Velocity Images - the MR Phase Contrast Technique

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SSIP 2004 – 12th Summer School in Image Processing, Graz, Austria

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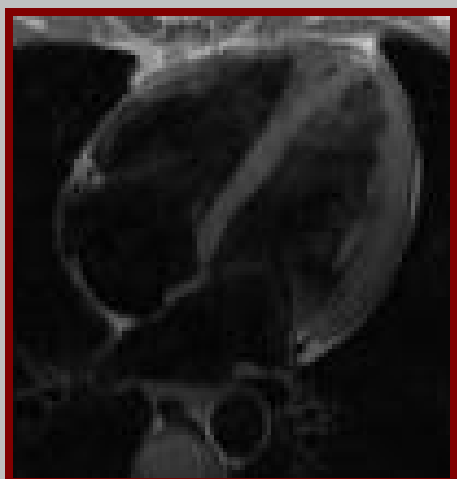
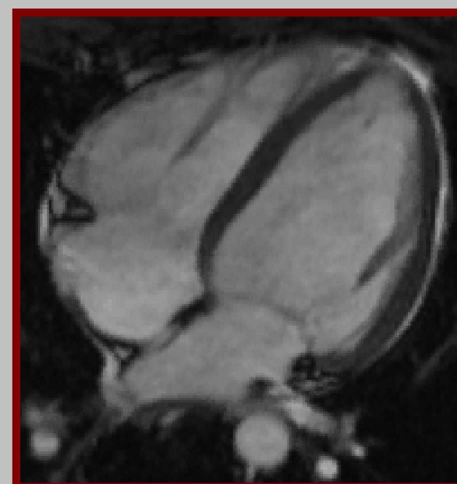
Introduction

Trend in medical imaging: From morphology to function.



„static“



„dynamic“

- Tissue movement
- Fluid flow
- Perfusion
- Diffusion
- Oxygenization and brain activation
- Metabolism

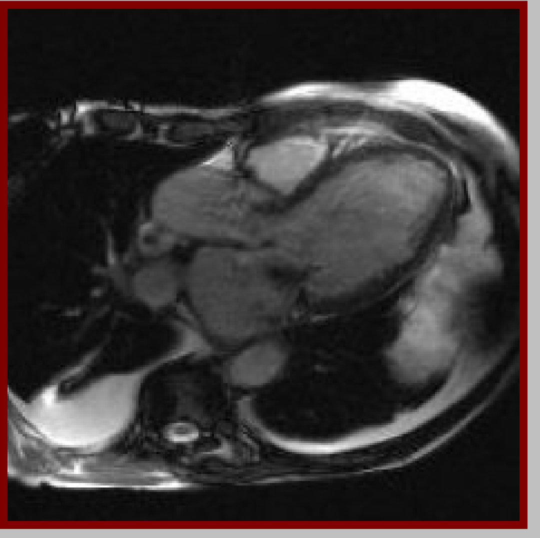
....

Introduction

Basic „macroscopic“ variables: Position **x** („morphology“) and velocity **v** („dynamics“).

MR imaging generally motion sensitive.

Blood flows through mitral valve directed apically, then turns around and flows through aortic valve.



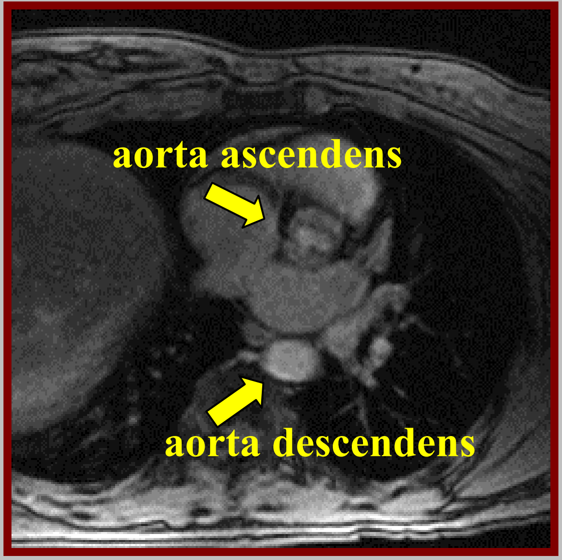
Turbulences (dark) at the mitral and aortic valve

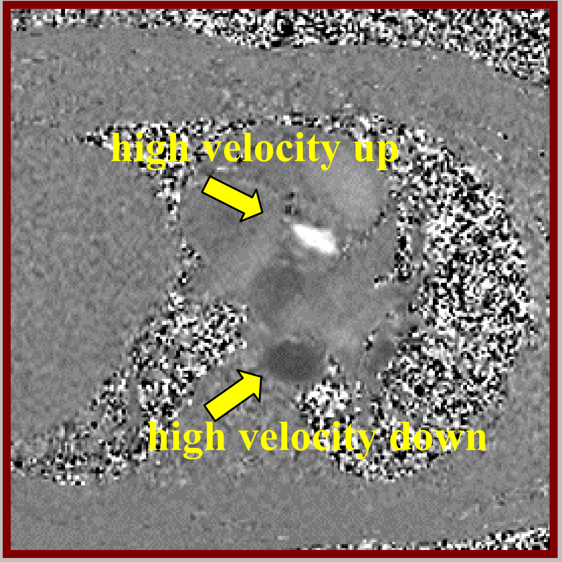
„Qualitative“ blood flow in the heart

Introduction

But MR via phase contrast technique can even produce pairs of images displaying morphology and velocity.

anatomy



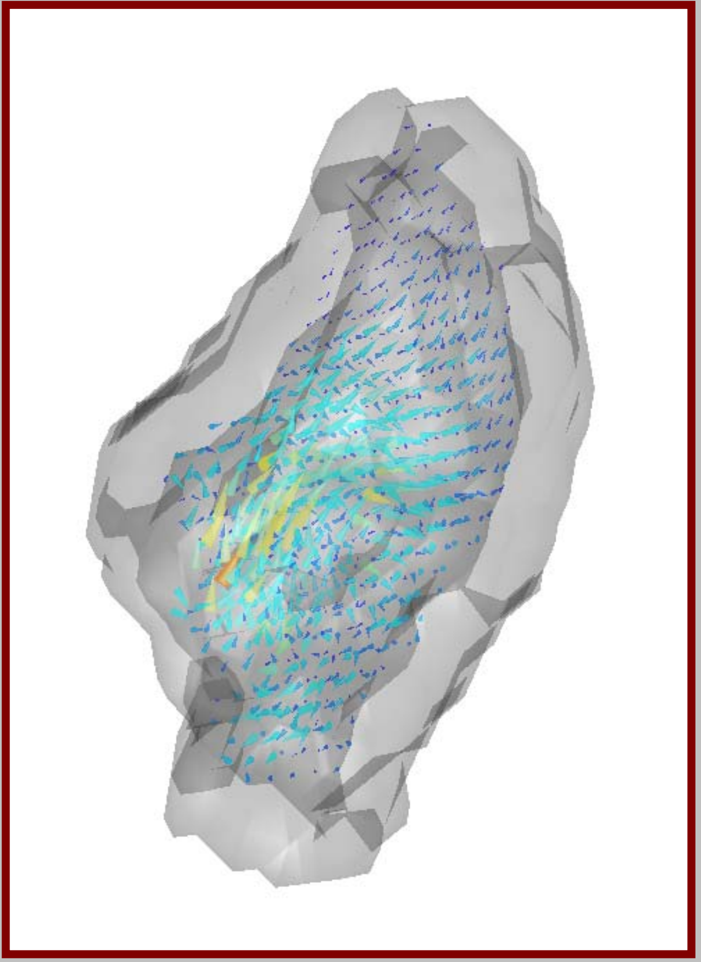


velocity ∝ gray scale

same tomographic slice

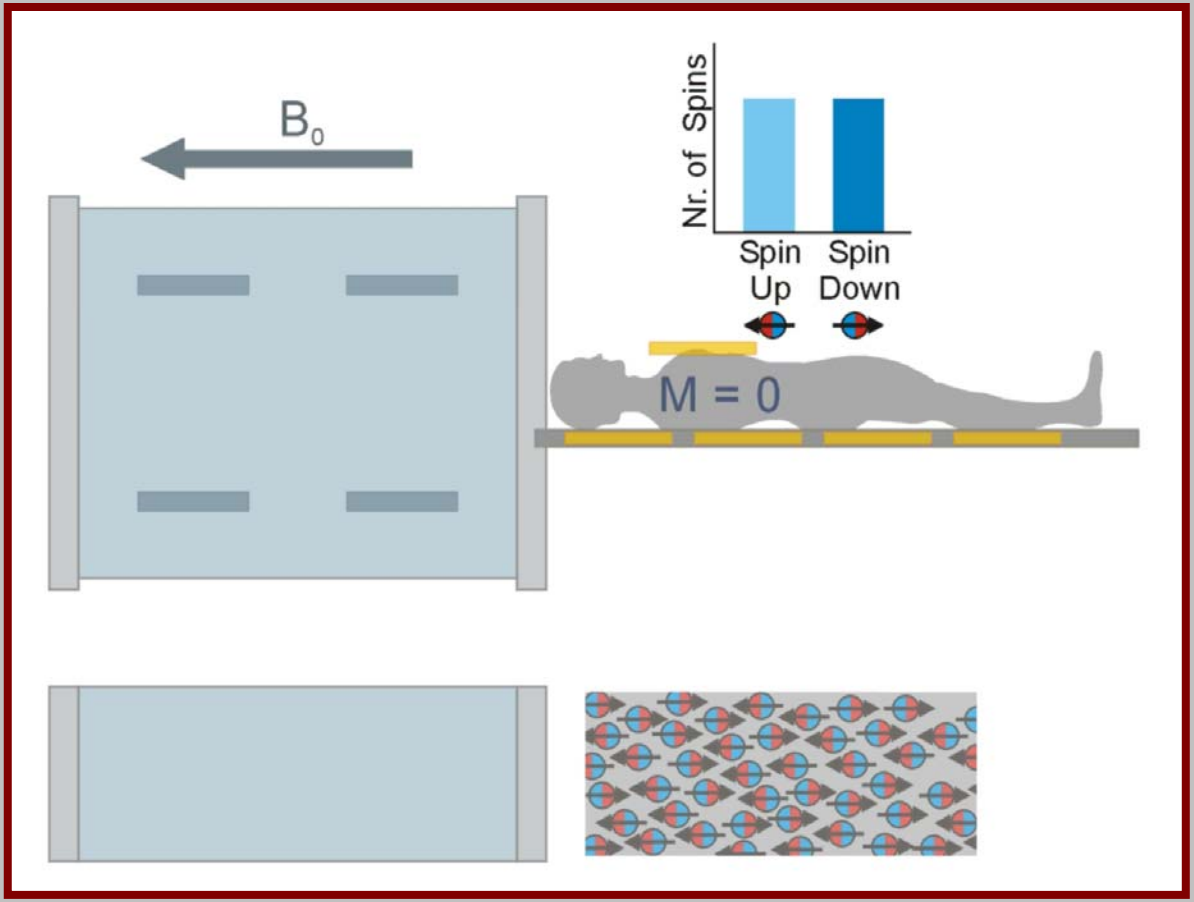
Introduction

- Idea of phase contrast method
- Pulsatility
- Archetypical postprocessing
- Advanced Considerations
- Application examples
- Perspectives



Phase contrast method

Introducing the notion of phase – MR in a nutshell

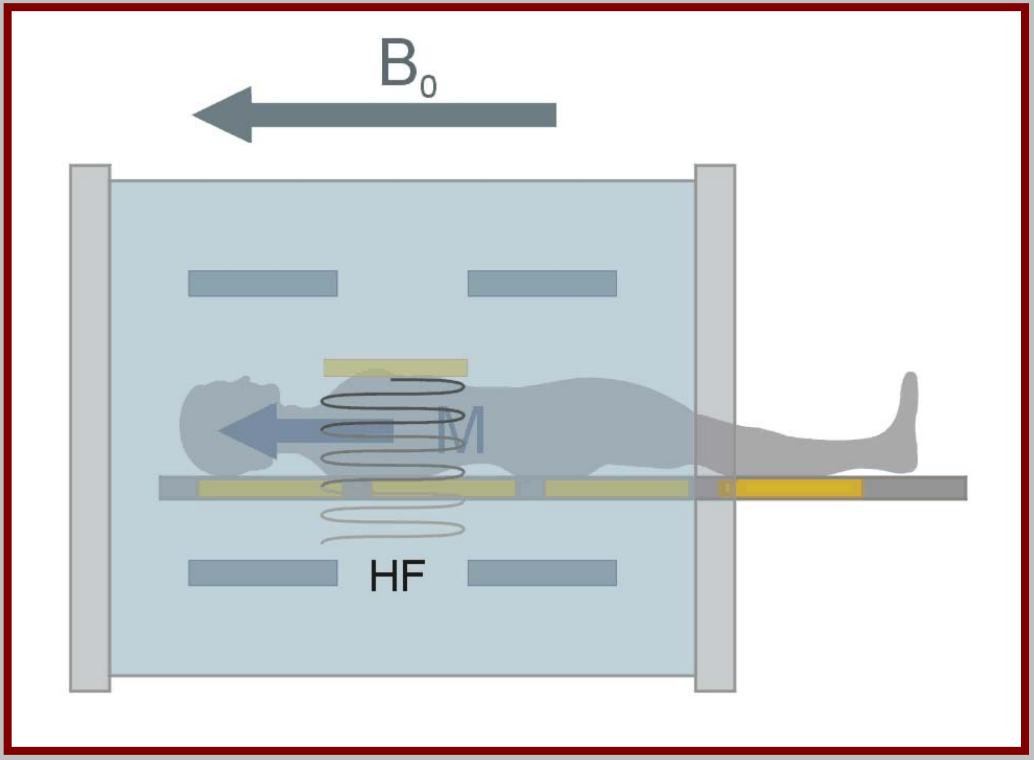


Hydrogen nuclei possess spin (are small magnets).

Static magnetic field $\mathbf{B}_0$:
Creation of net magnetization **M**

Phase contrast method

Introducing the notion of phase – MR in a nutshell



Electromagnetic waves at at Lamor frequency (HF)

$\omega_0 = \gamma B_0$

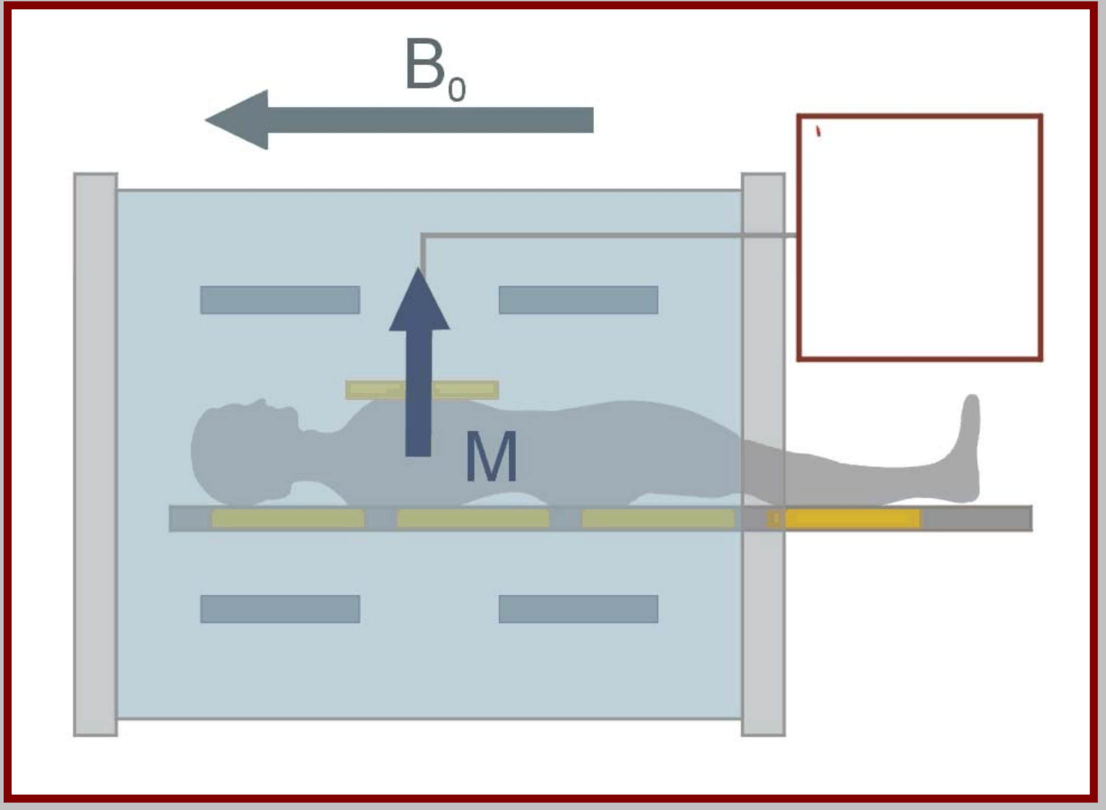
with γ gyromagnetic ratio.

➡ spins flip (resonance).

➡ net magnetization rotates away with ω_0.

Phase contrast method

Introducing the notion of phase – MR in a nutshell



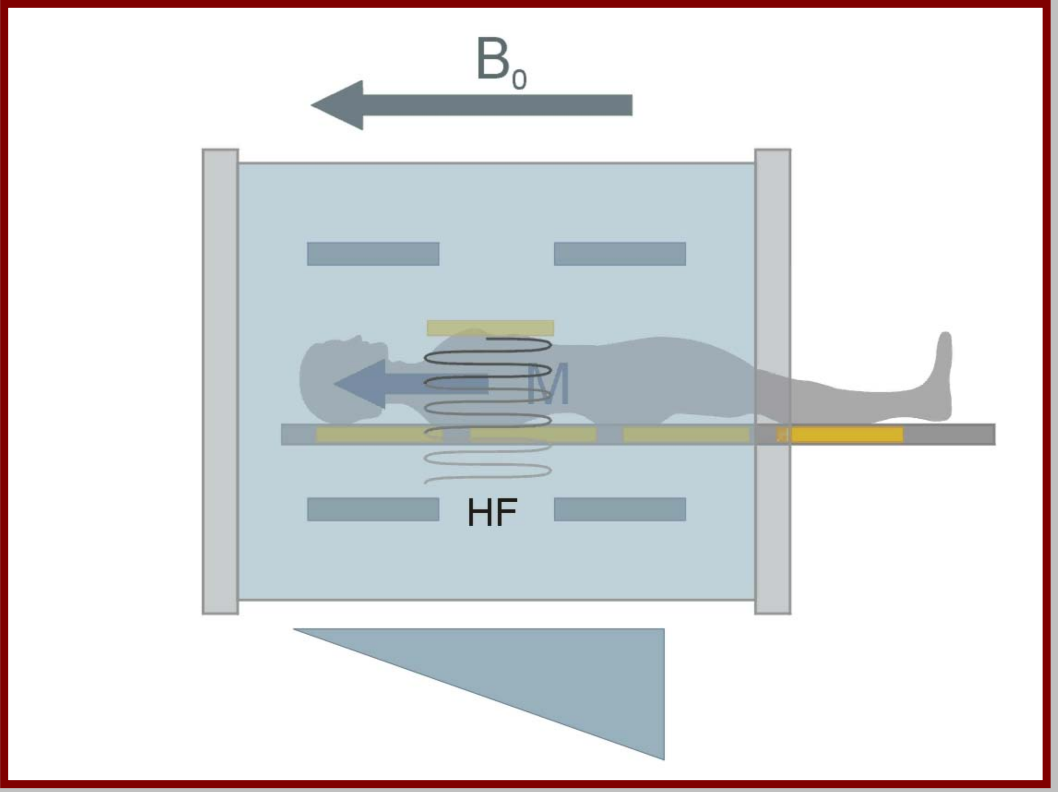
After excitation magnetization relaxes.

➡ Transversal (to $\mathbf{B}_0$) magnetization $\mathbf{M}_\perp$ induces signal in coil:

signal $\propto M_\perp$

Phase contrast method

Introducing the notion of phase – MR in a nutshell



Gradient magnetic fields

$\mathbf{B}_g \| \mathbf{B}_0$:

$$B_g(\mathbf{r},t) = \nabla B_g(t)\mathbf{r} = \mathbf{G}(t)\mathbf{r}$$

➡ Localization via spatial dependence of angular frquency:

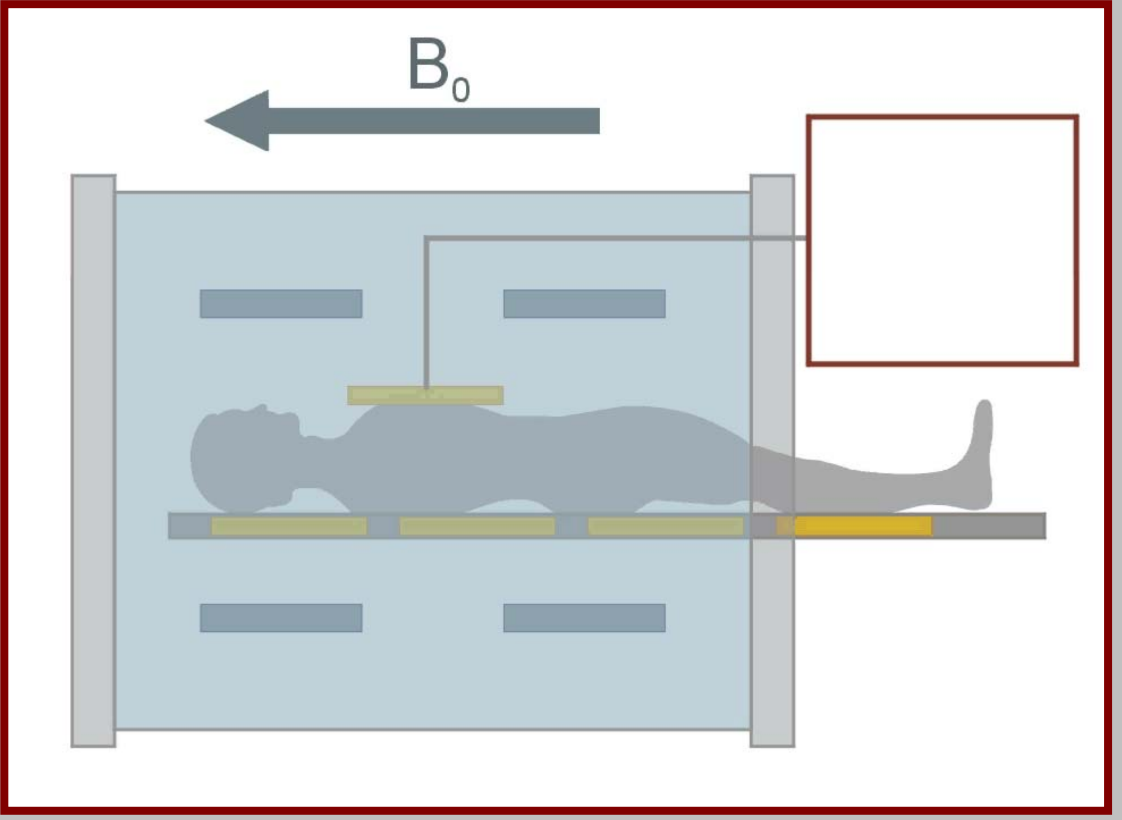
$$\omega(\mathbf{r},t) = \omega_0 + \gamma\mathbf{G}(t)\mathbf{r}$$

Phase contrast method

Introducing the notion of phase – MR in a nutshell

Signal after „simple“ HF excitation (free induction decay) not used for imaging.

➡ Echos, after HF pulses and gradient pulses



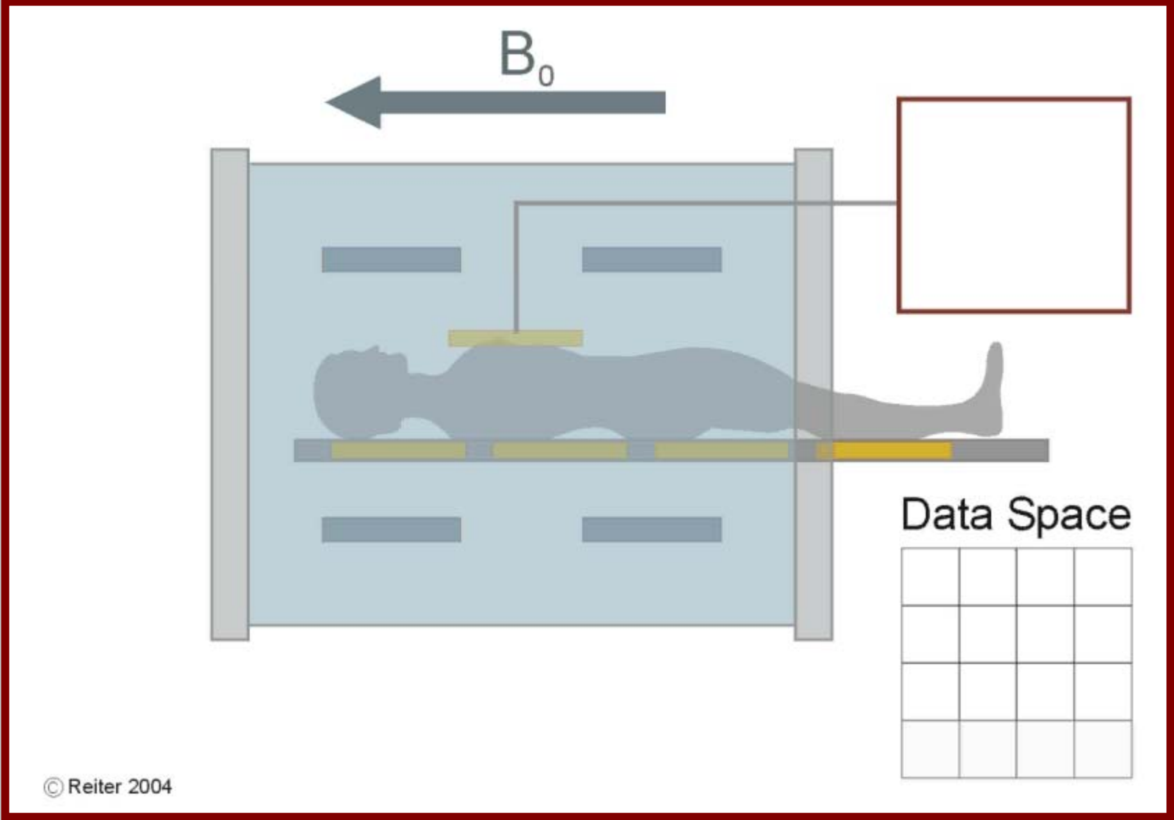
Phase contrast method

Introducing the notion of phase – MR in a nutshell

Echos with different „encoding“ ($\omega(\mathbf{r},t)$) used to fill data space.

➡ Sequence of HF and gradient pulses:

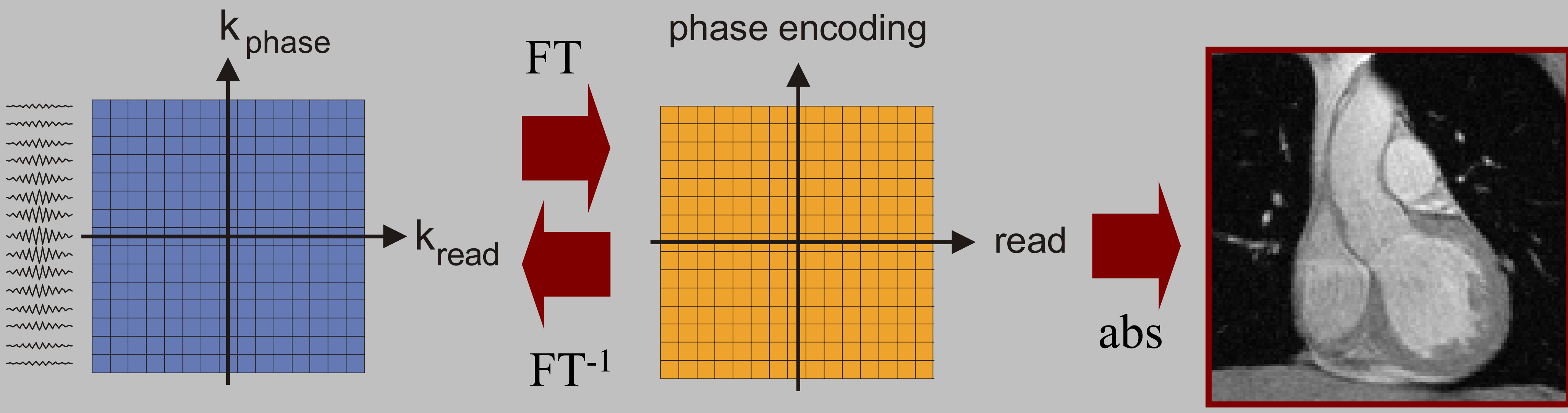
echo ≙ data line



Phase contrast method

Introducing the notion of phase – MR in a nutshell

Data space and image space connected via Fourier transform.



data space = k-space

complex image space

image

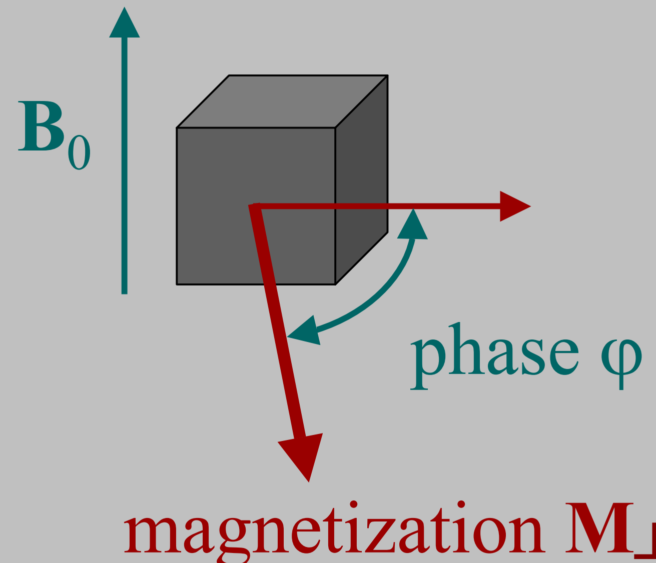
Phase contrast method

Introducing the notion of phase – MR in a nutshell

Pixels represent essentially transversal magnetization of corresponding voxels.

➡ magnitude $M_{\perp}$
(seen via abs)

➡ phase φ of $\mathbf{M}_{\perp}$,
(at echo time T_E or in a with ω_0 rotating coordinate system)

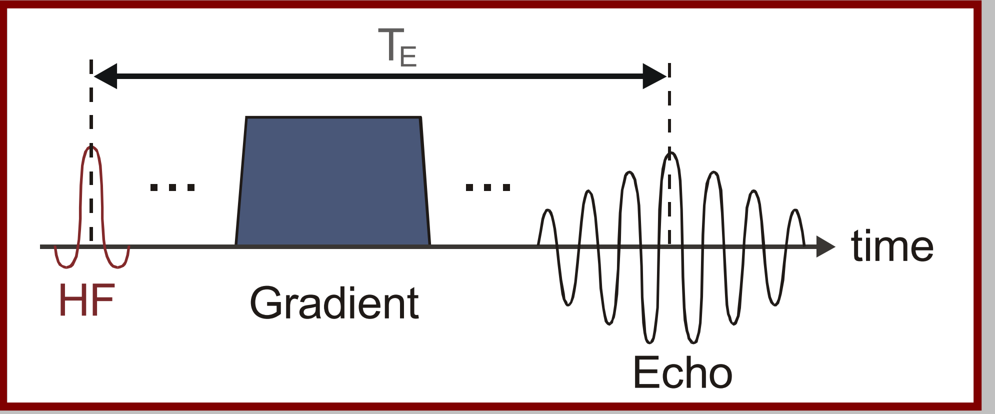


Phase contrast method

Gradients, phase and velocity

Application of a gradient changes rotational frequency by:

$$\omega_g(\mathbf{r},t) = \gamma \mathbf{G}(t)\mathbf{r}$$



Assume tissue is moving: $\mathbf{r}(t) = \mathbf{r}(0) + \mathbf{v}(0)t + O(t^2)$

➡ Additional phase:

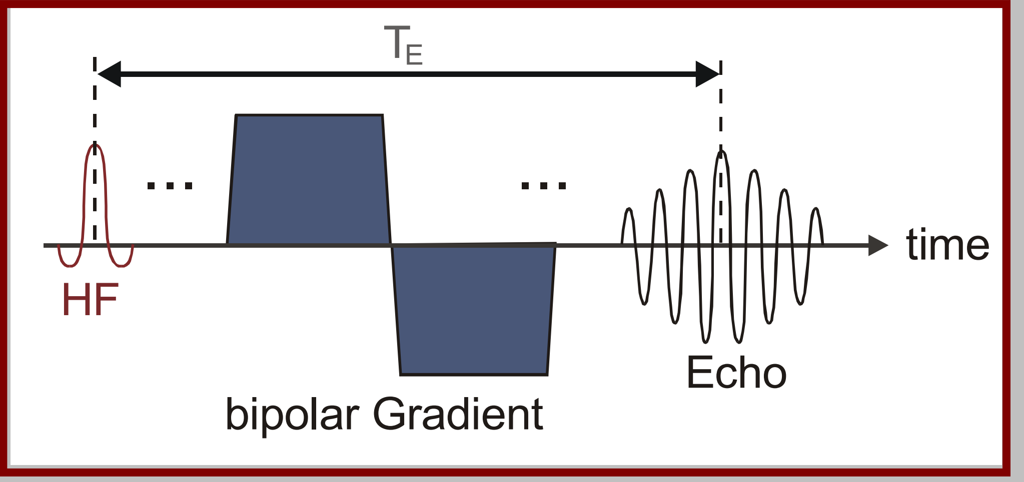
$$\varphi = \int_0^{T_E} dt\, \omega_g(\mathbf{r},t) = \gamma \mathbf{r}(0)\int_0^{T_E} dt\mathbf{G}(t) + \gamma \mathbf{v}(0)\int_0^{T_E} dt\, t\mathbf{G}(t) \underbrace{+ O(t^2)}_{\approx 0}$$

Phase contrast method

Bipolar gradients

Specifically bipolar gradient.

➡ $$\mathbf{m}_0 = \int_0^{T_E} dt\, \mathbf{G}(t) = 0$$

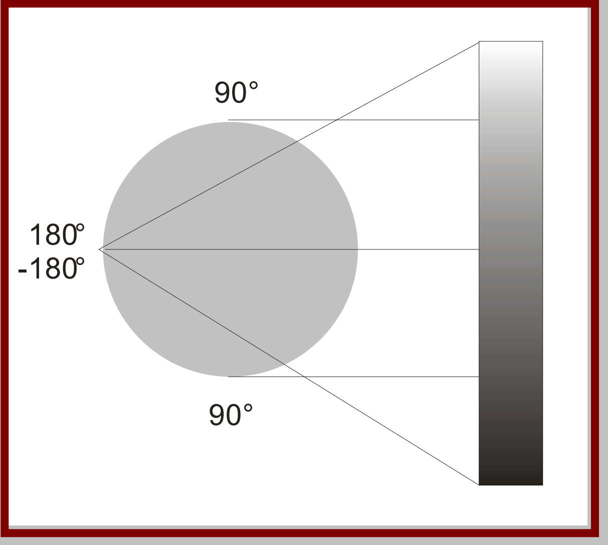


➡ Phase proportional to velocity:

$$\varphi = \gamma \mathbf{v}(0)\mathbf{m}_1 \qquad \mathbf{m}_1 = \int_0^{T_E} dt\, t\mathbf{G}(t)$$

Phase contrast method
Bipolar gradients

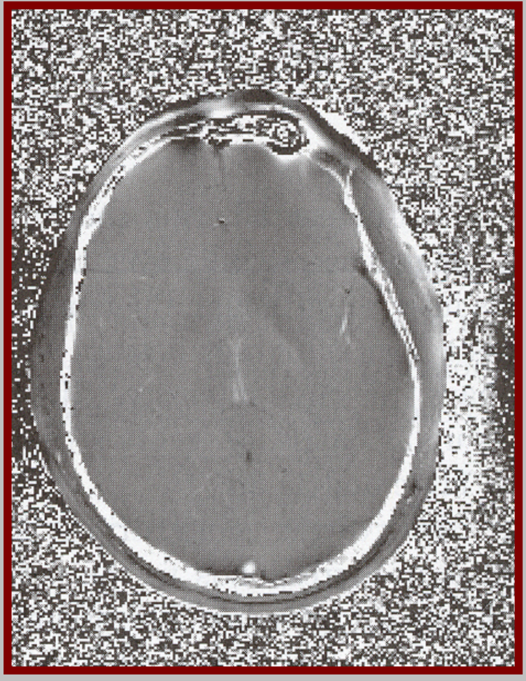
First idea: Sequence with bipolar gradient in some direction and map phase to gray scale.

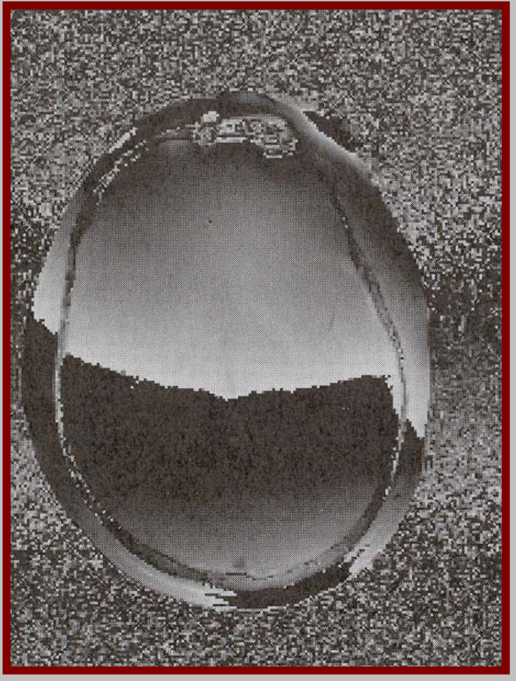


➡ Should give distribution of velocities in this direction.

Phase contrast method
Bipolar gradients

But: Many reasons for phase changes of transversal magnetization.





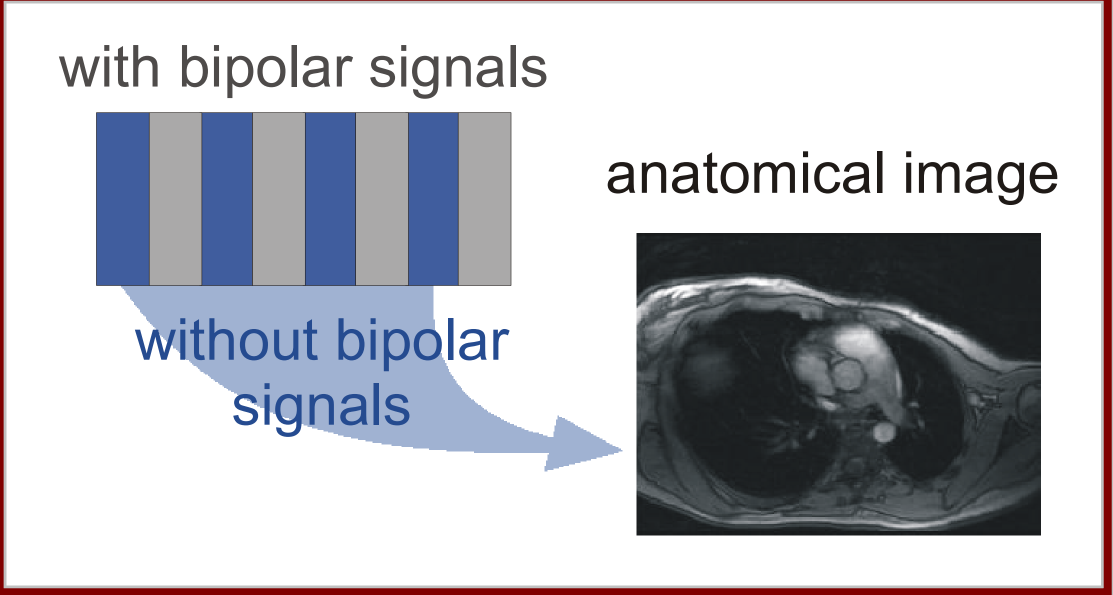
Phase images of the brain: B_0 (and consequently ω_0) is slightly changed by tissue, causing phase changes. Right image is a consequence of an additional small data acquisition error. (Taken from: Haacke EM, et al. Magnetic Resonance Imaging. Wiley, 1999.)

Phase contrast method
Subtraction

Phase contrast method: Measure echos (data lines) twice

- without bipolar gradient
- with bipolar gradient

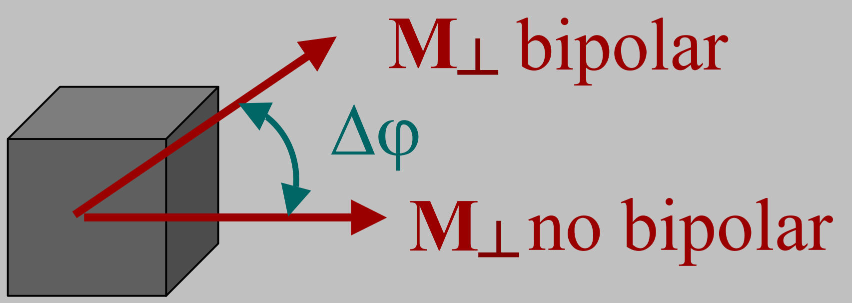
➡ Anatomical image:



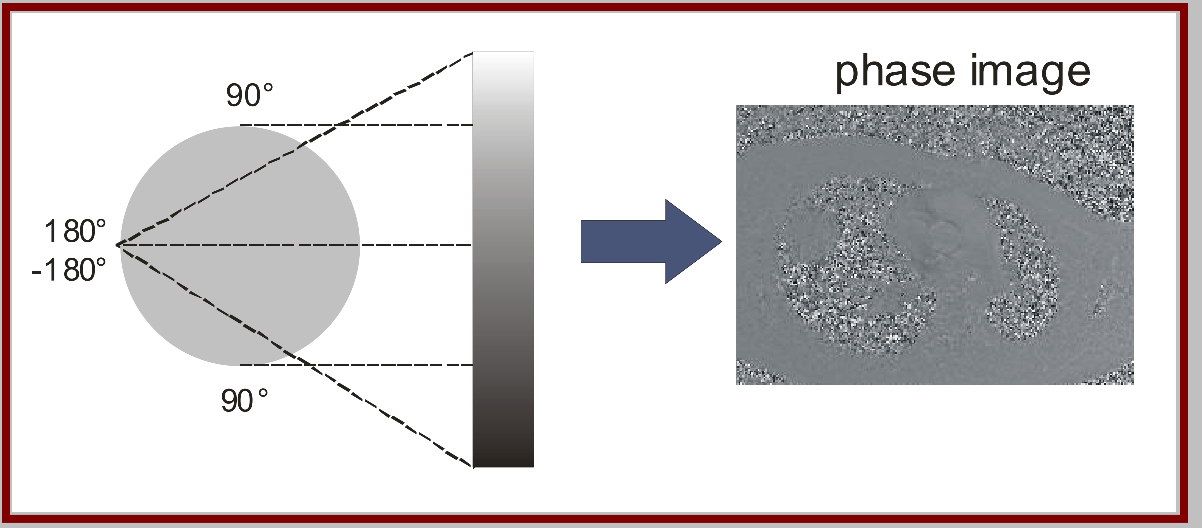
Phase contrast method

Subtraction

➡ Phase or velocity image:



$$\Delta\varphi = \gamma \mathbf{v}(0)\mathbf{m}_1$$



Phase contrast method
Velocity encoding and aliasing

Amount of phase difference caused by velocity determined by first order moments of bipolar gradients:

$$\Delta\varphi = \gamma \mathbf{v}(0)\mathbf{m}_1$$

→ m_1 small, large velocities give small phases

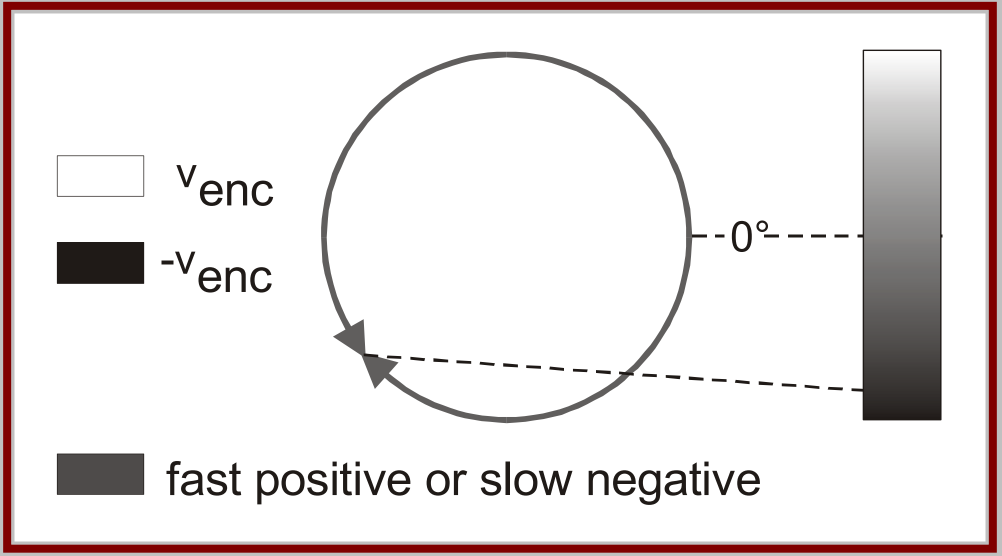
→ m_1 large, small velocities give large phases

Specify for measurement:

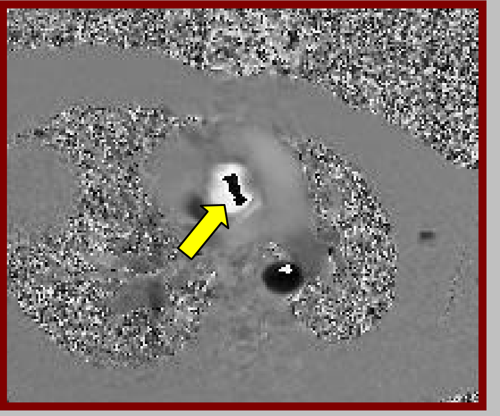
- Velocity encoding: v_{enc} = velocity for $\Delta\varphi = \pi$
- Direction of velocity encoding, typically through-plane

Phase contrast method
Velocity encoding and aliasing

Peculiarity of phase imaging: Aliasing



choice of v_{enc}



v_{enc}= 80 cm/s

v_{enc}= 100 cm/s

➡ Correction by assumptions.

Phase contrast method

Noise

Signal-to-noise ratio of phase contrast images:

$$SNR_v = \frac{\pi}{\sqrt{2}} \frac{v}{v_{enc}} SNR_{anat}$$

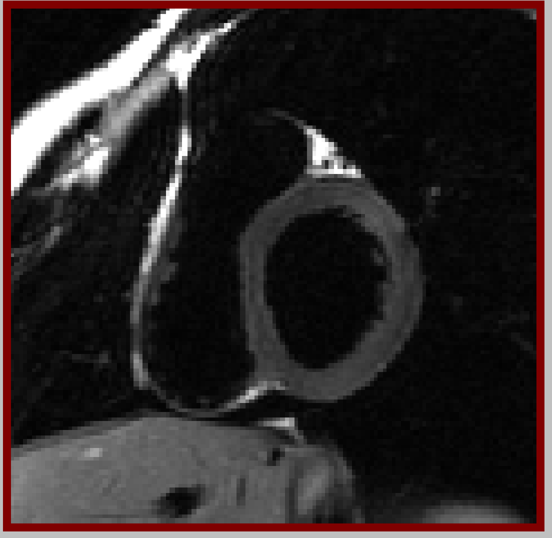
➡ Consequence 1 ($\propto 1/v_{enc}$):

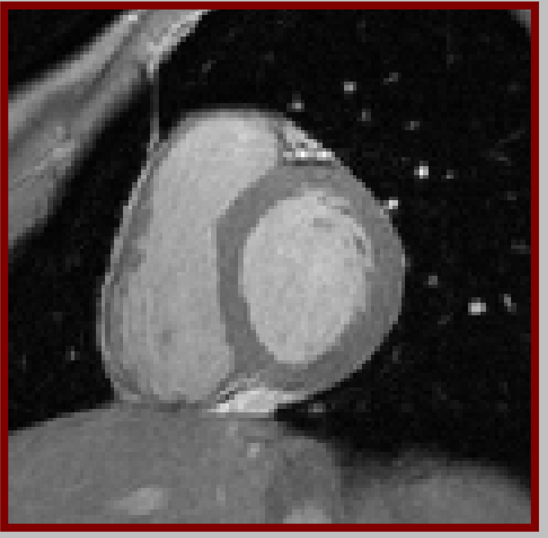
- v_{enc} as small as possible (keeping aliasing small)
- small velocities noisy

Phase contrast method
Noise

➡ Consequence 2 ($\propto SNR_{anat}$):

Spin echo sequence: Blood dark (additionally slowly)





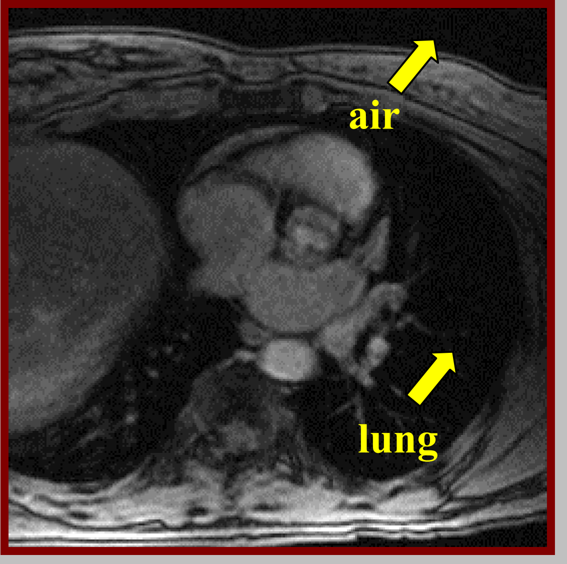
Gradient echo sequence: Blood bright (additionally fast)

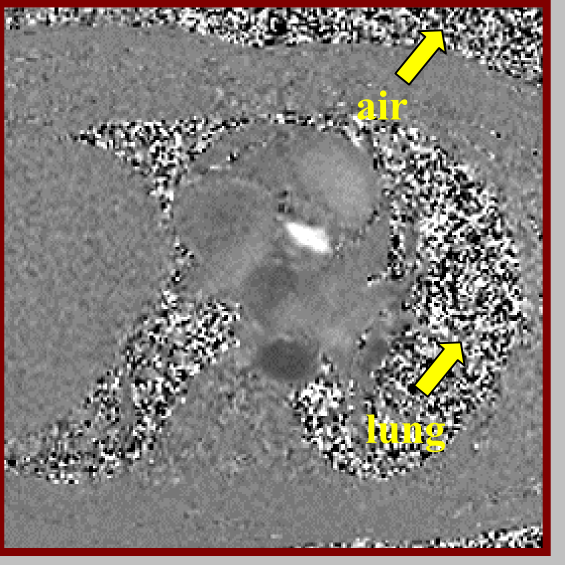
- gradient echo sequence

Phase contrast method
Noise

Additional remark: Air and lungs almost no signal in anatomical images.

➡ Phases purely accidental



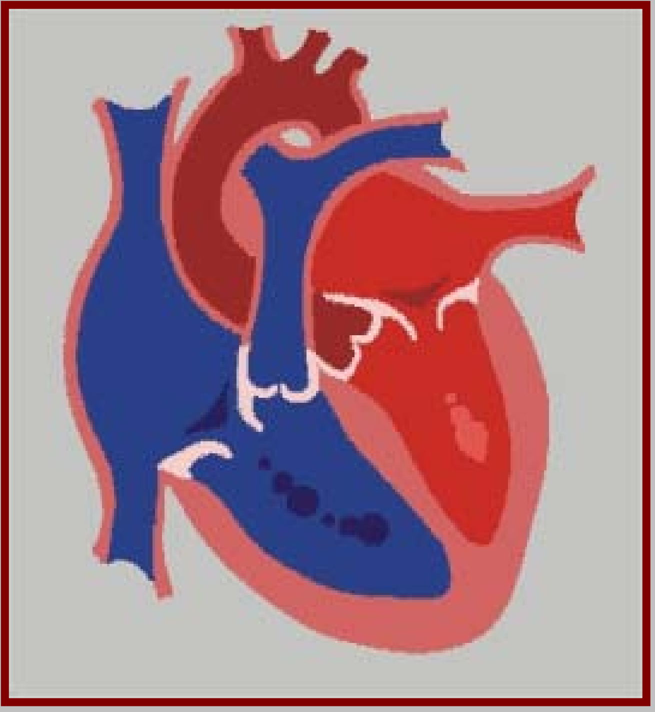


Pulsatility
ECG gating

Phase contrast technique concept as described up till now applies to stationary movement or flow.

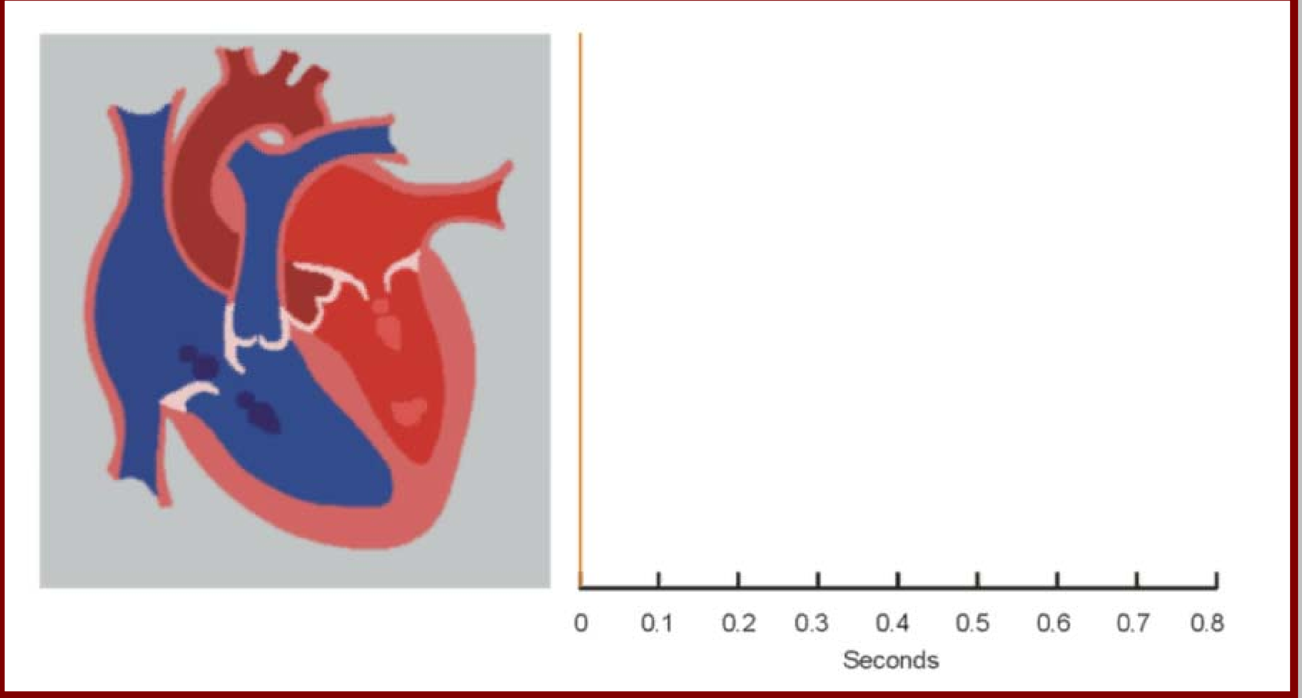
But most rapid and important movement of cardiovascular system is rapidly changing.

➡ Movement and flow (essentially) periodic.



Pulsatility
ECG gating

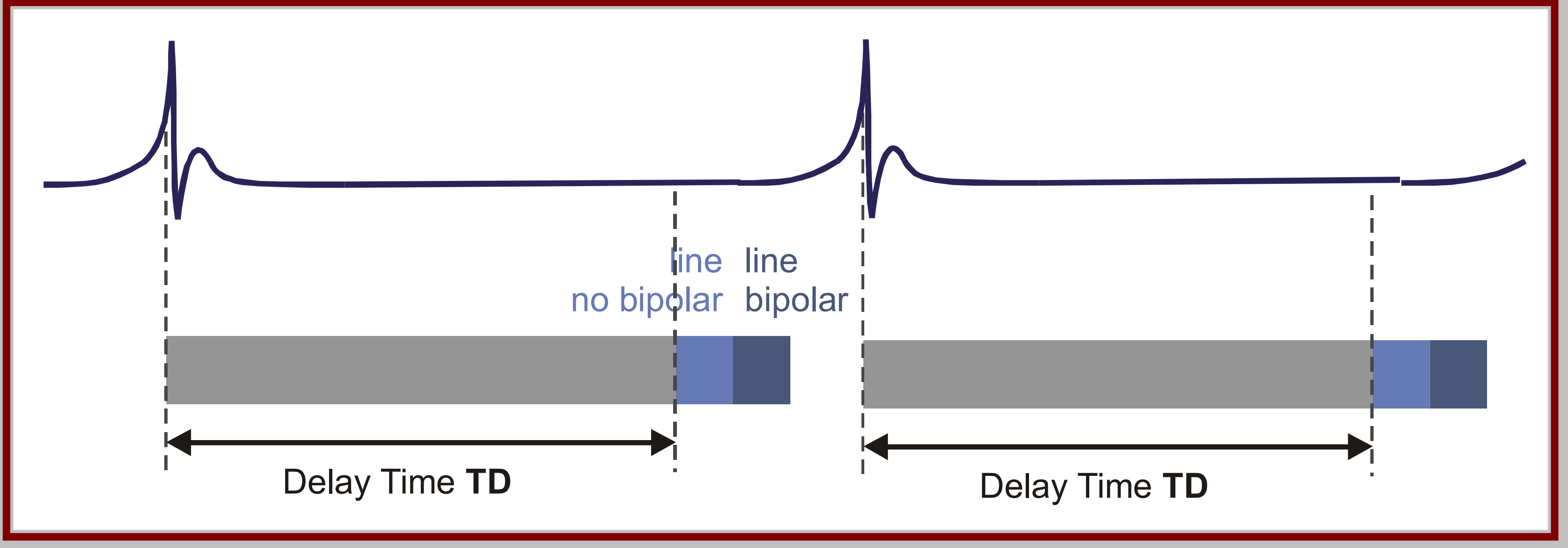
Periodic mechanical movement corresponds with periodical electrical activity (ECG).



Pulsatility
ECG gating

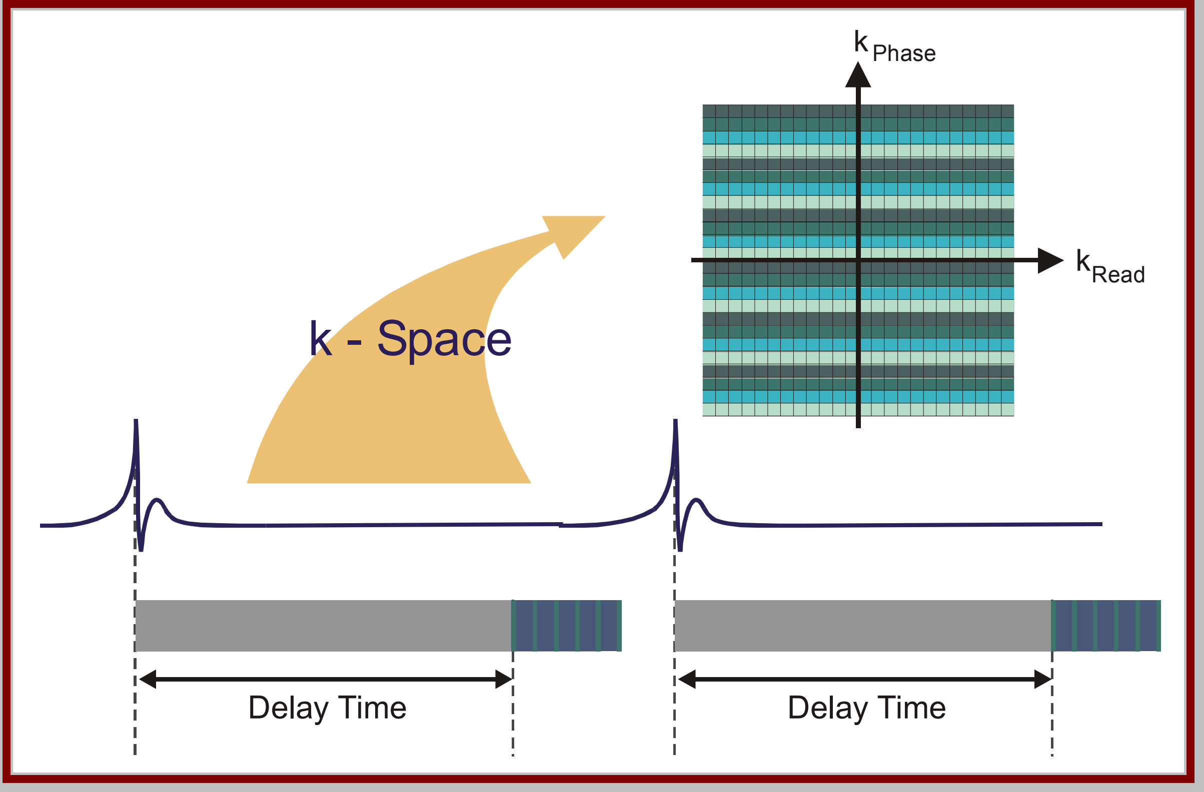
Synchronization of data acquisition and electrical activity
= ECG gating

Typical prospective. Basically:



Pulsatility
ECG gating

Segmentation to improve speed:

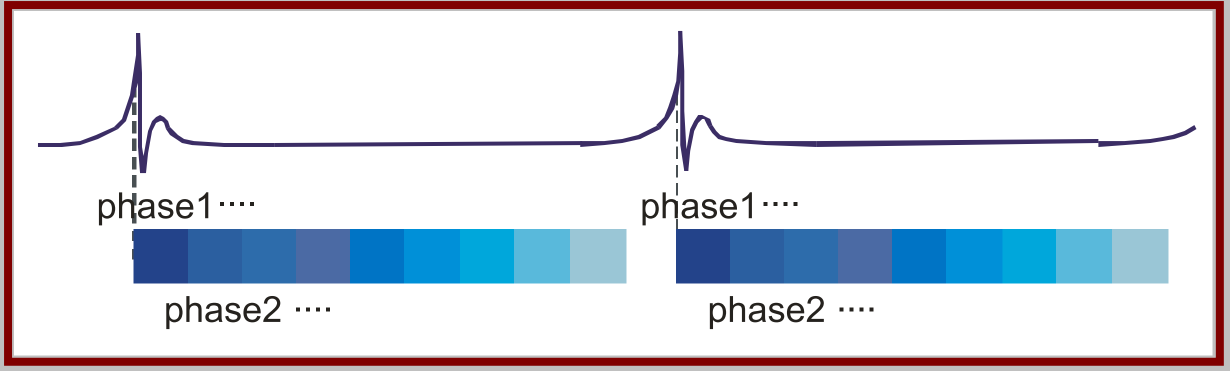


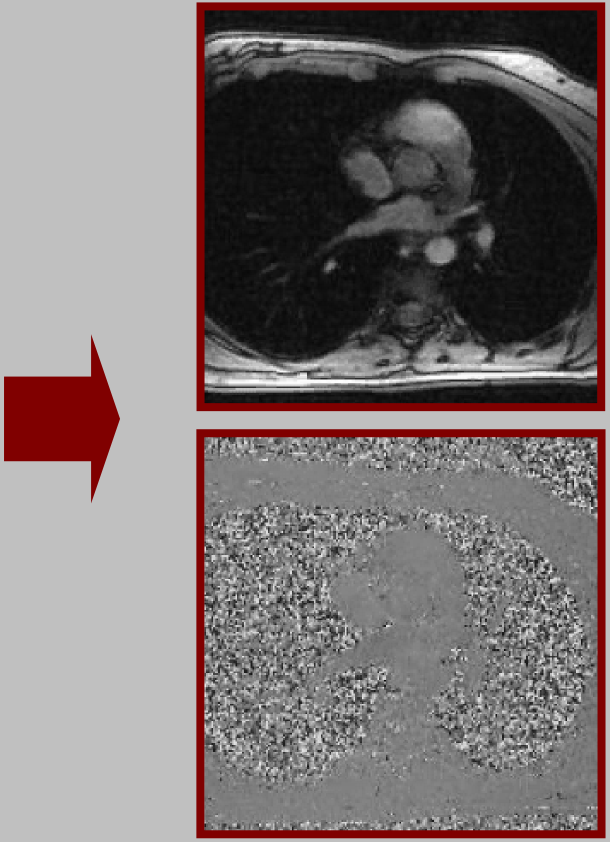
Longer time interval per heart beat, but outer data space lines do not contribute very much to „essential image information“.

Imaging time improvement here: 6 segments, consequently 4 instead of 24 heart beats.

Pulsatility
Cine Imaging

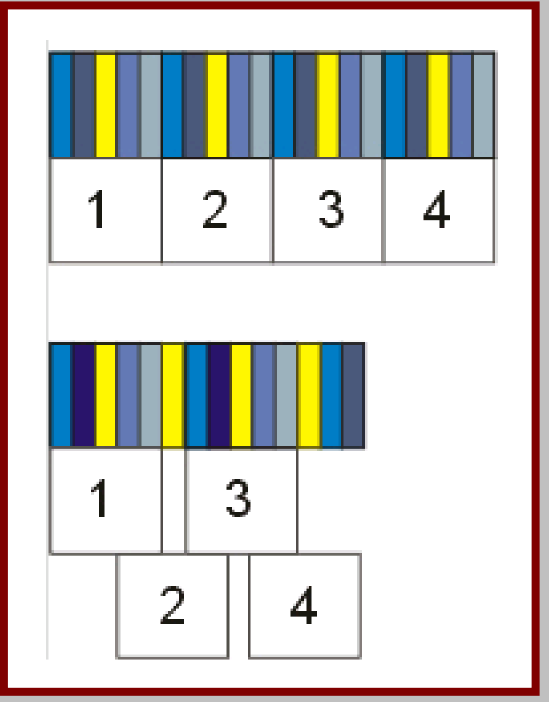
Images at different times in cardiac cycle within one sequence = cine imaging.





Pulsatility
Cine Imaging

Echo sharing to improve speed:



no echo sharing

echo sharing

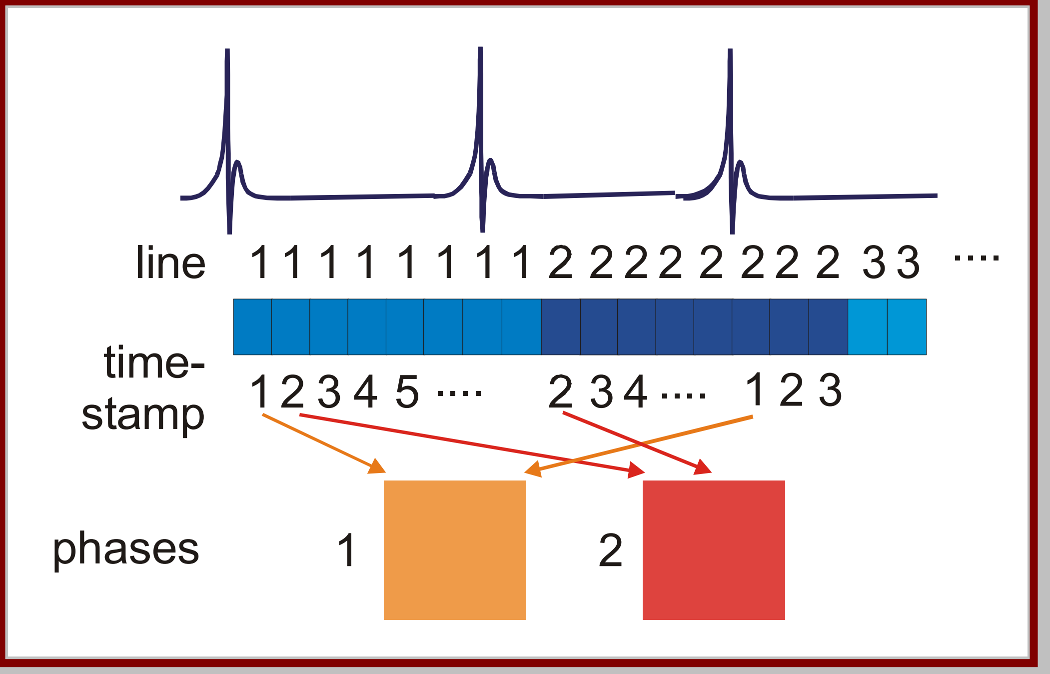
➡ with segmentation and echo sharing phase contrast measurement within one breathhold.

Pulsatility
Cine Imaging

Heart frequency is not absolutely constant.

➡ 5-15% of data at the end of RR-interval missing

Alternative retrospective ECG gating. Basically:

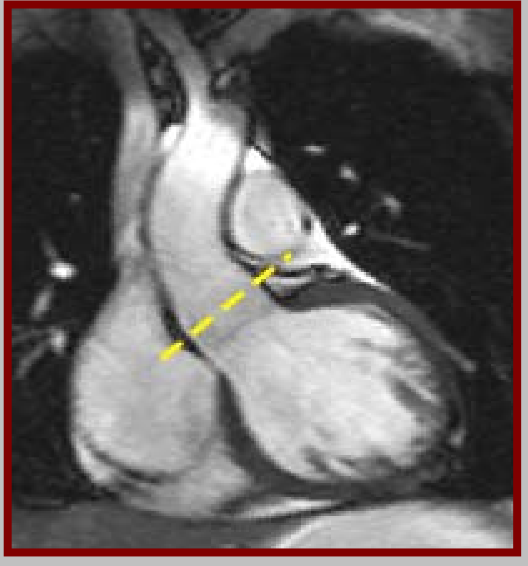


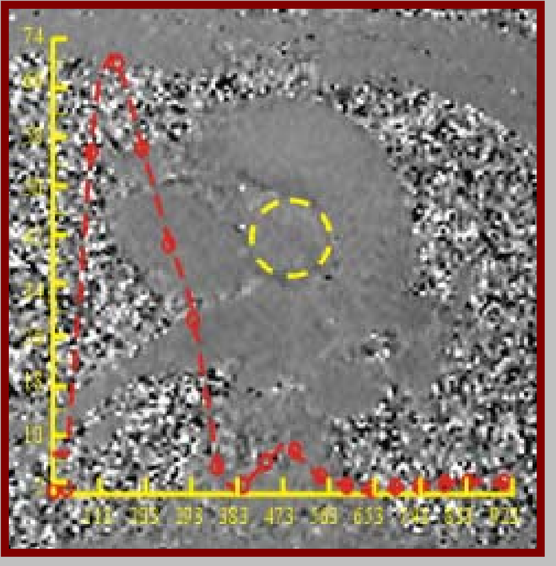
➡ Slower, but there are improvements.

Archetypical postprocessing

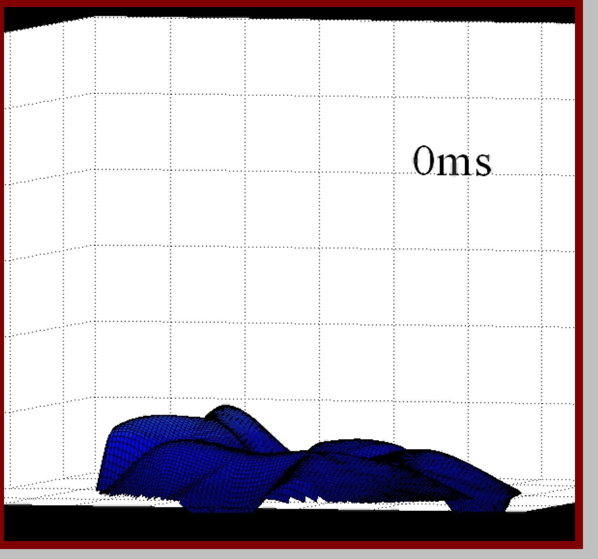
Typical application: Cine through-plane phase contrast imaging of vessel cross-section.

➡ Region-of-interest = vessel cross-section





average velocity

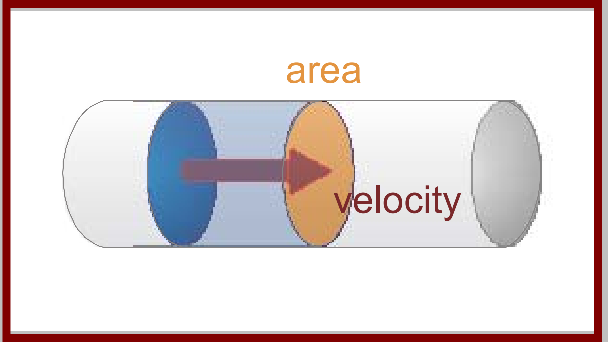


localized velocity

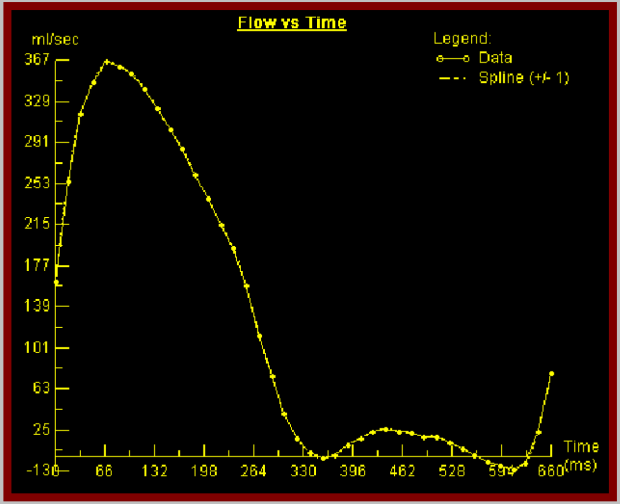
Archetypical postprocessing

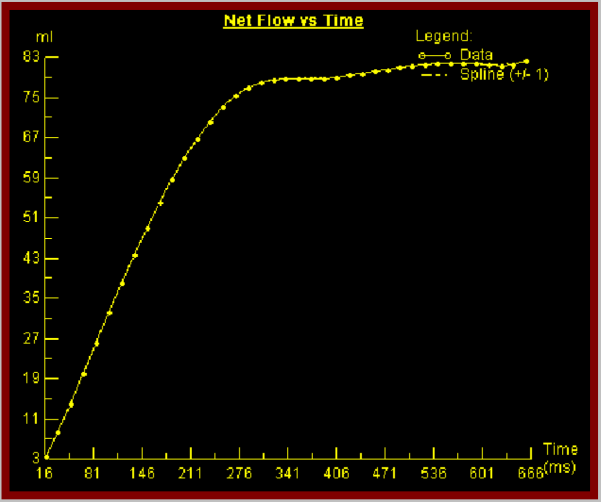
Flow: $I = A v_{avg}$

$$\left(I = \frac{\Delta V}{\Delta t} = \frac{A \Delta s}{\Delta t} = A v_{avg} \right)$$



time resolved flow

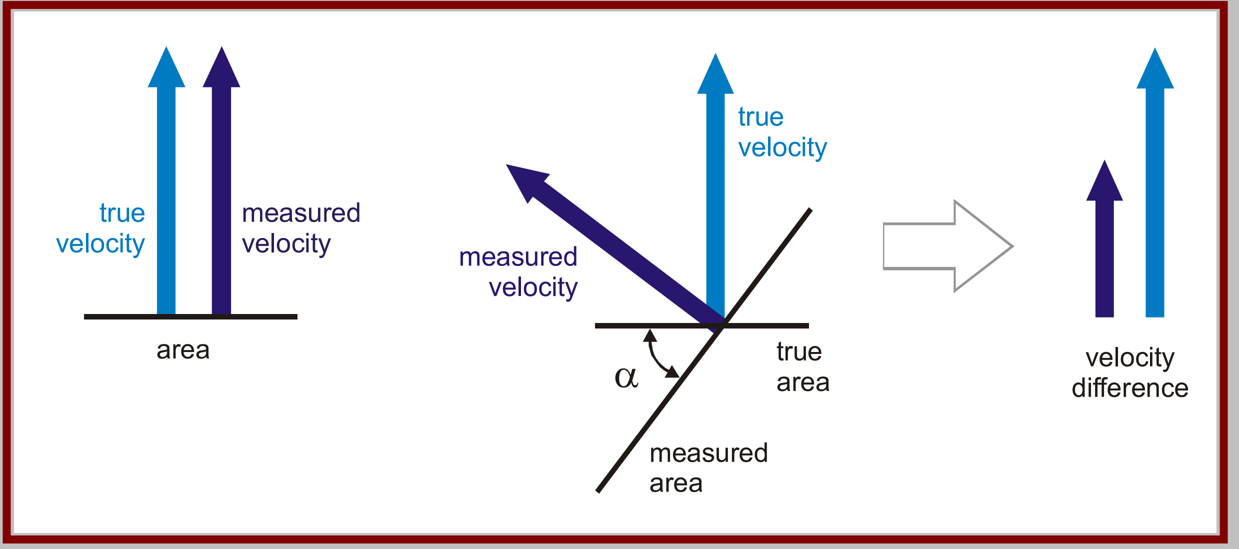




time integrated flow = volume passing per cardiac cycle

Archetypical postprocessing

Remark: Correct placement of imaging plane different role for different quantities.

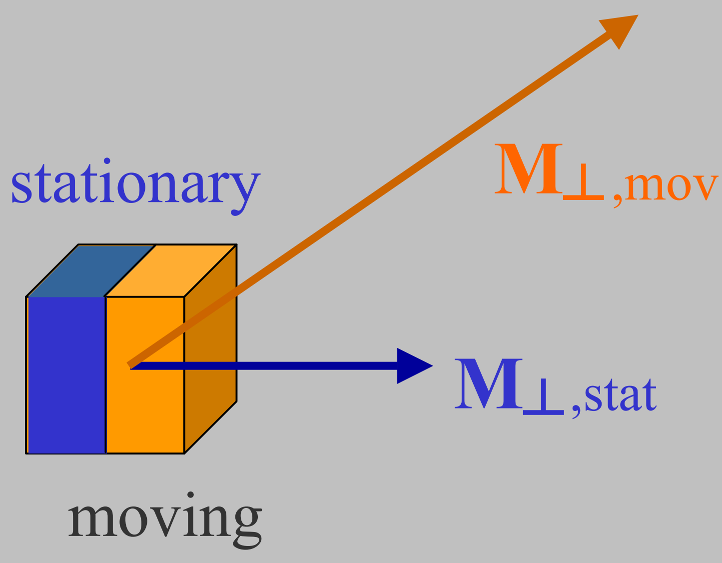


➡ Velocity: $v_{meas} = v_{true} \cos\alpha$

Flow: $I_{meas} = I_{true}$ $\left(A_{meas} = \frac{1}{\cos\alpha} A_{true}\right)$

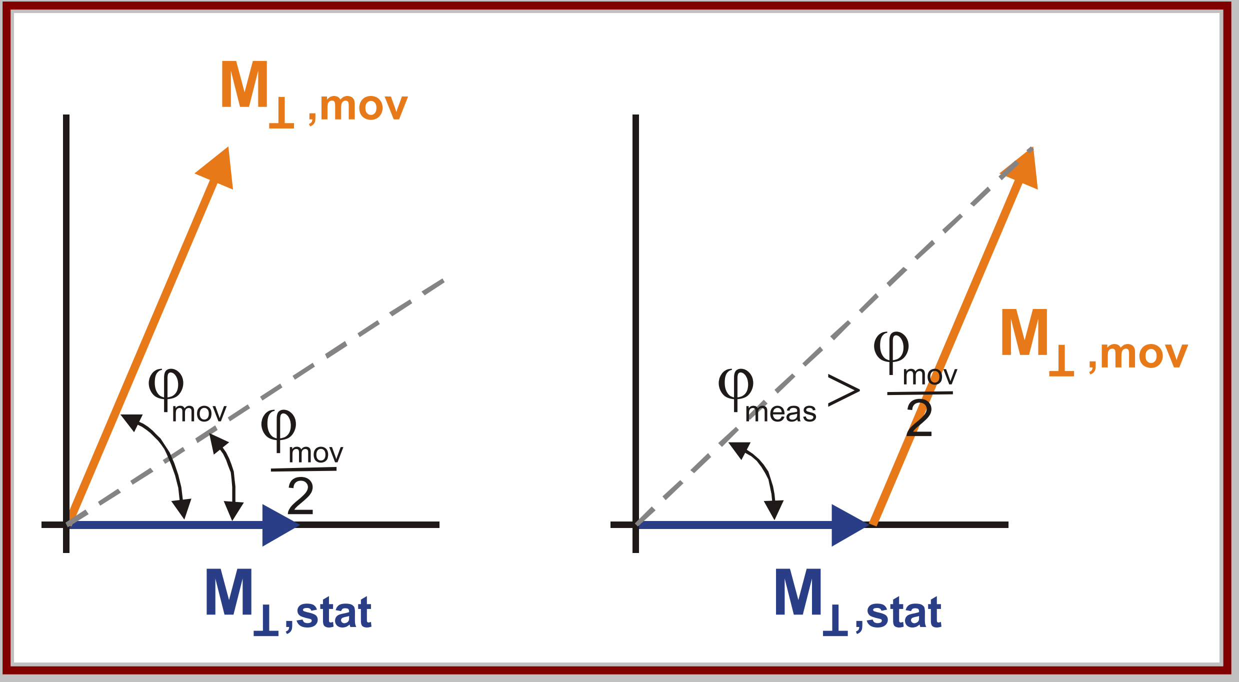
Advanced Considerations
Partial volume effect

Partial volume effects not linear in phase measurements.



Tissue moving into plane has higher signal than stationary tissue.

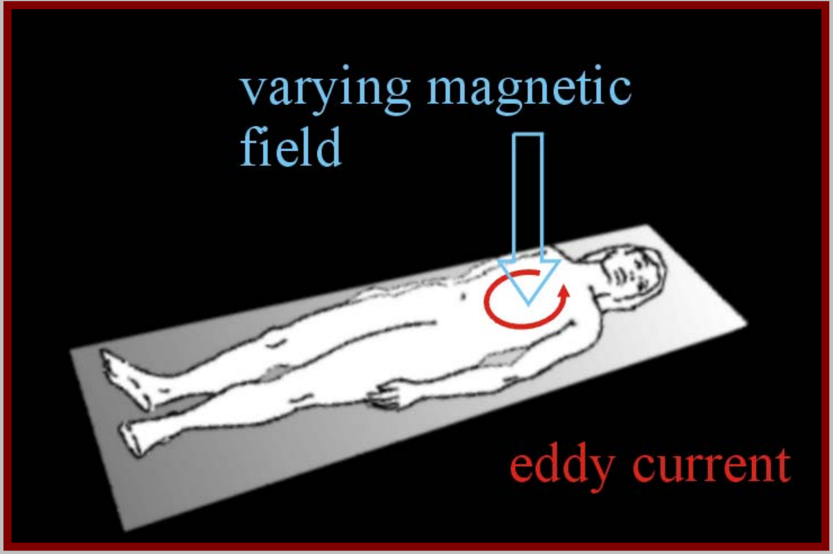
Advanced Considerations
Partial volume effect



➡ Partial volume effect will typically lead to overestimation of flow.

Advanced Considerations
Eddy currents

Subtraction scheme introduced to supress phase changes not caused by velocity. Bipolar gradients applied only for one data acquisition.



➡ influences phase(difference)

➡ Base line correction = subtraction of “velocity” of stationary objects

Advanced Considerations
Maxwell correction

Gradient field must obey Maxwell equations.

$0 = \mathrm{div}\, B_g(\mathbf{r},t)\mathbf{e}_z = \mathrm{div}(\mathbf{G}(t)\mathbf{r})\mathbf{e}_z$ ➡ $G_z = 0$

$0 = \mathrm{rot}\, B_g(\mathbf{r},t)\mathbf{e}_z = \mathrm{rot}(\mathbf{G}(t)\mathbf{r})\mathbf{e}_z$ ➡ $G_x = G_y = 0$

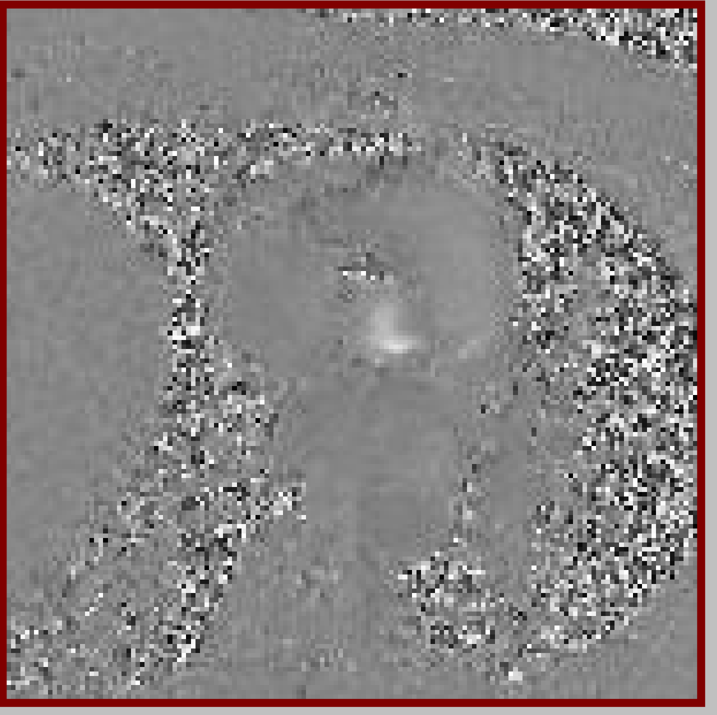
➡ Linear gradient field does not exist.

➡ Effect of lowest order $O(\mathbf{r}^2)$ on phase differences, with **r** distance to magnetic isocenter.

➡ Measurement close to isocenter or correction in image reconstruction.

Application examples

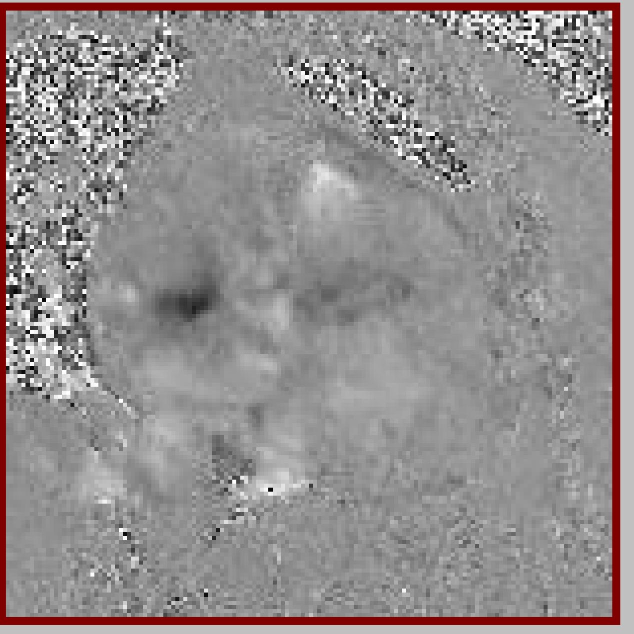
Application: Estimation of the degree of stenoses



v_{enc} = 280 cm/s,
blood velocity up to 285 cm/s.

Application examples

Application: Verification of shunts

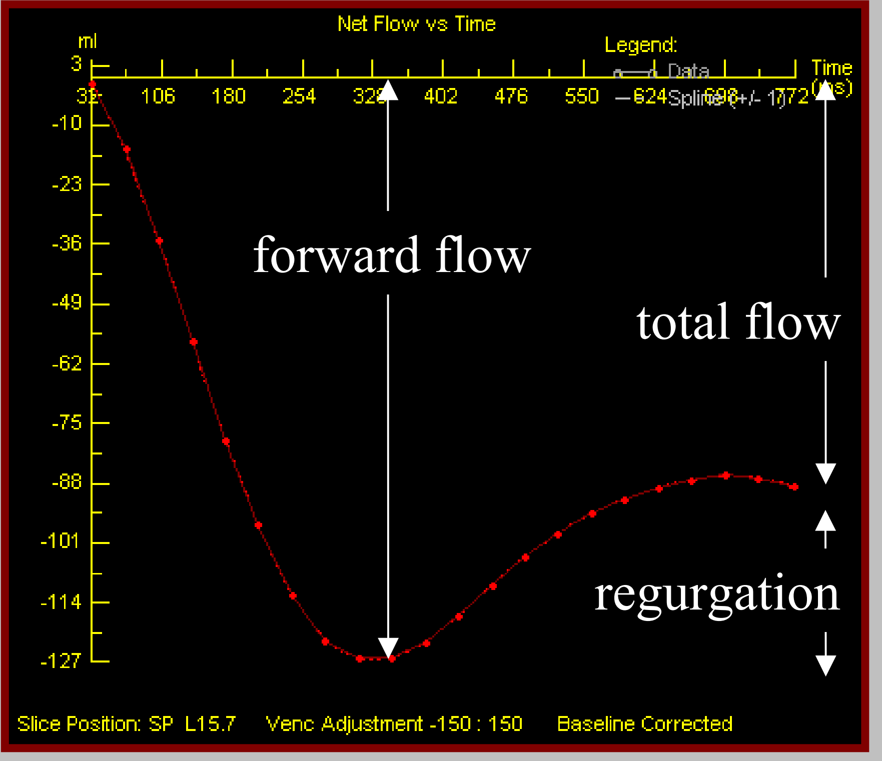


$v_{enc} = 100$ cm/s,
blood velocity up to 105 cm/s.

Shunt volume = SV pulmonalis – SV aorta

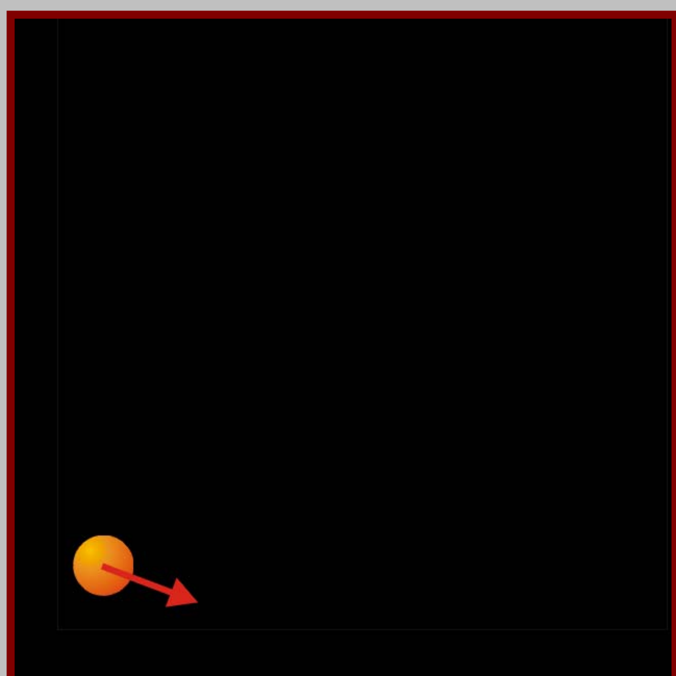
Application examples

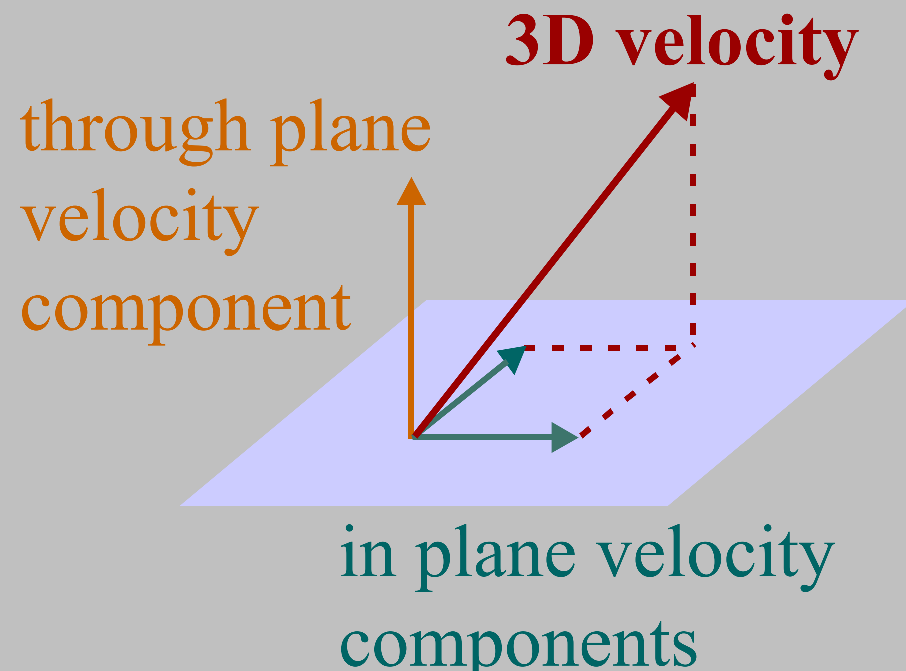
Application: Determination of regurgitation volume, e.g. for in patients after tetralogy of Fallot repair.



Perspectives

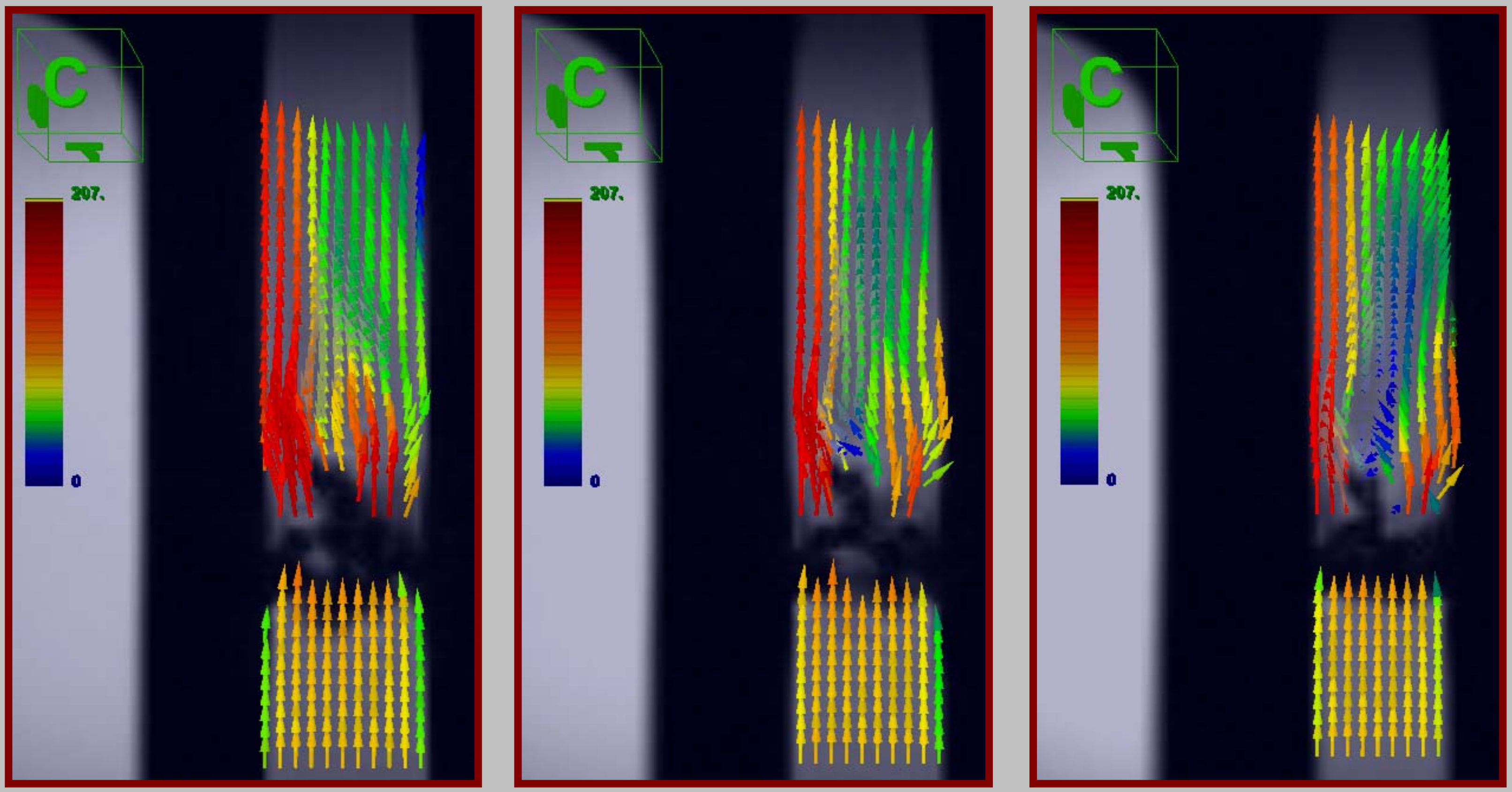
- Sequences (SNR, speed, parallel acquisition, navigator, ...)
- Segmentation ((semi)automatic contour detection)
- 3D or 4D velocity field





Perspectives

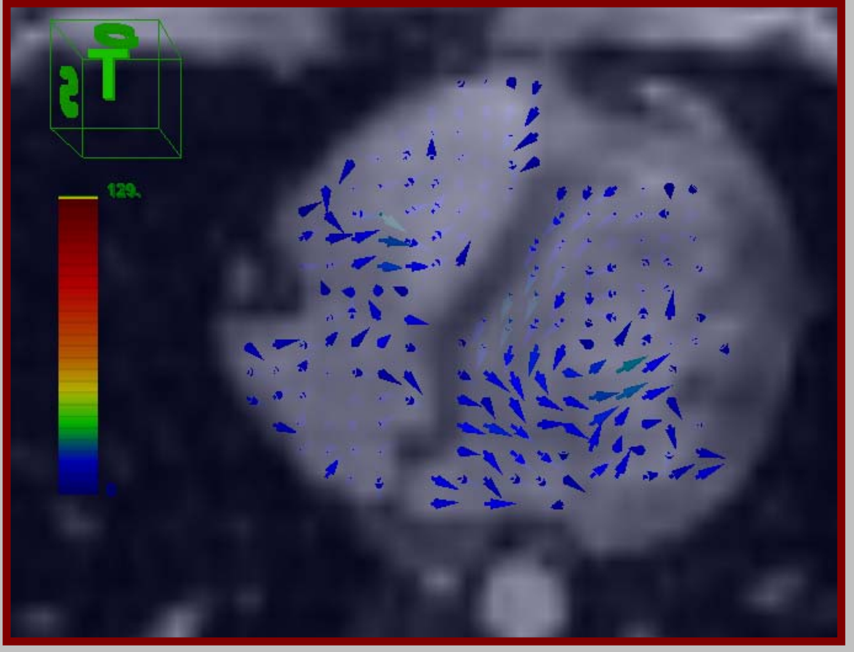
➡ Flow patterns in models.



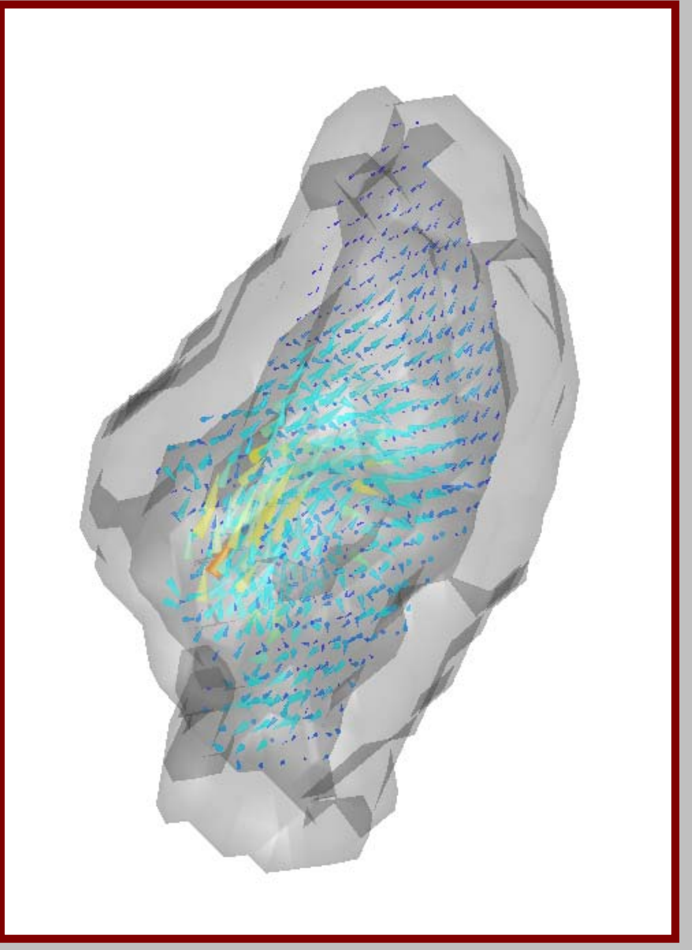
Stationary water flow through tube with mechanical valve.

Perspectives

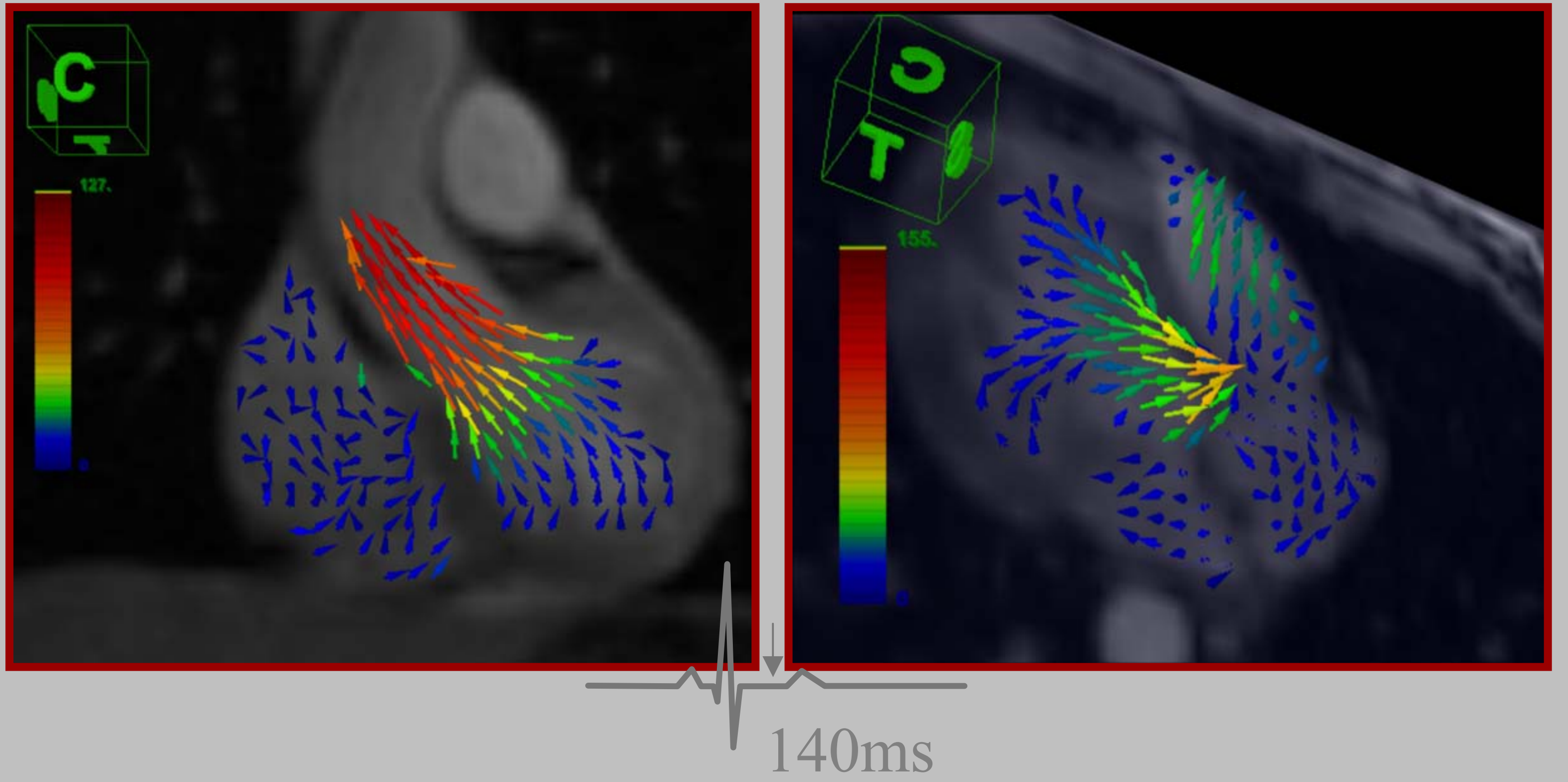
➡ Mechanical properties of cardiovascular system.



Normal blood flow in the heart.

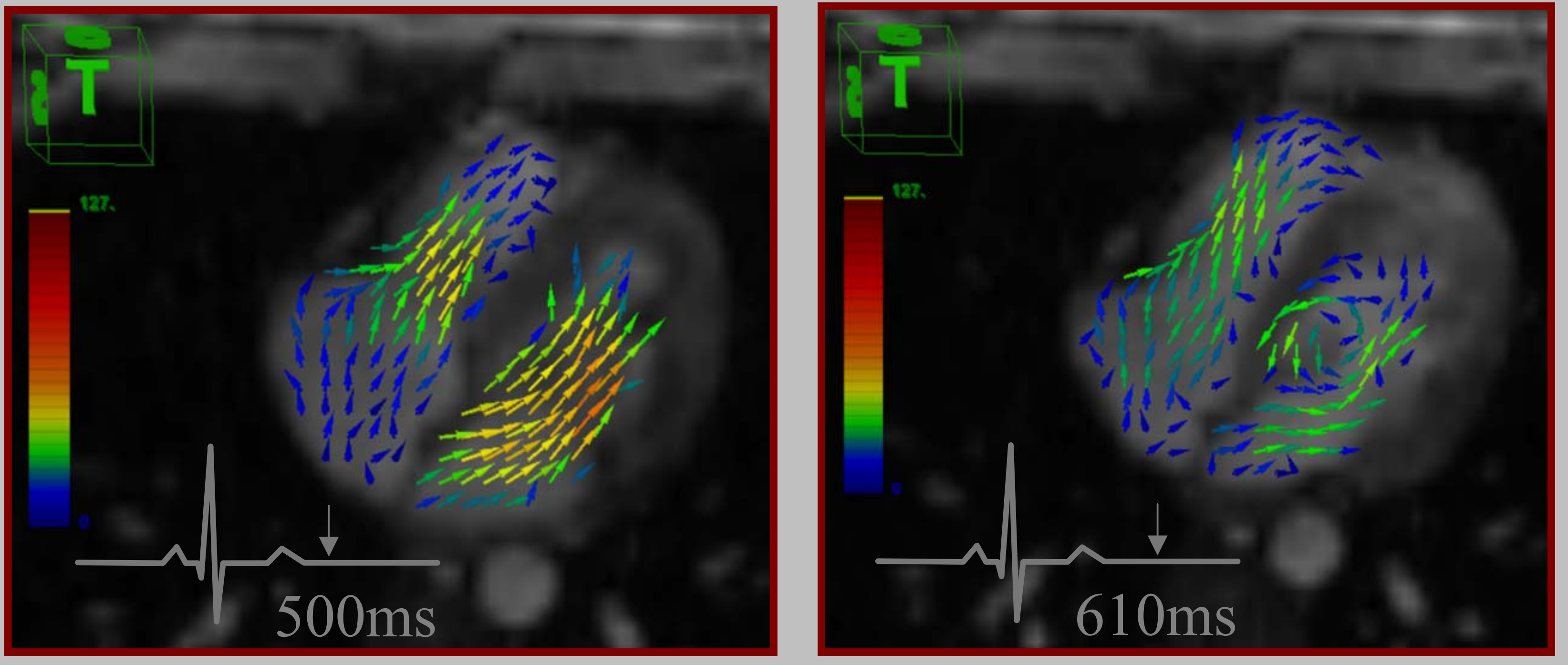


Perspectives



Normal left ventricular blood flow patterns in the systole – flow uniformly directed towards aorta.

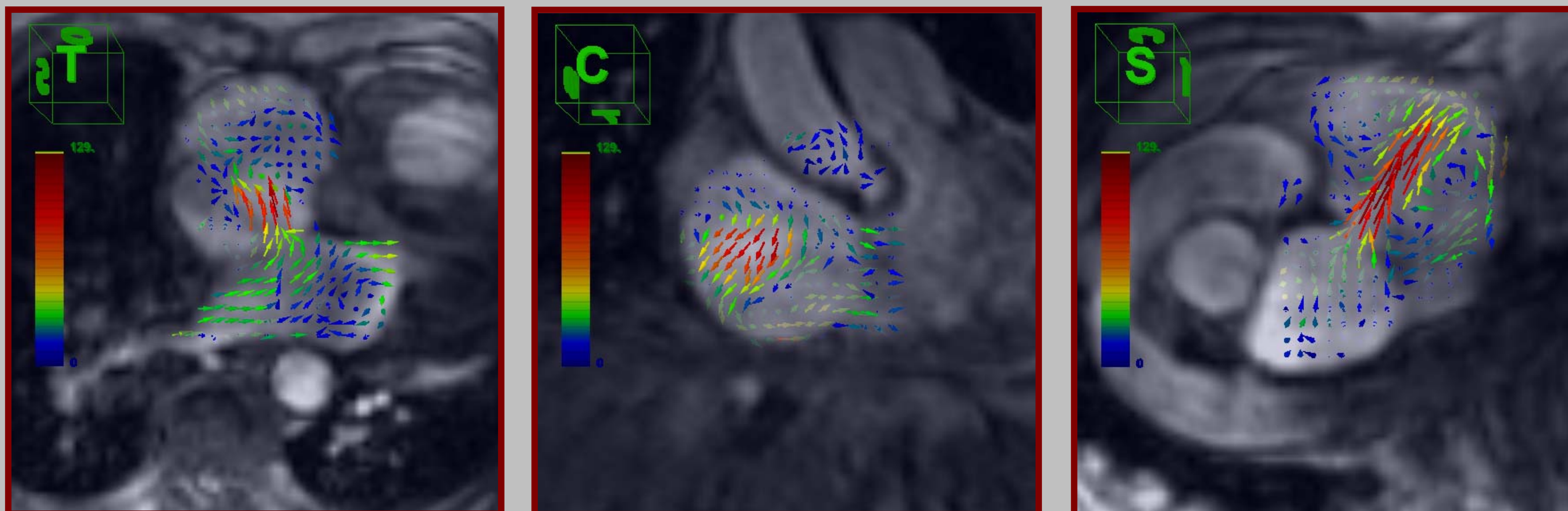
Perspectives



Normal left ventricular blood flow patterns in the diastole – first rather uniformly across whole orifice directed apically, then vortex formation.

Perspectives

➡ Detection and analysis of pathologies of cardiovascular system.



Blood flow through a shunt.