Velocity-Encoded Magnetic Resonance Imaging: Acquisition, Reconstruction and Applications

Joao L. A. Carvalho

Department of Electrical Engineering, University of Southern California

Outline

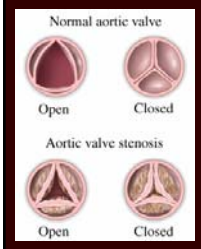
- Introduction
  - Cardiovascular disease
  - MR flow imaging
- Contributions
  - Spiral FVE
  - Accelerated spiral FVE
  - Intravascular shear rate
- Conclusions

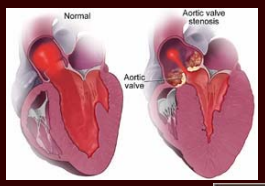
Cardiovascular disease

American Heart Association Statistics 2005 Update

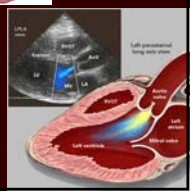
- Leading cause of death in the U.S.
  - 870k deaths in 2004 (36%)
  - 81M people with cardiovascular disease
- Forms:
  - High blood pressure: 73M
  - Coronary disease: 16M
  - Stroke: 6M
  - Heart failure: 5M
- Abnormal blood flow

Valvular disease



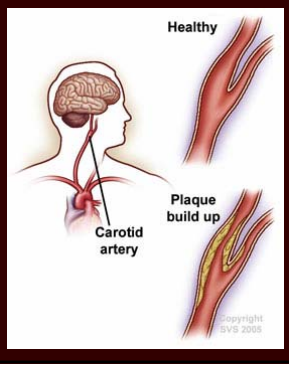


Aortic Stenosis



Aortic Regurgitation

Carotid atherosclerosis



Doppler ultrasound

- Non-invasive gold standard

Normal

Patient

Why MRI?

- Doppler ultrasound
  - Requires acoustic window
    - Fat, air, bone, surgical scar
  - Must align beam with flow axis
    - Angle correction
  - 18-40% velocity overestimation [Wrinkler, 1995; Hoskins, 1996]
- MRI
  - Potential “one-stop shop”
  - Any angle/direction
  - Less operator-dependent

MRI signal equation

$$s(k_x) = \int m(x)\, e^{-i\,2\pi\, k_x\, x}\, dx$$

MR signal = Fourier transform of spatial distribution

$$k_x(t) = \frac{\gamma}{2\pi} \int_0^t G_x(\tau)\, d\tau$$

Gradients “move” along Fourier dimension

MRI signal equation

$$x'(t) = x + v\,t$$ ← moving spins

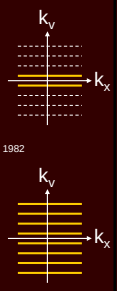
$$s(k_x, k_v) = \int\int m(x, v)\, e^{-i\,2\pi\,(k_x\, x + k_v\, v)}\, dx\, dv$$

$$k_x(t) = \frac{\gamma}{2\pi} \int_0^t G_x(\tau)\, d\tau$$ spatial distribution

$$k_v(t) = \frac{\gamma}{2\pi} \int_0^t G_x(\tau)\, \tau\, d\tau$$ velocity distribution

MR flow quantitation

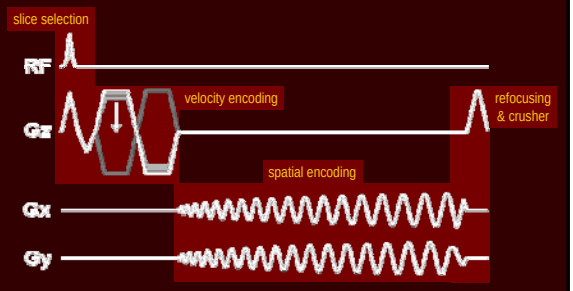
- Phase contrast [O'Donnell, 1985]
  - Fast
  - One velocity estimate for each voxel
  - May underestimate flow jets
- Fourier velocity encoding (FVE) [Moran, 1982]
  - Slow
  - Velocity distribution in each voxel
  - More appropriate for flow jets

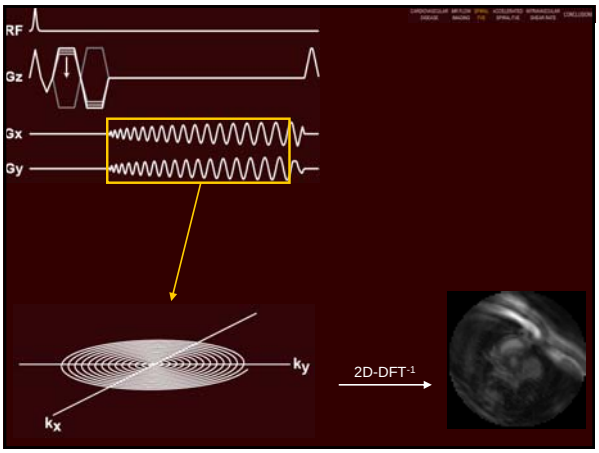


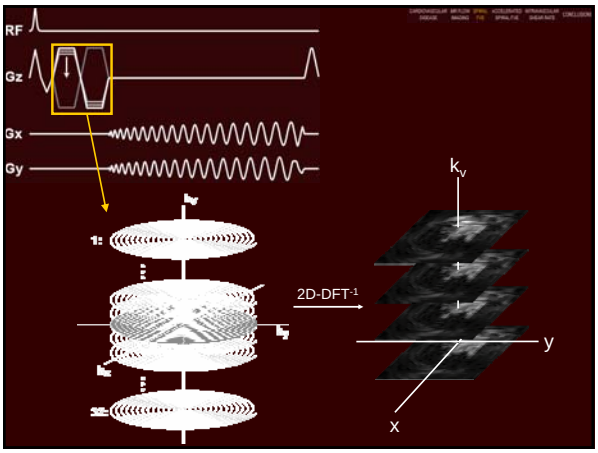
Spiral FVE: motivation

- Existing FVE methods:
  - Slow [Moran, 1982]
  - Poor spatial localization of flow [Feinberg, 1985; Hu, 1993]
- Applications:
  - Peak velocity in flow jets
  - Flow in small vessels
  - Intravascular shear rate

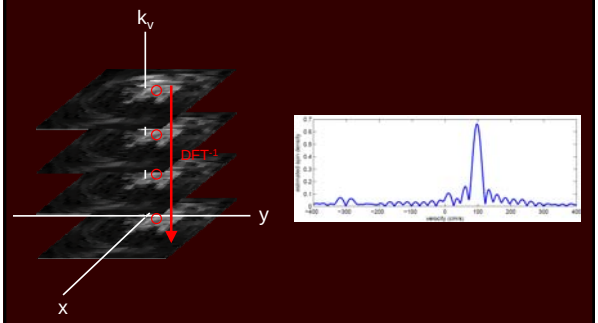
Spiral FVE: pulse sequence



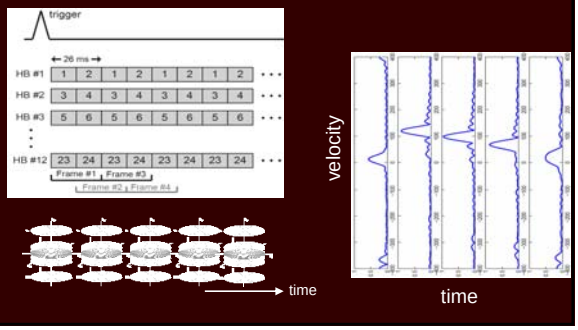




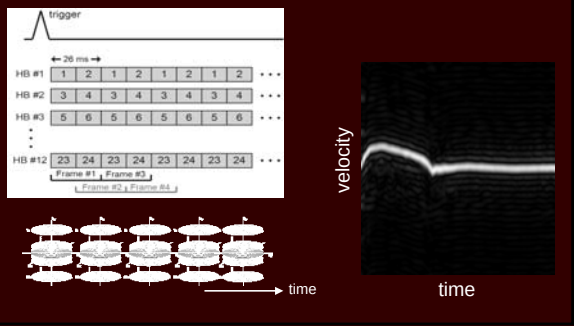
Spiral FVE: reconstruction



Time-velocity distribution



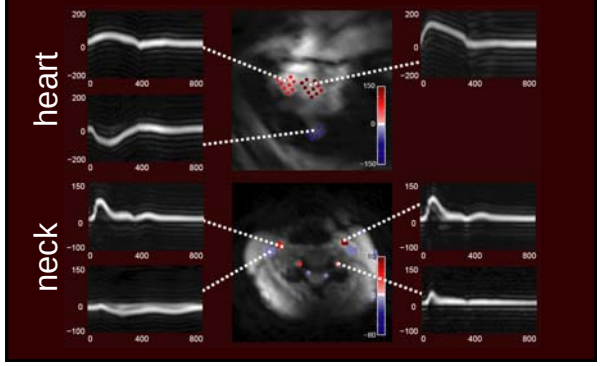
Time-velocity distribution



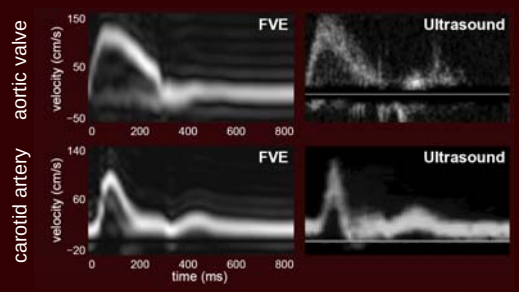
Experimental methods

- Pulse sequence implemented in EPIC
- Scan parameters
  - Heart: 7 mm, 25 ms, 33/±400 cm/s, 12 hb
  - Neck: 2.5 mm, 26 ms, 17/±200 cm/s, 48 hb
- Experiments in 3T scanner at UNH
  - 7 healthy volunteers
  - 2 patients (aortic stenosis)
- Data reconstructed in Matlab
- Validation against Doppler ultrasound

Regions of interest

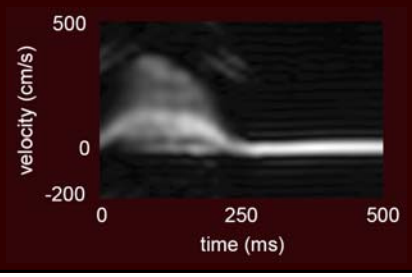


Spiral FVE vs. Doppler ultrasound



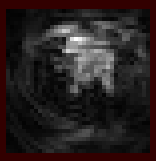
Spiral FVE: patient results

- Aortic stenosis
- 4 m/s flow jet

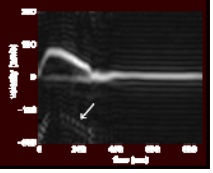


Spiral FVE: limitations

- Low spatial resolution
- Blurring due to off-resonance



- Insufficient velocity FOV
- Moderate temporal resolution



Accelerated spiral FVE

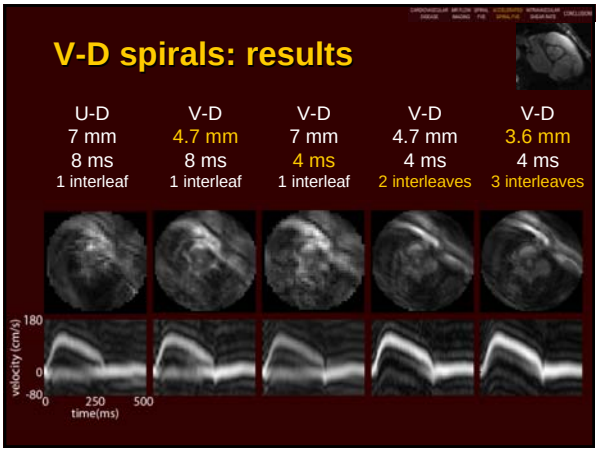
- Techniques:
  - Variable-density spirals
  - Temporal acceleration
  - Partial Fourier reconstruction
- Exploit sparseness, symmetries, and other *a priori* information

Variable-density spirals

Tsai, 2000

- Shorter readouts
  - Reduced off-resonance artifacts
  - Higher temporal resolution
- Higher spatial resolution
  - Better spatial localization of flow

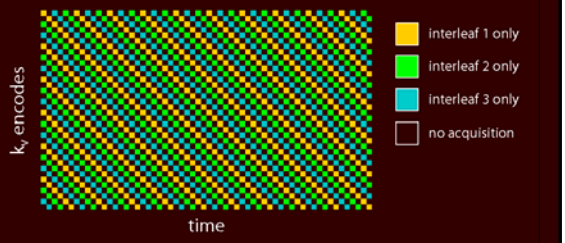
V-D spirals: results



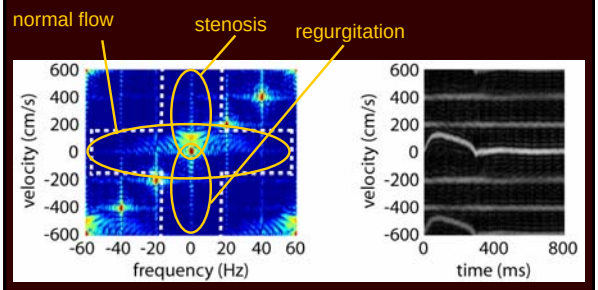
Temporal acceleration

Madore, 1999; Tsao, 2002

- *k-t* space

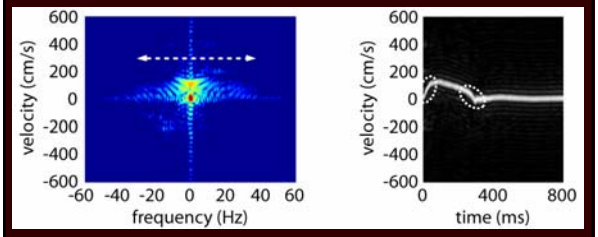


Temporal acceleration: results



assumption: flow jets are temporally smooth

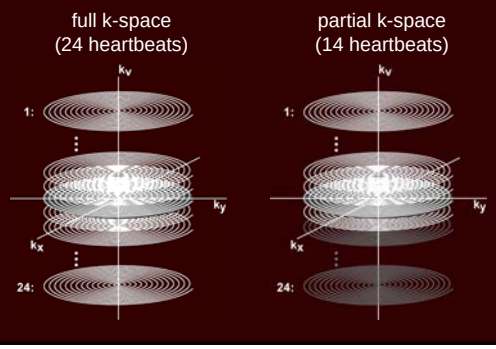
Temporal acceleration: results



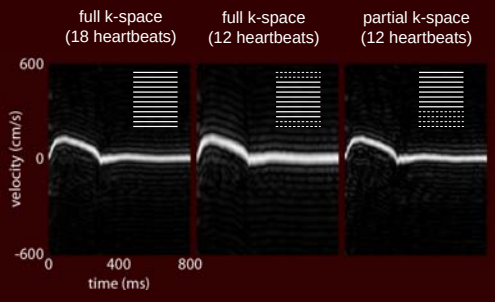
6-fold acceleration

Partial Fourier along k_v

Noll, 1991

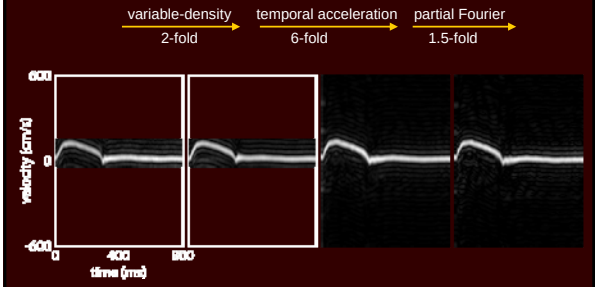


Partial Fourier: results



1.5-fold acceleration

Combined results



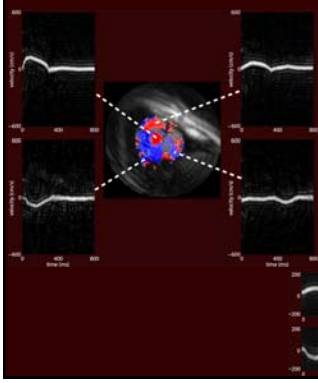
non-accelerated
36 heartbeats
(216 heartbeats)

2-fold accelerated
18 heartbeats
(108 heartbeats)

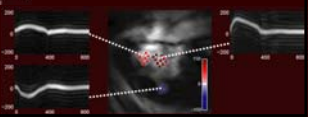
12-fold accelerated
18 heartbeats

18-fold accelerated
12 heartbeats

Before and After



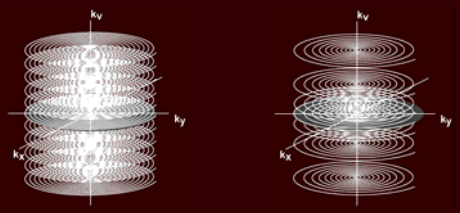
- Spatial resolution
- Off-resonance
- Temporal resolution
- Velocity FOV



Variable-density sampling in k_v

DiCarlo, 2005

- Increased efficiency in FVE imaging

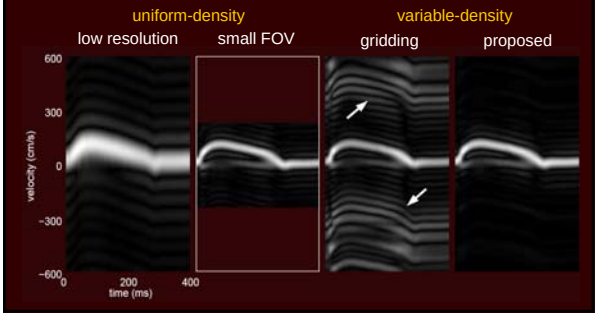


uniform

variable-density

Variable-density spiral FVE

- Healthy volunteer



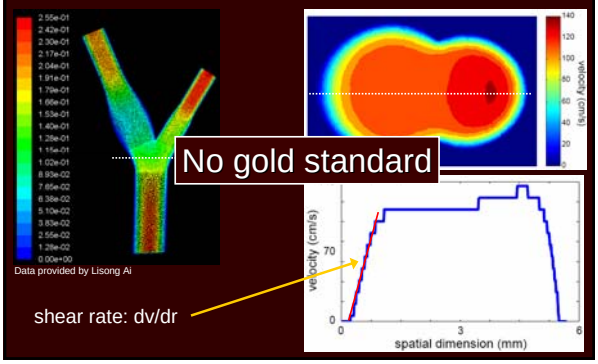
Spiral FVE: applications

- Peak velocity in flow jets
  - Valvular disease
  - Carotid stenosis
- Flow in small vessels
- Intravascular shear rate

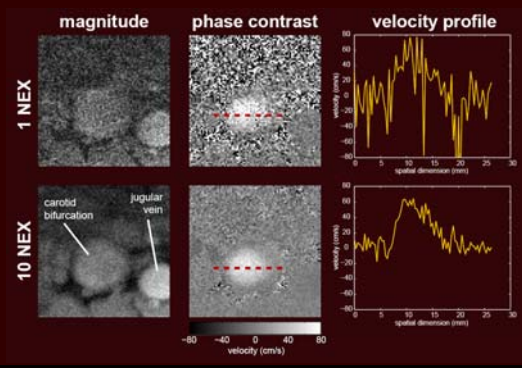
Wall shear

- Wall shear stress:
  - "drag force acting on the vessel wall as a result of blood flow" Cheng, 2006
- Indicators of risk for atherosclerosis:
  - Low WSS Zaris, 1983
  - Oscillatory WSS Ku, 1985
  - High WSS Thubrikar, 1995
- WSS = blood viscosity x wall shear rate

Fluid shear rate

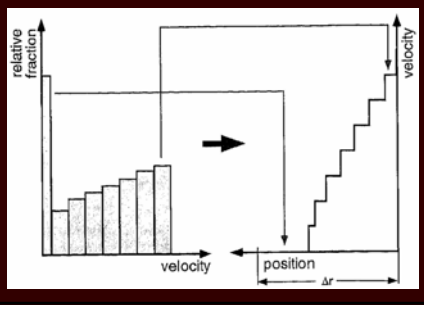


FSR w/ phase-contrast MRI



FSR with FVE: Frayne method

velocity distribution ⟶ velocity profile



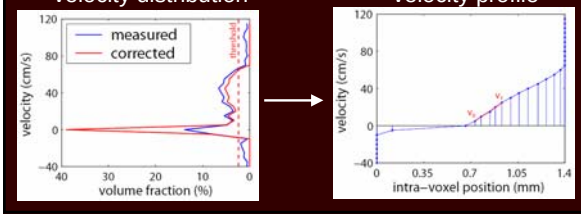
Frayne, 1995

Pre-processing

Frayne, 1995

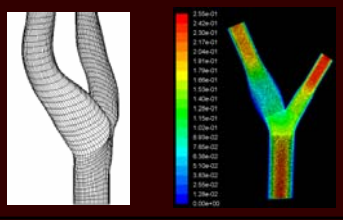
- Blood / arterial wall signal differences
- Flow enhancement
- Noise

velocity distribution → velocity profile



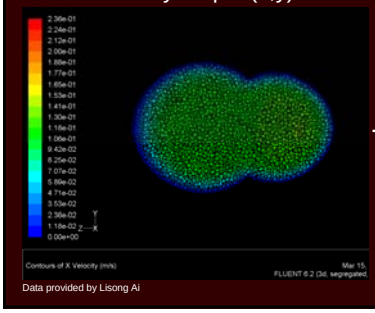
Simulation using CFD data

- No gold standard for FSR
  - Difficult to validate *in vivo*
- Computational fluid dynamics (CFD)



Simulation using CFD data

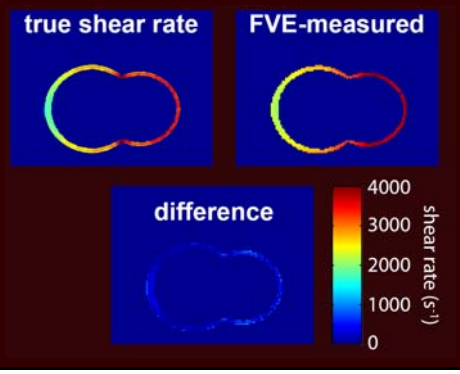
velocity map: v(x,y)



simulated FVE data

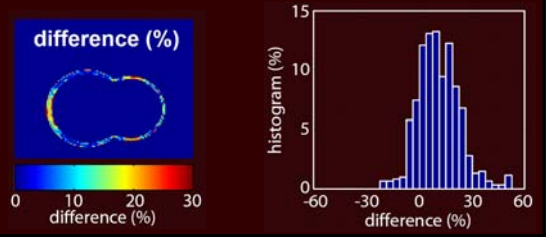
Δr, Δv ⟶ s(x,y,v)

Simulation results



Simulation results

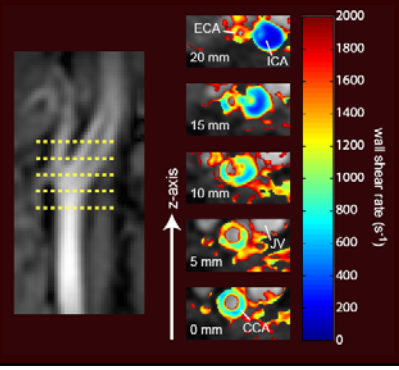
- 10% accuracy for 50% of the voxels
- 20% accuracy for 80% of the voxels
- 30% accuracy for 95% of the voxels



In vivo experiments

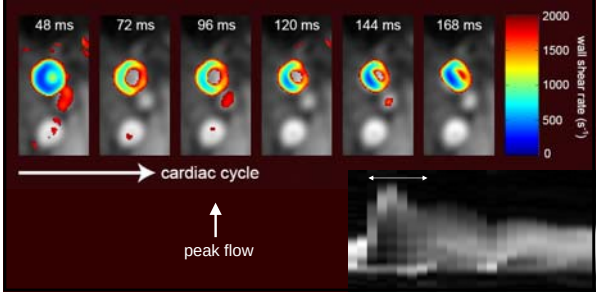
- Resolution:
  - Spatial: 1.4 mm (8 interleaves)
  - Velocity: 5 cm/s (32 vencs)
  - Temporal: 24 ms (2 views/heartbeat)
- Scan time: 2 minutes per slice
  (not accelerated)

In vivo results



In vivo results

- Oscillatory pattern (CCA)



Shear rate: summary

- First in vivo results using the Frayne method
- High temporal resolution → oscillatory pattern
- Scan time can be reduced
- Known issues:
  - FSR measured near but not at the wall
  - Voxel shape, intra-voxel weighting
  - Slice must be perpendicular to wall

Summary of contributions

- Spiral FVE: a new MRI method for rapid blood flow quantitation
- Combination of three different acceleration techniques (18-fold)
- A new reconstruction scheme for variable-density FVE
- Spiral FVE can be used to estimate carotid fluid shear rate

Publications

- Journal
  1. JLA Carvalho, KS Nayak. Rapid quantitation of cardiovascular flow using slice-selective Fourier velocity encoding with spiral readouts. Magn Reson Med, 57(4):639-646, 2007. USC-EE best student paper award.
  2. JLA Carvalho, KS Nayak. Accelerated spiral Fourier velocity encoding. In preparation.
  3. JLA Carvalho, AB Kerr, JM Santos, JC DiCarlo, KS Nayak. Reconstruction of variable-density Fourier velocity encoding data. In preparation.
  4. JLA Carvalho, JF Nielsen, KS Nayak. Measurement of carotid wall shear rate using spiral FVE. In preparation.
  5. JLA Carvalho, HS Carvalho, KS Nayak. Assessment of beat-to-beat variability of stroke volume using real-time spiral phase contrast. In preparation. (not discussed)
- Patent
  1. JLA Carvalho, KS Nayak. Spatially resolved velocity distribution measurement using magnetic resonance imaging. Submitted.

Publications (continued)

- Conference
  1. JLA Carvalho, KS Nayak. Rapid cardiovascular flow quantitation using slice-selective spiral Fourier velocity encoding. In Proc, ISMRM, 14th Annual Meeting, page 1906, Seattle, 2006.
  2. JLA Carvalho, KS Nayak. Accelerated spiral Fourier velocity encoding using UNFOLD and partial Fourier reconstruction. In Proc, ISMRM, Flow and Motion Study Group Workshop, New York, 2006.
  3. JLA Carvalho, GM Pohost, KS Nayak. Stroke volume and cardiac output measured on a beat-to-beat basis. In Proc, ISMRM, 15th Annual Meeting, page 248, Berlin, 2007.
  4. JLA Carvalho, KS Nayak. Accelerated spiral Fourier velocity encoded imaging. In Proc, ISMRM, 15th Annual Meeting, page 588, Berlin, 2007.
  5. JLA Carvalho, JC DiCarlo, AB Kerr, KS Nayak. Reconstruction of variable-density data in Fourier velocity encoding. In Proc, ISMRM, 15th Annual Meeting, page 2514, Berlin, 2007.
  6. JLA Carvalho, HS Carvalho, KS Nayak. Measurement of beat-to-beat variability of stroke volume In Proc, SCMR, 11th Annual Scientific Sessions, page 249, Los Angeles, 2008.
  7. JLA Carvalho, JF Nielsen, KS Nayak. Validation of the spiral Fourier velocity encoding method. In Proc, SCMR, 11th Annual Scientific Sessions, pages 422-423, Los Angeles, 2008.
  8. JLA Carvalho, HS Carvalho, KS Nayak. Assessment of stroke volume variability using real-time spiral phase contrast. In Proc, ISMRM, 16th Annual Meeting, page 383, Toronto, 2008.
  9. JLA Carvalho, JF Nielsen, KS Nayak. Carotid wall shear rate measured with spiral Fourier velocity encoding. In Proc, ISMRM, 16th Annual Meeting, page 908, Toronto, 2008.

4 oral presentations

Obrigado

(Thank you)

http://mrel.usc.edu

jcarvalh@usc.edu, April 24th 2008