Variable-density² spiral FVE (with partial k-space)

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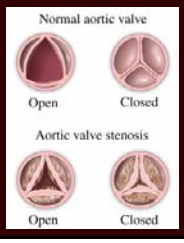
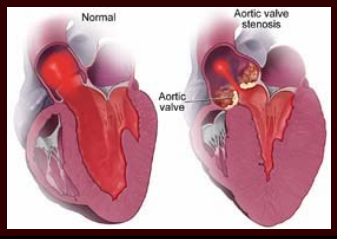
Spiral FVE - Motivation

- Assessment of valve disease
  - Stenosis
  - Regurgitation
- Phase contrast is inadequate to measure flow jets

Aortic stenosis

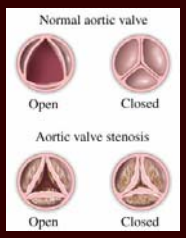
- Aortic valve does not open fully
- Jet with multiple velocities
- High peak velocity



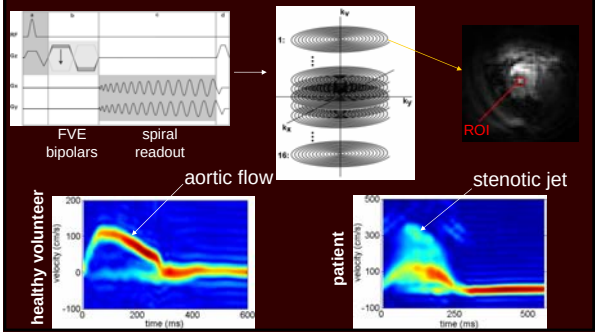


Aortic regurgitation

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



Spiral FVE in review



Spiral FVE without acceleration

- In-plane spatial resolution: 7x7 mm
- Temporal resolution: 25 ms
- Velocity resolution: 25 cm/s
- Velocity FOV: ±300 cm/s
- Breath-hold duration: 12 heartbeats

Acceleration goals

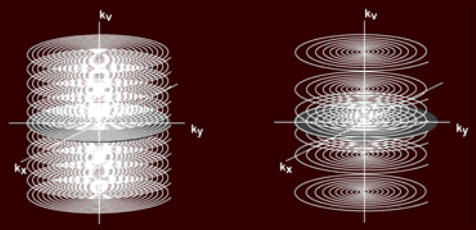
- Improve spatial resolution
- Double velocity FOV
- Maintain useful time-velocity resolution
- Shorten breath-hold a little

Acceleration techniques

- Variable-density sampling
  - k_v-FoCuSIn'
  - V-D spirals
- Partial Fourier
  - Along k_v
  - Along k_x,k_y
- Temporal acceleration (*k-t*)
  - Not today

Variable-density^2 Spiral FVE

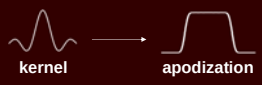
- k_v-FoCuSIn'
- V-D spirals



uniform variable-density^2

V-D along k_v: good news

- Gridding along 1D only
- Small number of data points
- Sinc interpolation
  - Flat apodization

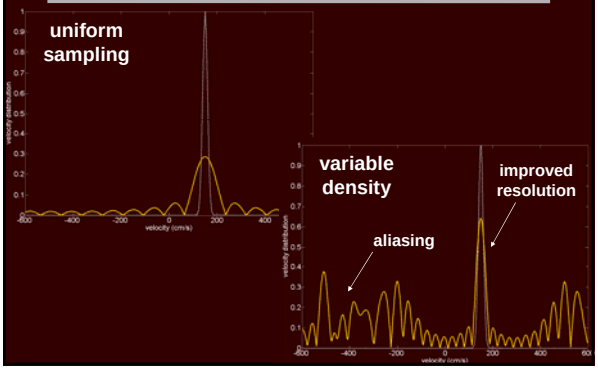


  - No deapodization required!

V-D along k_v: bad news

- V-D assumption:
  - High-frequency components have little energy
  - If undersampled, artifacts will be insignificant
- Plug flow / static spins
  - Impulse in velocity domain
  - Spreads in k_v domain
- Assumption violated
  - Strong aliasing artifacts
  - Limited acceleration

Variable-density along k_v



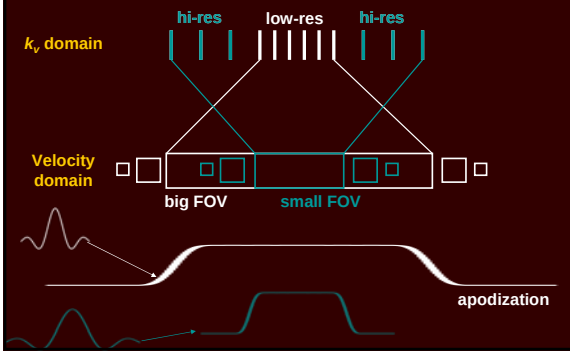
Resolution/FOV requirements

- Plug flow
  - Narrow in velocity domain
  - Wide in k_v domain
  - Requires high resolution, but small FOV
- Jets
  - Wide in velocity domain
  - Narrow in k_v domain
  - Requires big FOV, but low resolution
- Perfect scenario for variable-width kernel interpolation

Variable-density intuition

- Low-frequency components
  - Spacing is small
  - FOV is big
- High-frequency components
  - Spacing is large
  - FOV is small
  - Aliasing
- Resolution-FOV trade-off

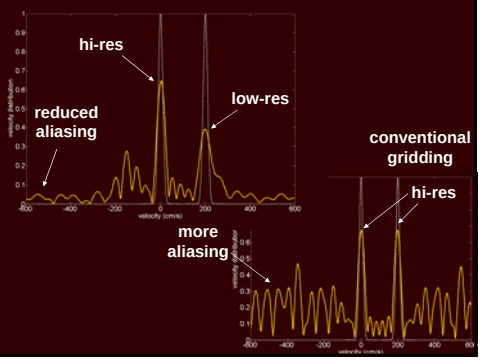
Variable-density intuition



Variable-width kernel recon

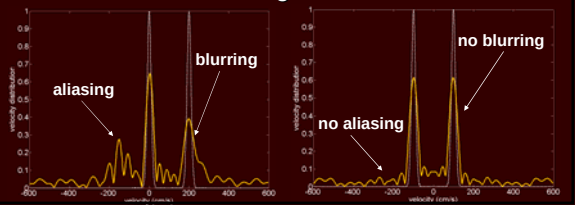
- Undersampled components contribute only to center of FOV
  - Less aliasing
- Outter portions of FOV receive no contribution from hi-freq components
- High resolution at center of FOV
- Low resolution outside

Variable-width kernel recon



Variable-width kernel recon

- Objects outside center of FOV: blurred
- This blurring induces aliasing
- No blurring/aliasing if objects are at center
- Idea: FOV centering



FOV centering

- Estimate center of distribution
  - Take $k_v(0)$ and $k_v(1)$
  - Find phase contrast
  - That's the average velocity
- Shift distribution to center of FOV
  - Multiply k_v samples by a linear phase
- After gridding, multiply again to shift back

k_v-FoCuSIn'

- FOV-Centering Sinc Interpolation
- A different sinc width is used for each k_v sample
  - Width is calculated from Voronoi distances
  - Cleans most of the aliasing
- Dynamic FOV centering
  - Each temporal frame separately
  - Maximizes resolution through distribution
  - Further reduces artifacts

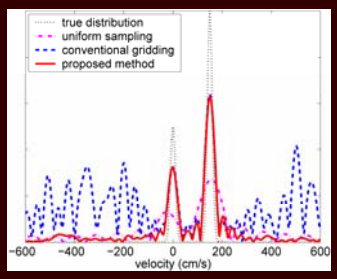
k_v-FoCuSIn'

- Unaliased FOV = v_{FOV}/ρ = 1200/4 = 300 cm/s
- Method's assumptions:
  - Velocities >300 cm/s in few temporal frames
  - Signal >300 cm/s has weak high-freq components
- Artifacts only in frames where peak velocity exceeds 300 cm/s
  - Plug flow is aliasing free!
- Jets tolerate low resolution at edges
  - Unnoticeable blurring & weak artifacts

Perfect reconstruction in most temporal frames!

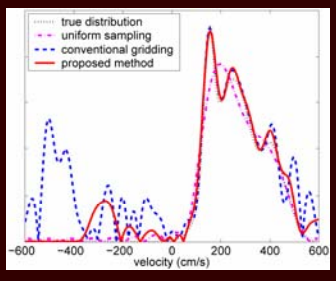
k_v-FoCuSIn' - Simulation

- Plug flow

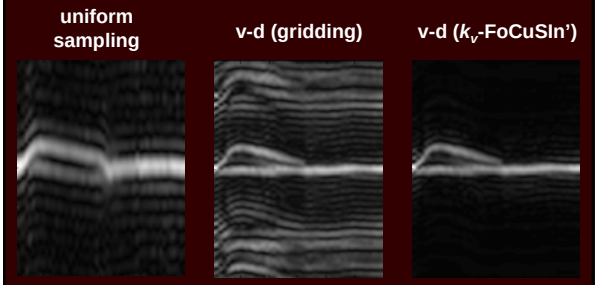


k_v-FoCuSIn' - Simulation

- Stenosis



k_v-FoCuSIn' - *In vivo*



k_V-FoCuSIn' - Summary

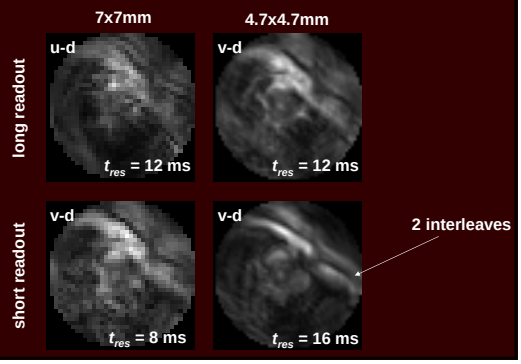
- 2.6-fold acceleration
- Wider v_{FOV} and better v_{res}
- No significant artifacts
- No artifacts at all in most temporal frames

Variable-density spirals

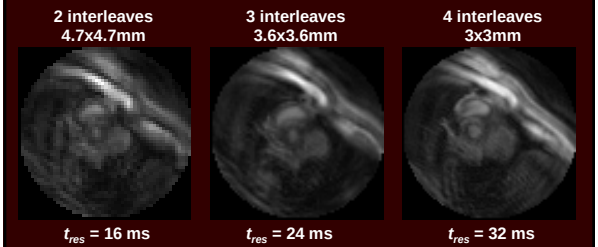
Variable-density spirals

- For spatial images, V-D assumption generally holds
- Higher resolution or shorter readouts?
- Higher resolution
  - More voxels inside aortic valve
  - Cleaner velocity profiles
- Shorter readout
  - Less off-resonance (less blurring)
  - Shorter TR (better t_{res})

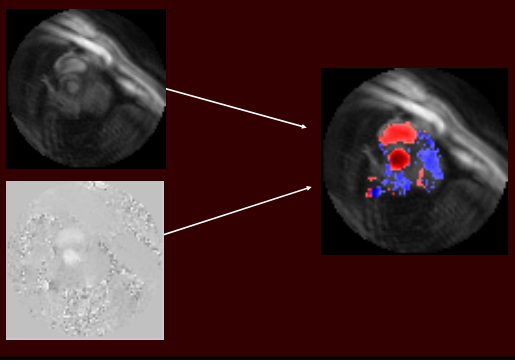
Hi-res or shorter readouts?



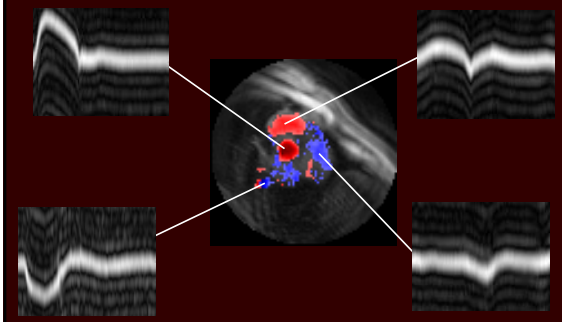
Multi-interleaf V-D spiral



Color flow: finding ROIs



Finding ROIs



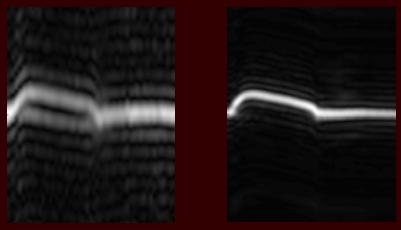
V-D spiral - Summary

- Less off-resonance (shorter readout)
- Better temporal resolution
  Or
- Better spatial resolution
- Bottom line: cleaner velocity profiles

Variable-density²

- V-D spiral + k_v-FoCuSIn'

uniform | variable-density²

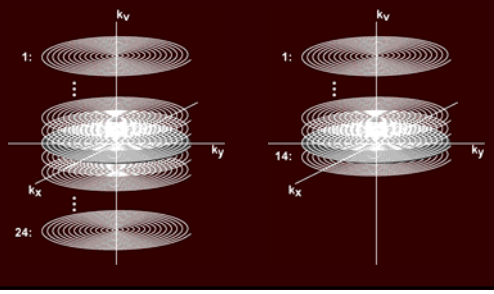


Partial Fourier

- Along k_v
- Along k_x,k_y

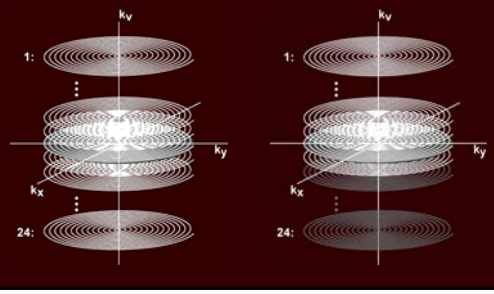
Partial Fourier along k_v

full k-space (12 heartbeats) | partial k-space (7 heartbeats)

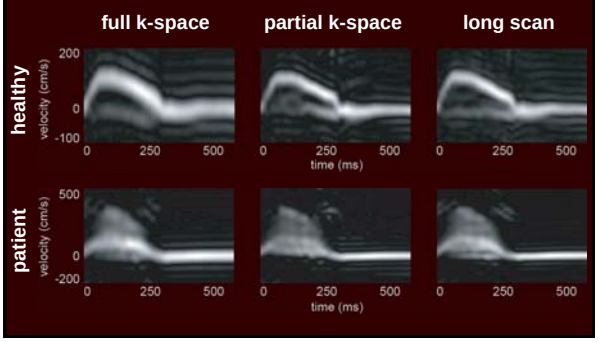


Partial Fourier along k_v

full k-space (12 heartbeats) | partial k-space (7 heartbeats)



Partial Fourier along k_v

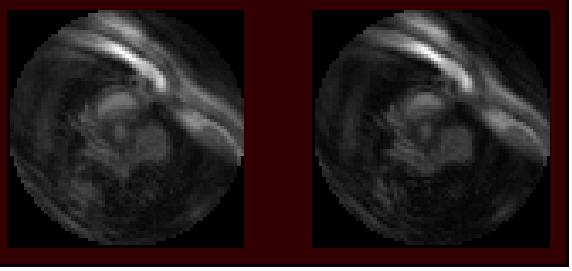


Partial Fourier along k_x,k_y

- Homodyne recon of spirals
- Goal: reduce V-D artifacts
- Phase estimate: central portion of k-space
- Weighting function: Voronoi areas
- Requirement: odd number of interleaves
- Assumption: phase image is smooth

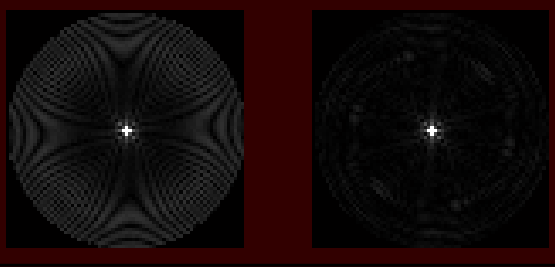
Partial Fourier along k_x,k_y

- Magnitude image
  - Reduced aliasing artifacts



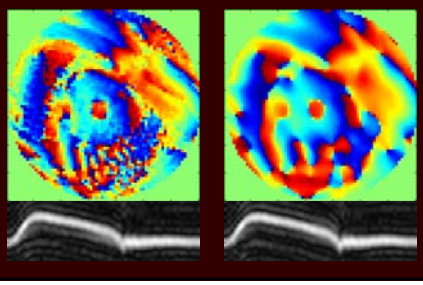
Partial Fourier along k_x,k_y

- Magnified PSF



Partial Fourier along k_x,k_y

- Smooth-varying phase assumption holds



Partial Fourier along k_x,k_y

- Homodyne reconstruction
  - Didn't work

- Maybe POCS will work… (?)

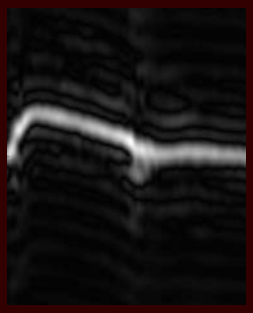
Spiral FVE without acceleration

- In-plane spatial resolution: 7x7 mm
- Temporal resolution: 25 ms
- Velocity resolution: 25 cm/s
- Velocity FOV: ±300 cm/s
- Breath-hold duration: 12 heartbeats

Improved Spiral FVE

- Improvements:
  - *2x wider* v_{FOV}
  - 4x more in plane pixels
  - Shorter spiral readout
- Without acceleration: 64 heartbeats
- Accelerating:
  - V-D spiral: 48 hb
  - k_v-FoCuSIn': 18 hb
  - Partial Fourier: 10 heartbeats

Combined Accel - Results



- t_{acq} = 8 heartbeats
- xy_{res} = 3x3 mm
- v_{FOV} = ±600 cm/s
- v_{res} = 33 cm/s
- t_{res} = 33 ms

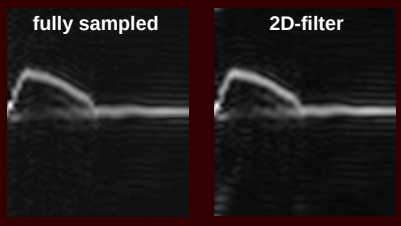
Conclusions

- V-D spiral:
  - Less off-resonance
  - Improved t_{res} or xy_{res}
- k_v-FoCuSIn': 2.6-fold acceleration
  - Improved v_{res} and v_{FOV}
  - No significant artifacts
- Partial Fourier: 1.8-fold acceleration
  - Reduced scan time
  - Some artifacts

Combined: 6.4-fold acceleration

Teaser - Next talk

- Temporal acceleration (k_v-t)
  - Robust 2-fold acceleration



  - Can't be combined with v-d along k_v? ☹

Future work

- Temporal acceleration along x-y
  - k_{xy}-t
  - k_{xyv}-t
- Maybe up to 4-fold acceleration (?)
  - Combined to 13-fold acceleration!!

The End

Thank you!

http://mrel.usc.edu

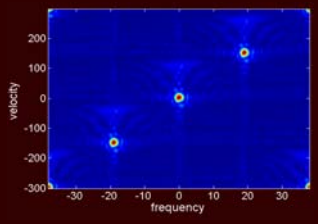
jcarvalh@usc.edu, Aug 30th 2006

2D-Filter approach

- 2-fold acceleration
- Explores knowledge about signal in *v-f* space

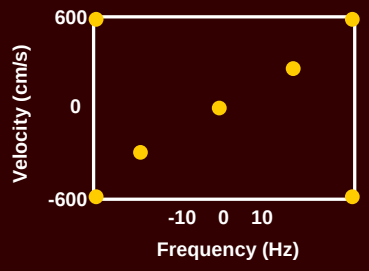
Undersampling

- 4-fold undersampling PSF



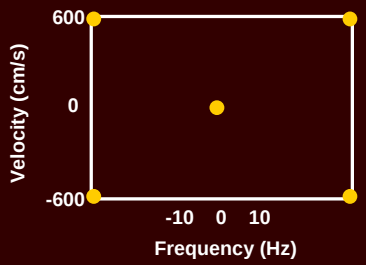
Undersampling

- 4-fold undersampling PSF

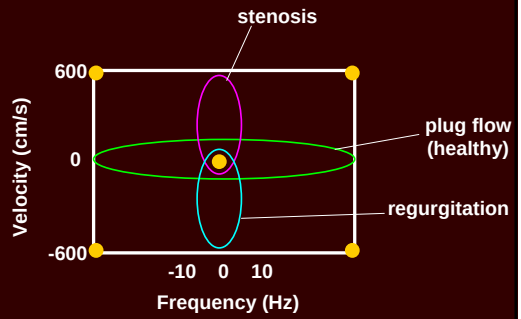


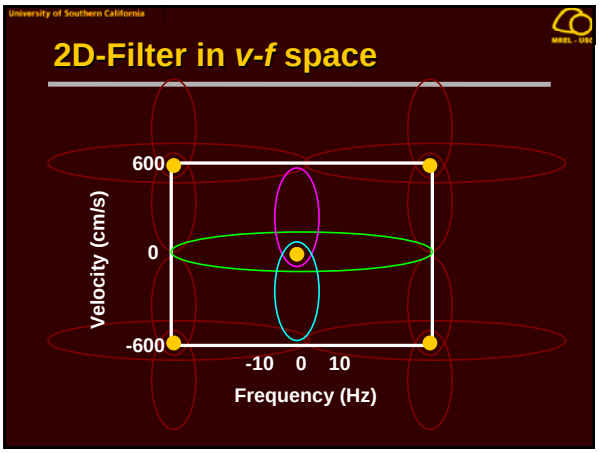
Undersampling

- 2-fold undersampling PSF



2D-Filter in *v-f* space

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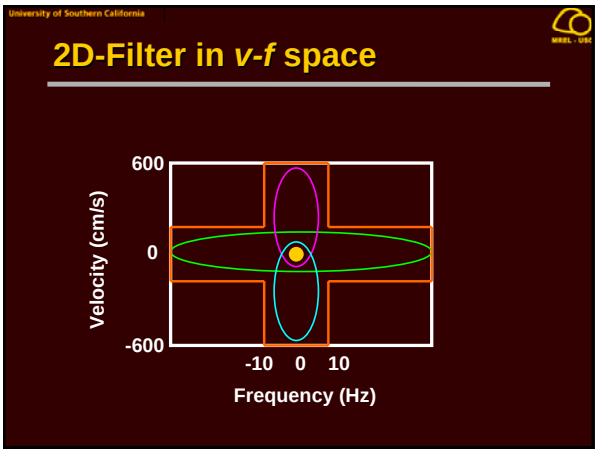
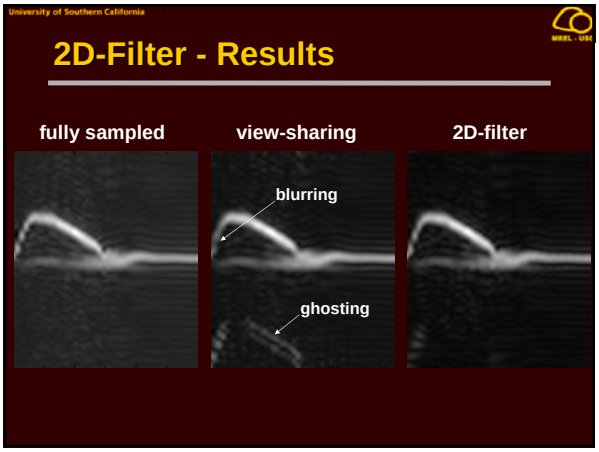
2D-Filter in v-f space
600
0
-600
Velocity (cm/s)
-10 0 10
Frequency (Hz)


University of Southern California
2D-Filter in v-f space
600
0
-600
Velocity (cm/s)
-10 0 10
Frequency (Hz)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2D-Filter - Results
fully sampled
view-sharing
2D-filter
blurring
ghosting