
  - Branching and bifurcations
  - Not straight and smooth
  - Strongly pulsating flow
  - Valves in the heart and veins
- All of these effects should give rise to
  - Non-laminar flow
  - Disturbed or turbulent flow

Velocity in carotid bifurcation

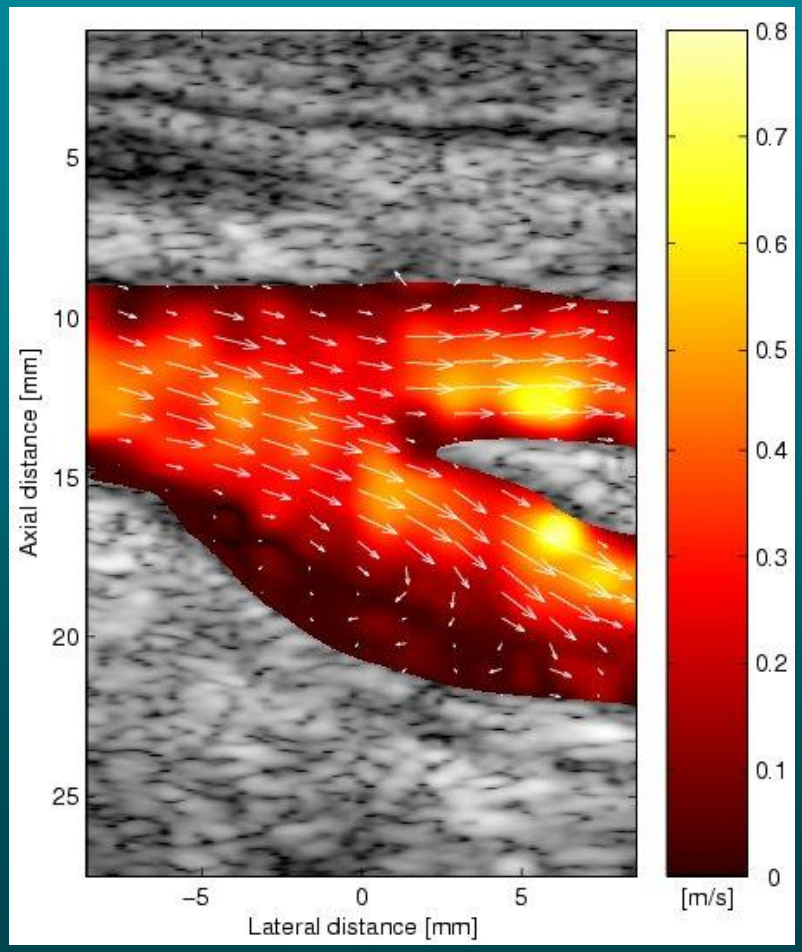


New method

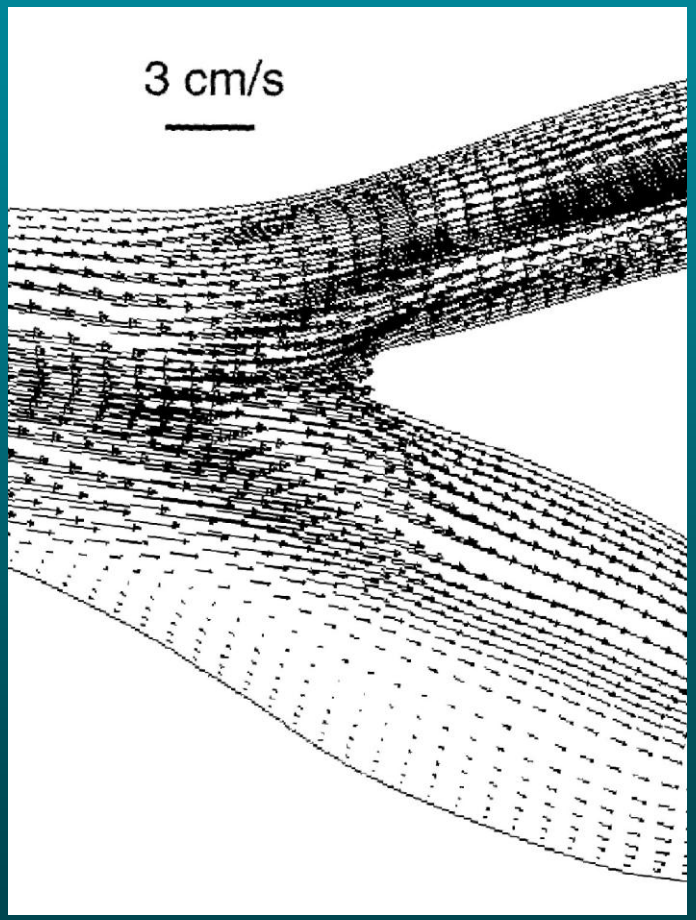
Conventional method

Velocity in carotid bifurcation at peak systole

Measured



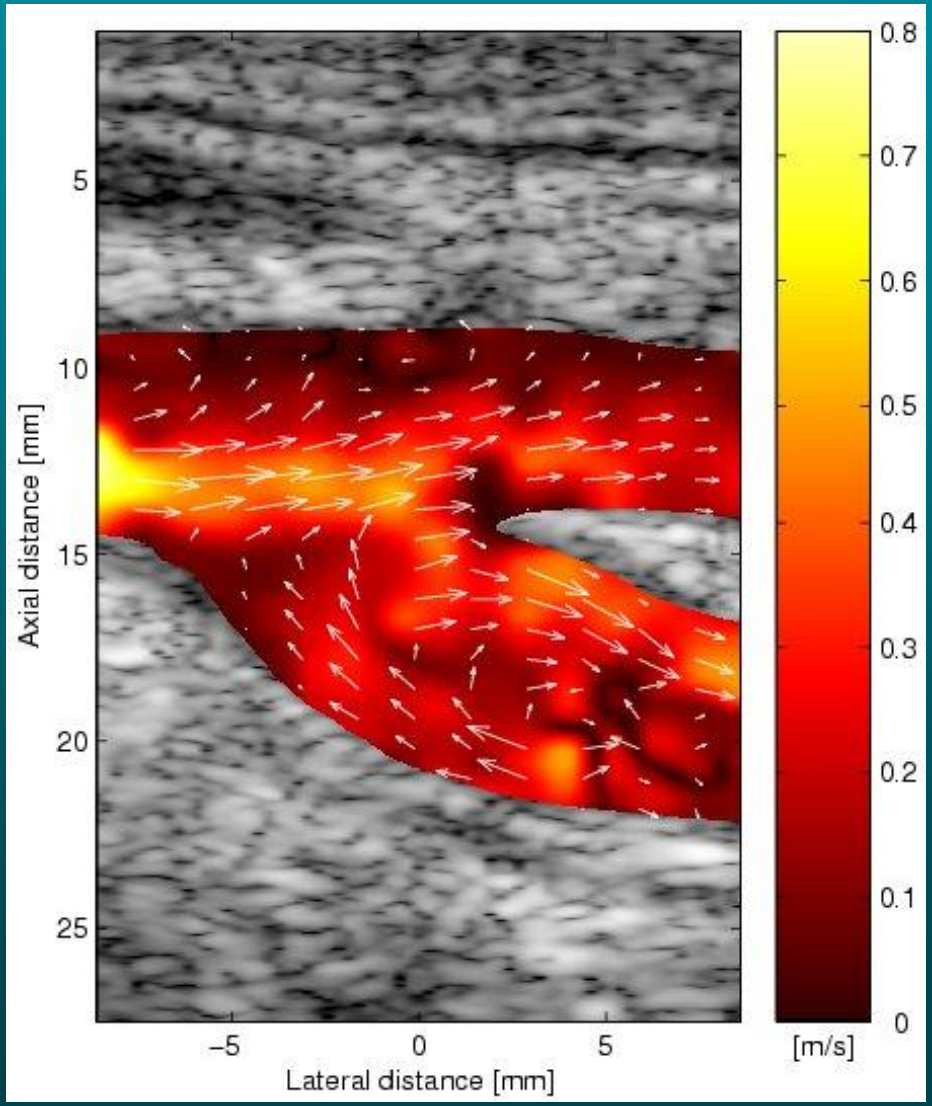
Simulated



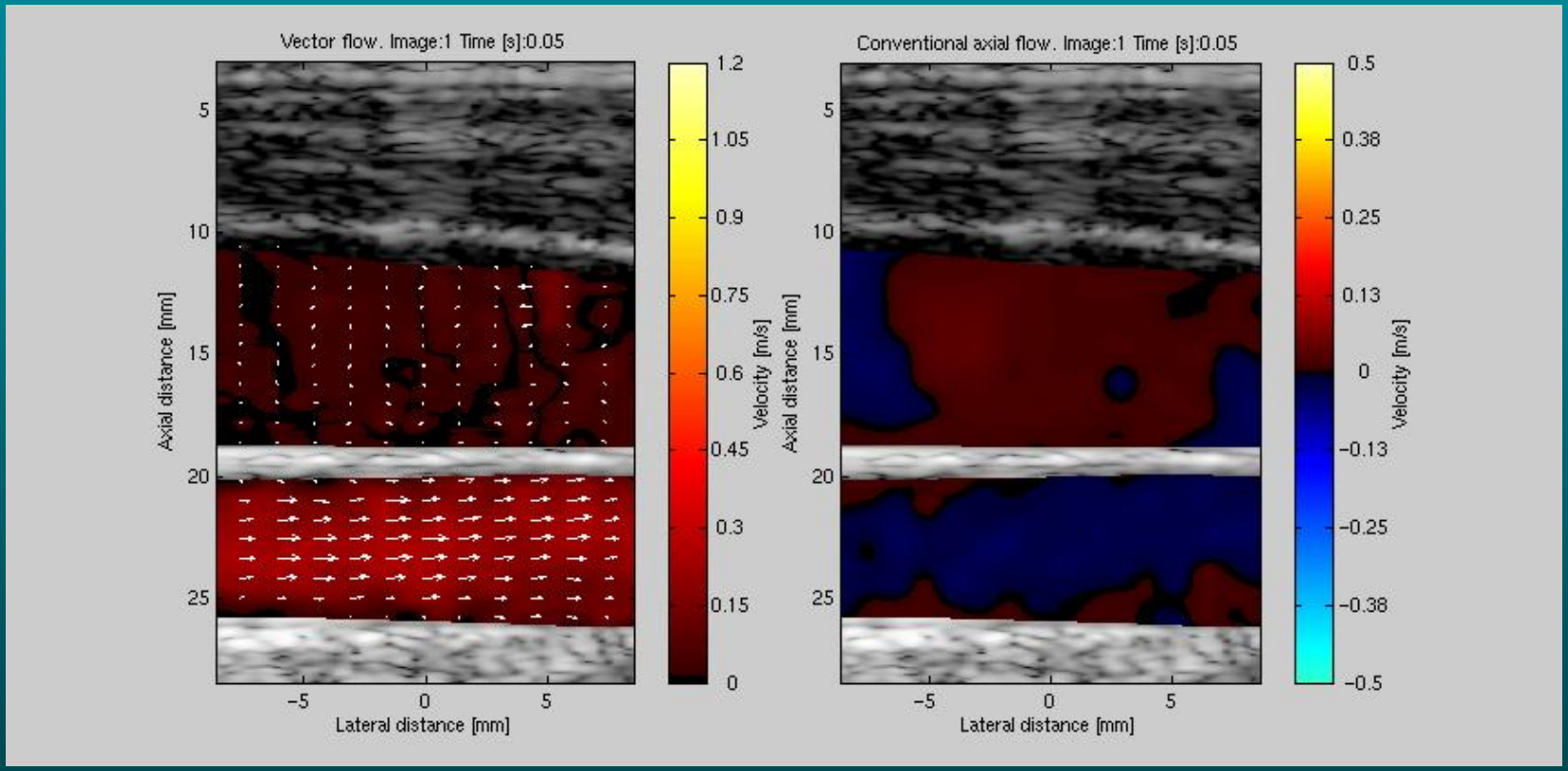
From Marshall et al. (2004), Journal of Biomechanics

CfU

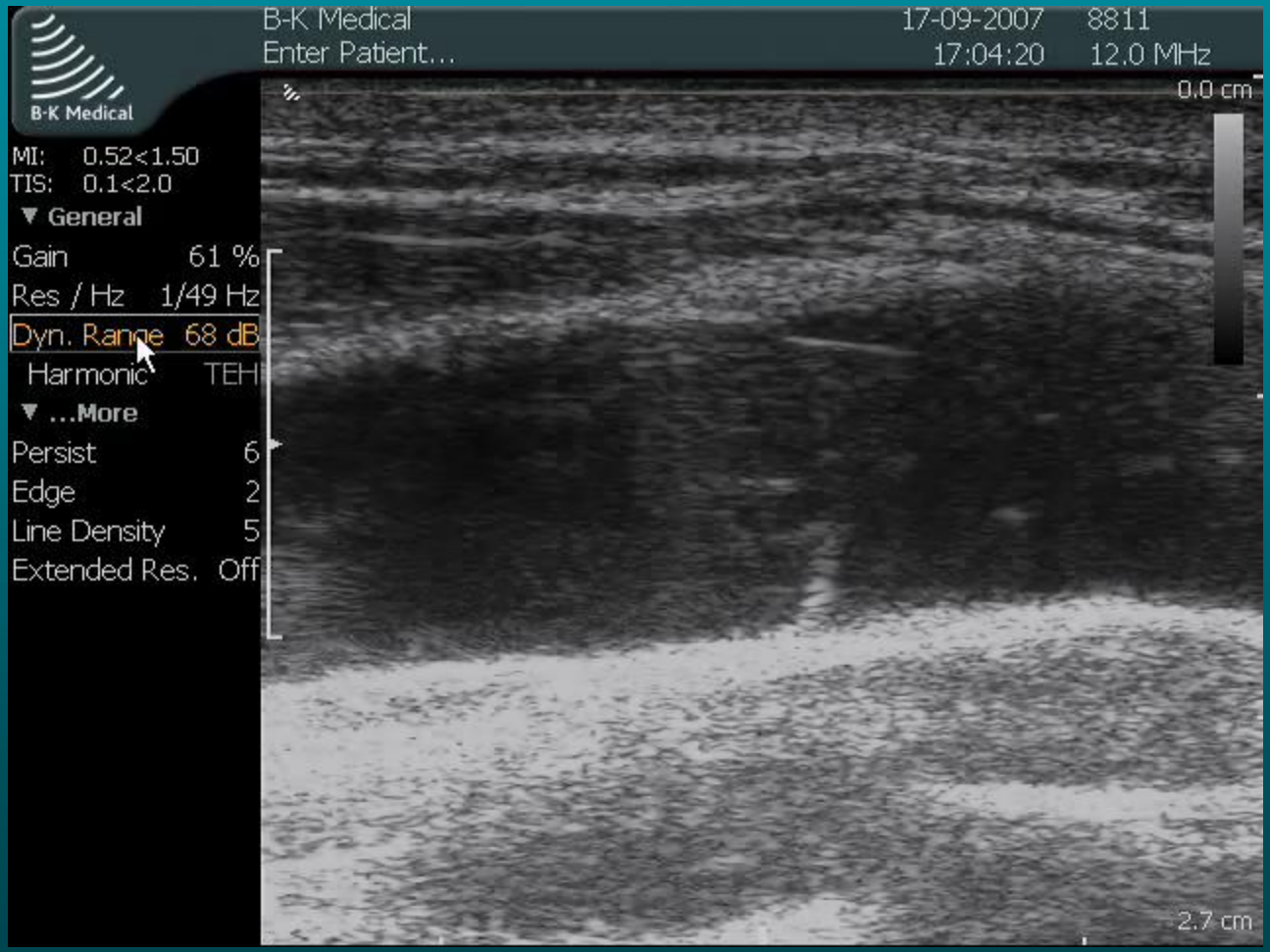
Velocity after peak systole in carotid bifurcation



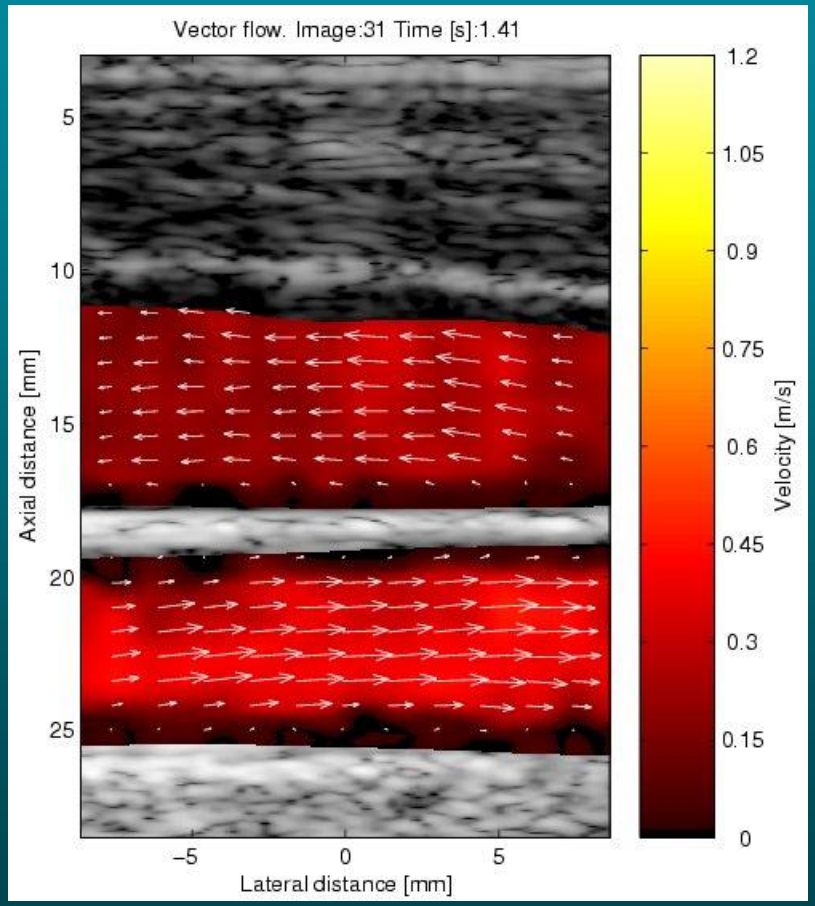
Flow in jugular vein and carotid artery

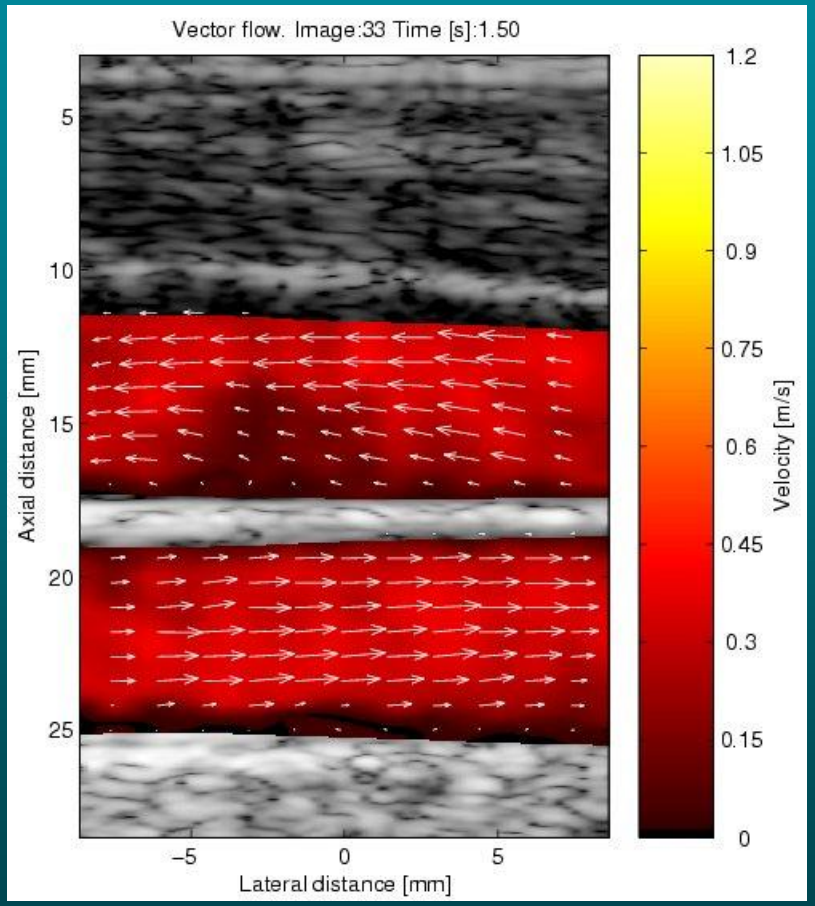


Valve in Jugular vein

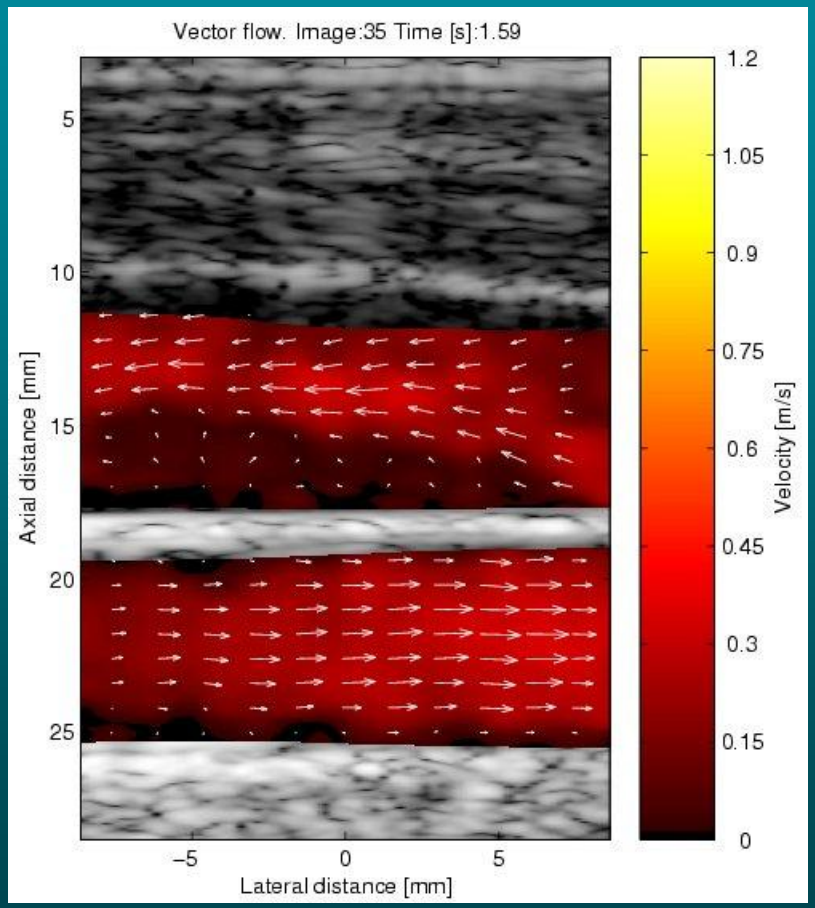


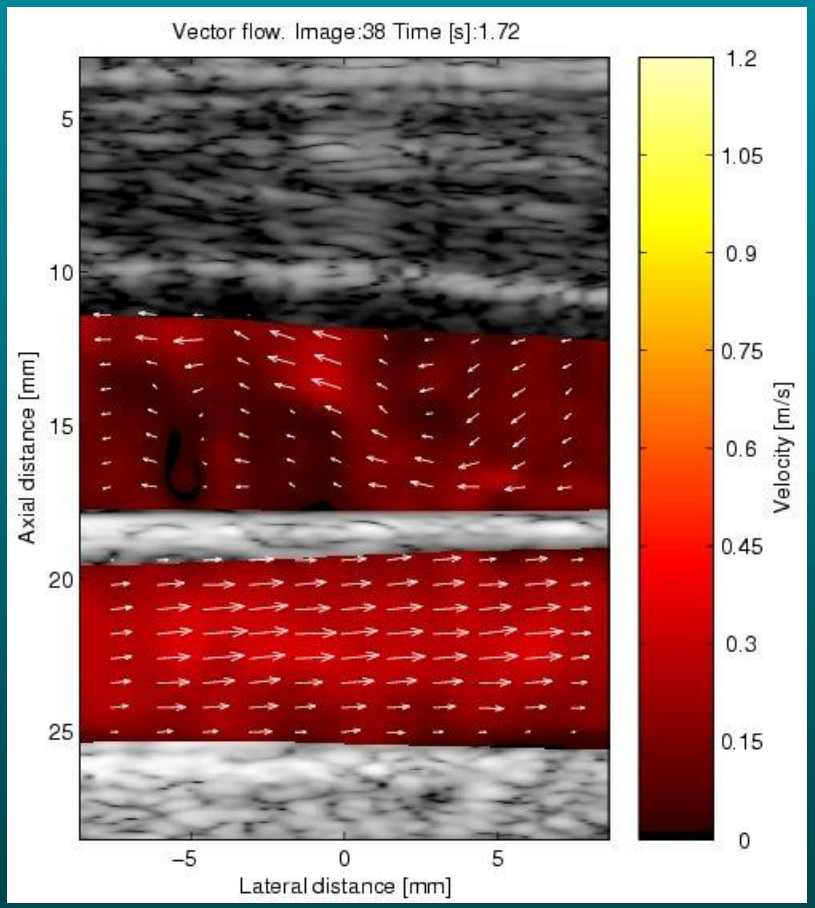
Before and at valve closure



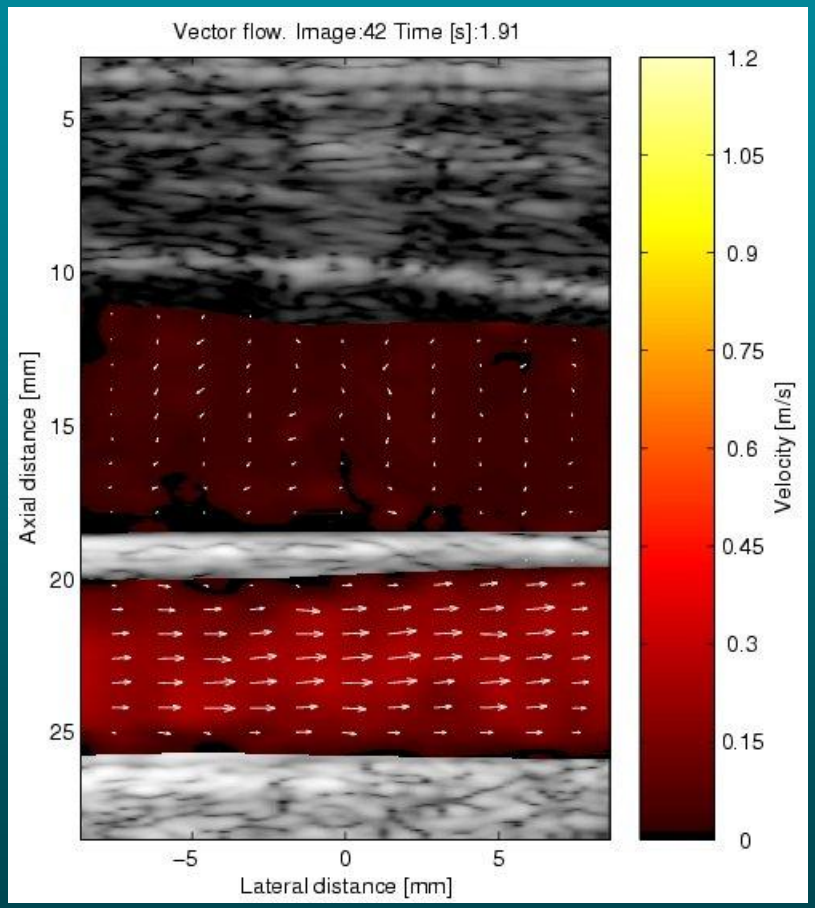


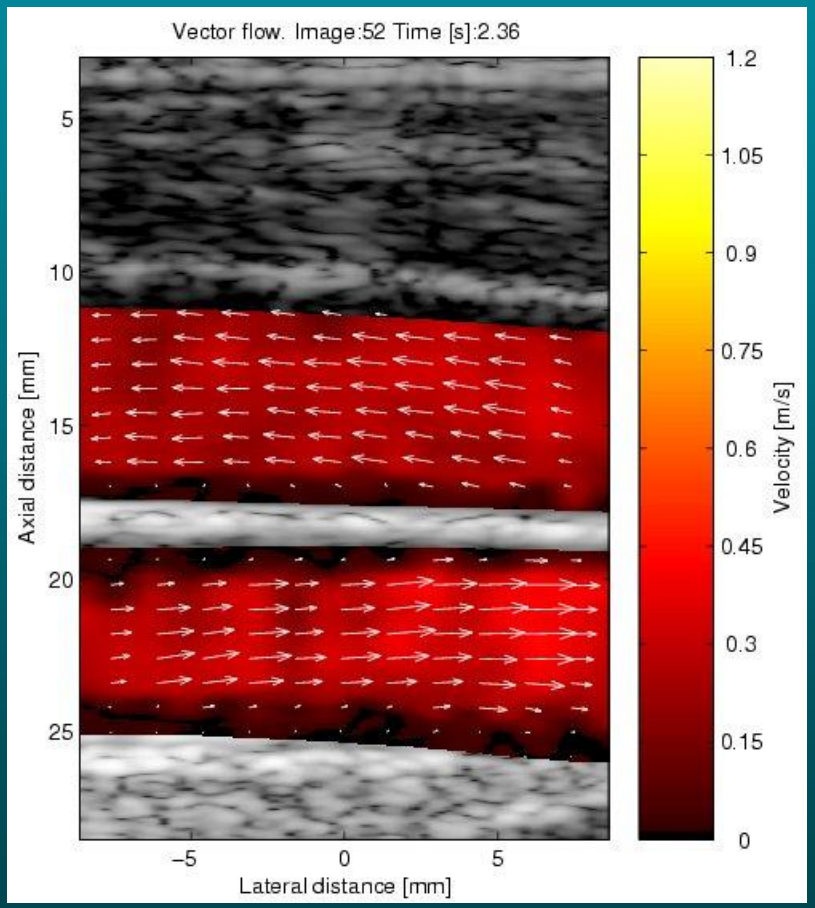
During valve closure





After valve closure





Conclusion

- Technique for vector velocity estimation presented
- Significantly increase accuracy and information about complex and turbulent flow
- Clinical study conducted comparing MR to TO Ultrasound showing a strong linear correlation (0.91, $p<0.01$) between modalities
- In conventional system it looks like turbulence, but it is a repeatable disturbed flow