MREL - USC

Rapid cardiovascular flow quantitation using slice-selective Fourier velocity encoding with spiral readouts

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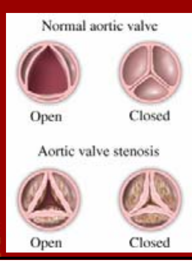
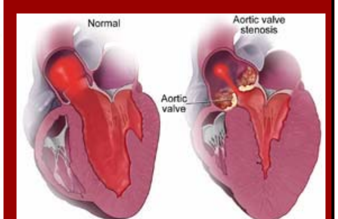
Clinical Importance

- Valve disease affects 10% of patients with heart disease in the U.S.
- Most important valve diseases:
  - Stenosis
  - Regurgitation

Aortic Stenosis

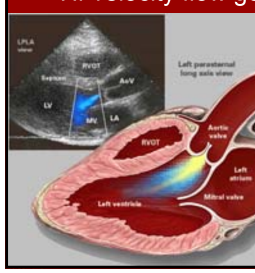
- Aortic valve does not open fully
- High velocity jets

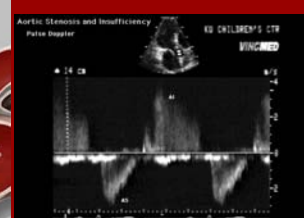




Aortic Regurgitation

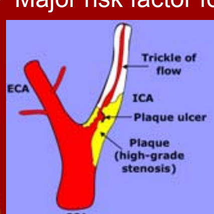
- "Leaky" valve: doesn't close properly
- Hi-velocity flow going backwards

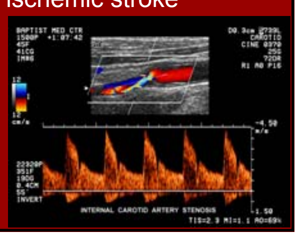




Carotid Artery Stenosis

- Narrowing of vessel
- Caused by plaque
- Major risk factor for ischemic stroke





Ultrasound vs. MRI

- Gold standard: Doppler ultrasound
  - Pros: low cost, high spatial and temporal resolution
  - Cons: velocity measurement is imprecise, requires acoustic window
- Why MRI?
  - Acoustic window? ☺
  - Complete cardiovascular evaluation in a single examination (potentially)
  - Measurement precision to be evaluated

MR Flow Imaging

- Sorry about the equations…

$$\phi(\mathbf{r}) = \gamma \int_0^{TE} \mathbf{G}(t)\,\mathbf{r}(t)\,dt$$

Phase accrual — Gradients Played — Time-varying position of a particular spin

- If moving along *z* with constant velocity v_z:
  - $r(t) = z_o + v_z t$

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Plugging in $r(t) = z_o + v_z t$ …

$$\phi = \gamma \int_0^{TE} G_z(t)\,(z_o + v_z t)\,dt$$

Rewriting…

$$\phi = z_o\gamma \int_0^{TE} G_z(t)\,dt + v_z\gamma \int_0^{TE} G_z(t)\,t\,dt$$

Gradient Area (M_0) — First Moment (M_1)

$$\phi = z_o\gamma M_0 + v_z\gamma M_1$$

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Bipolar Gradient

- Gradient area is null ($M_0 = 0$)
- First moment (M_1) is proportional to gradient amplitude
- Phase accrual is proportional to velocity:

$$\phi = v_z\gamma M_1$$

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Phase Contrast (PC)

- Velocity is not the only source of phase accrual in MR imaging
- Uses 2 acquisitions to measure velocity:
  - 1 reference, 1 with bipolar
  - or 2 with ± bipolar
- Measures average velocity for each voxel
- Requires high spatial resolution
- Popular approaches:
  - Cine PC (gated, long acquisition time)
  - Color Flow (real-time, but low temporal res.)

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Fourier Velocity Encoding (FVE)

- Multiple (16+) acquisitions for 1 measurement
- Kv encoding with different bipolar amplitudes: $k_v = \frac{\gamma}{2\pi} M_1$
- Inverse DFT to get velocities
- Full velocity distribution within each voxel
- Low spatial resolution is OK

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Speeding up FVE

- Multiple acquisitions → Long scan time
- Usually reduced by minimizing spatial-encoding
- Rapid FVE Methods:
  - No Phase-Encoding FVE
  - No Spatial-Encoding FVE
  - One shot FVE
  - Spiral FVE

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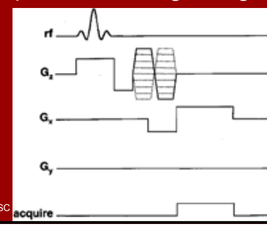
No Spatial-Encoding FVE

- Slice-select + Bipolar + DAQ
- Too much signal from static spins
- Dynamic range problem: background noise
- Requires static-tissue suppression
- There might be the need to:
  - Resolve different vessel/chambers in-plane
  - Measure more than peak velocity

No phase-encoding FVE

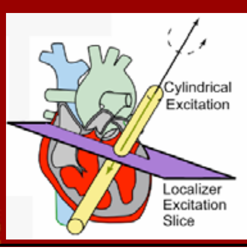
- Similar to a 2DFT sequence
- Phase encoding is replaced by velocity encoding
- Spatial encoding along x-axis only



Doesn't solve the problem!

One Shot FVE

- Full FVE acquisition in 1 TR
- Very fast (real-time)
- 2D excitation instead of slice-selective



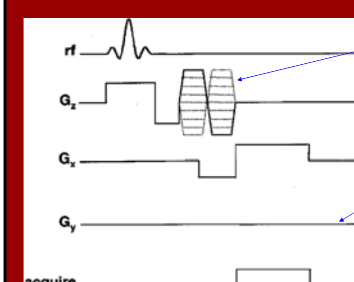
Discussion: One Shot FVE

- Pros:
  - Good temporal resolution
  - Real-time (MR Doppler)
  - No breath-holding required
- Cons:
  - Low spatial resolution: 14x14x17 mm
  - Only a "line" of pixels is available
  - Localization is difficult

Spiral FVE

- Cons:
  - Not real-time
  - Breath-holding is required
- Pros:
  - Comparable temporal resolution
  - Higher spatial resolution: 7x7x5 mm
  - Easier localization
    - Classic plane localization
    - 2D image instead of a line → auto-ROI
  - Breath-hold is short (8-16 seconds)
  - Carotid imaging also possible (modified PSD)

Back to No Phase-Encoding FVE…



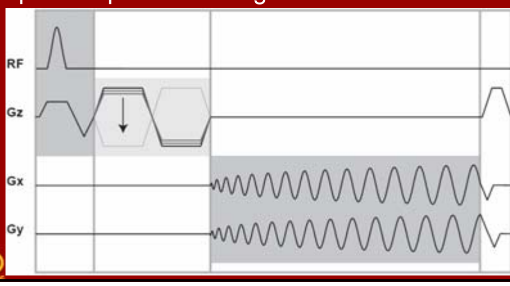
Velocity encoding instead of phase-encoding

No Ky encoding!

Can we acquire Kx,Ky simultaneously?

Spiral FVE

- Replacing the 1D readout gradient with a pair of spiral readout gradients:



Proposed Method

- Use slice-selective excitation (5 mm)
- Acquire full Kx,Ky in a single spiral readout
  - 7x7mm in-plane resolution, 25 cm FOV
- Cine MR technique

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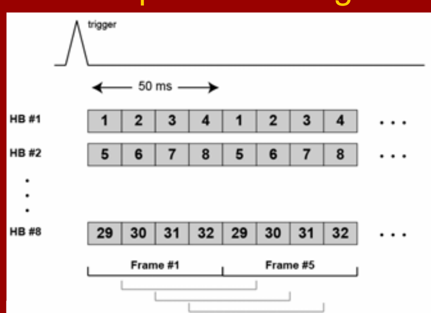
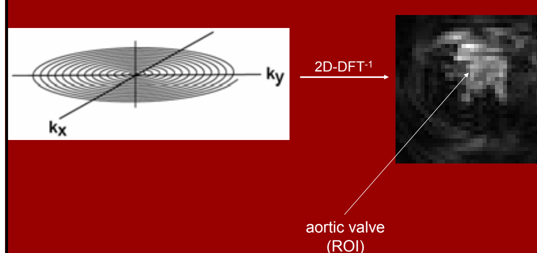
Sequence Timing



Images are reconstructed every TR!
(although that's not the true temporal resolution)

K-Space



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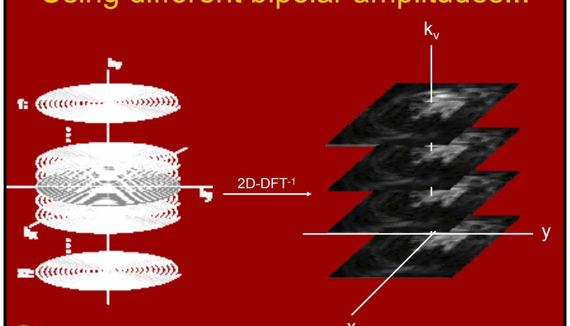
Using different bipolar amplitudes...



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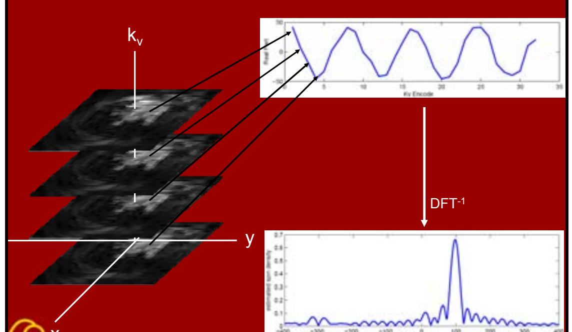
Select ROI and iDFT



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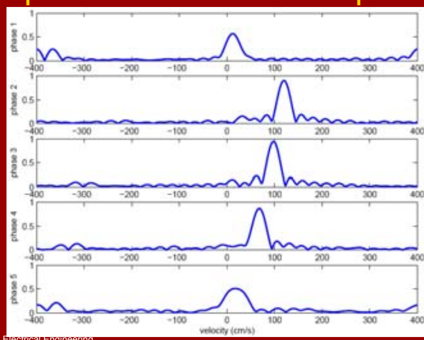
Repeat for each cardiac phase



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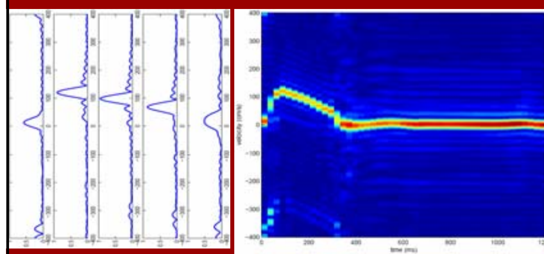
3D plot



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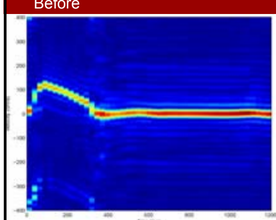
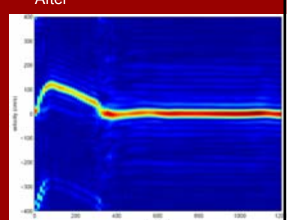
Sliding-Window

- Increases the number of samples along t

Before



After



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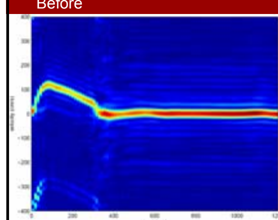
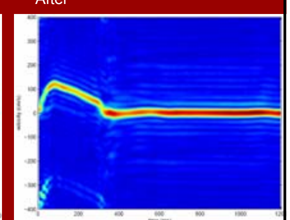
Interpolation

- Using cubic splines interpolation along t …

Before



After



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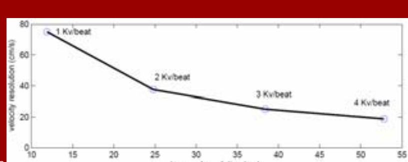
Time/Velocity Resolution trade-off

- We need 16-24 Kv encodes (600 cm/s FOV)
- During an 8-sec breath-hold we can acquire:
  - 8 Kv's: 1 Kv/beat → 12.5 ms time resolution
  - 16 Kv's: 2 Kv/beat → 25 ms time resolution
  - 32 Kv's: 4 Kv/beat → 50 ms time resolution



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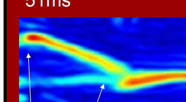
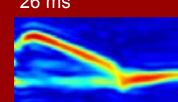
Temporal Resolution

51ms



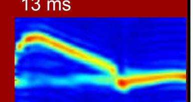
8 sec 4 Kv/beat

26 ms



16 sec 2 Kv/beat

13 ms



32 sec 1 Kv/beat

Low-pass effect

- Important to visualize rapid-changing velocities
- Even more important when flow is turbulent:
  - Peak velocity underestimation

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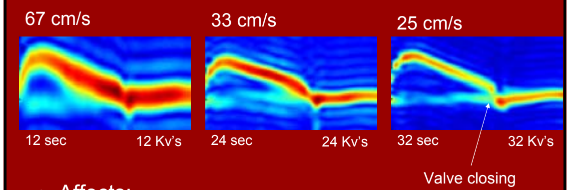
Velocity Resolution



- Affects:
  - The precision to resolve peak velocity
  - The ability to visualize features in the waveform
- high v-res + low t-res = discontinuities on slopes

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Ways to improve velocity resolution

- Reduce the velocity FOV
  - Peak velocity is usually not known before hand
- Acquire more Kv encodes
  - Extra heartbeats (longer breath-hold)
  - More vencs/beat (lower time-resolution)
- Future work: (?)
  - Partial k-space along Kv
  - Variable density along Kv

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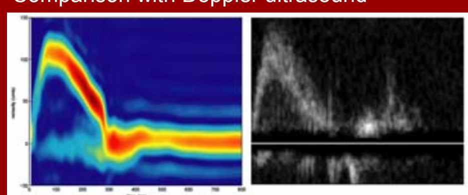
Validation

- Comparison with Doppler ultrasound



- Scan parameters:
  - 25 ms time resolution
  - 600 cm/s velocity FOV
  - 12 second acquisition

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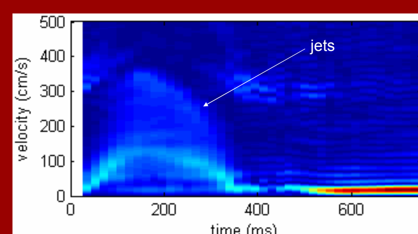
Patient Validation

- Preliminary results (1.5T)
- Patient with aortic stenosis



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Spiral FVE for Carotid Imaging

- Needs higher spatial resolution
- But no breath-hold required:
  - Can increase scan-time
- Modified PSD:
  - 4 spiral interleaves
  - reduced FOV
  - 2.5 x 2.5 mm in-plane resolution
- Scan-time is 4x longer

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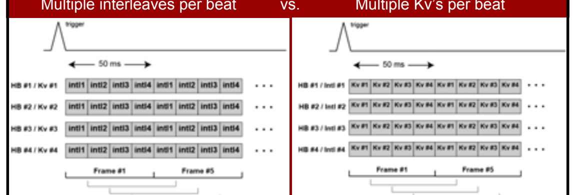
Sequence timing

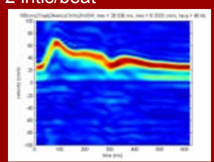
Multiple interleaves per beat vs. Multiple Kv's per beat



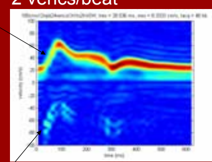
- Velocities may change during acquisition
- Multiple spiral interleaves:
  - motion artifacts (swirling) in spatial domain
- Multiple Kv encodes:
  - motion artifacts (ghosting) in velocity domain

Kv Segmentation Artifacts

2 intls/beat



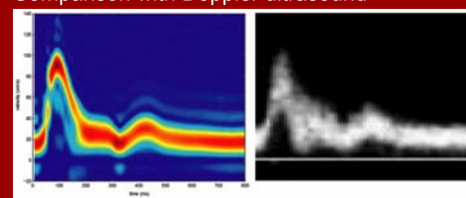
2 vencs/beat



- Interleave segmentation artifacts aren't noticeable:
  - Visible only in spatial domain
  - Don't overlap with ROI

Validation

- Comparison with Doppler ultrasound



- Scan parameters:
  - 25 ms time resolution
  - 400 cm/s velocity FOV
  - 48 second acquisition

Conclusions

- Full velocity distribution in a short breath-hold
- Slice-select excitation method:
  - Scan plane localization with classic protocols
- Multiple in-plane voxels:
  - ROI localization is easy (or even automatic)
- Fully localized: less signal from static tissue
- Works for both heart and carotid arteries
- Temporal & velocity resolutions comparable to Doppler ultrasound

Ideas for future work

- Improved auto-ROI selection
- Auto-detection of stenosis & regurgitation
- Peak velocity measurement (image processing problem?)
- Improve velocity resolution using partial k-space and variable density
- Improve temporal resolution using Kt-flow
- Improve spatial resolution using parallel imaging and VD-spirals

The End

Thanks to everyone that volunteered!