In vivo measurement of carotid wall shear rate using spiral Fourier velocity encoding

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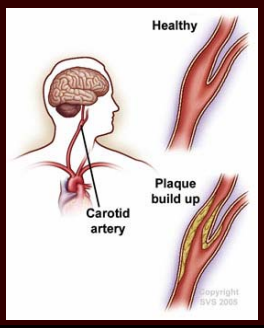
Motivation

Carotid Atherosclerosis



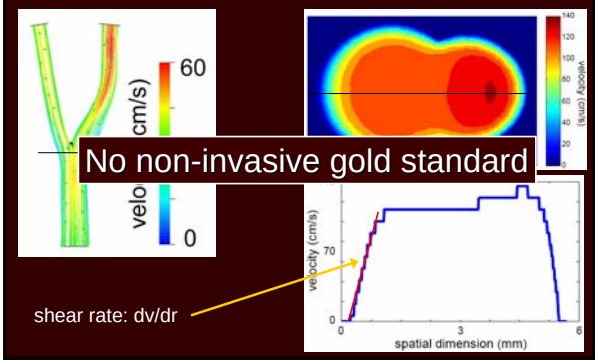
Plaque ↔ WSS

WSS = μ WSR

blood viscosity

wall shear rate

Wall-shear rate



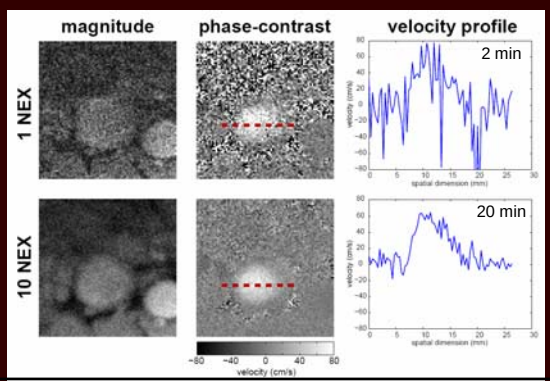
No non-invasive gold standard

shear rate: dv/dr

WSR w/ Phase-contrast MRI

- PC assumes one velocity per pixel
- Velocity is rapidly spatially-varying
- Partial volume
  - Signal loss
  - Inaccuracy
- High spatial resolution required
  - Very poor SNR
- Very long scan time
  - Motion, cardiovascular variabilities
  - Clinically prohibitive

WSR w/ Phase-contrast MRI



WSR w/ Fourier Velocity Encoding

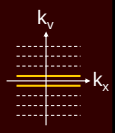
- MRM 34:378 (1995)
- University of Western Ontario, Canada

Richard Frayne

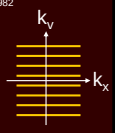
Brian Rutt

FVE vs Phase Contrast

- Phase contrast [O'Donnell, 1985]
  - Fast
  - One velocity estimate for each voxel
  - Typically high-resolution

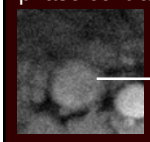


- Fourier velocity encoding (FVE) [Moran, 1982]
  - Slow
  - Velocity distribution in each voxel
  - Typically low-resolution



FVE vs Phase Contrast
→ within a voxel

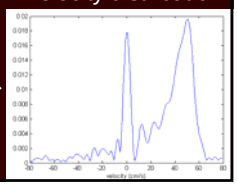
phase contrast



→ one velocity value: e.g. 60 cm/s

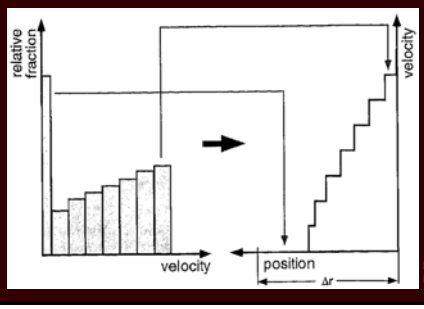
velocity distribution

FVE



Frayne method

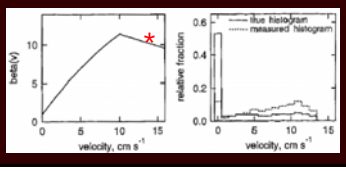
velocity distribution → velocity profile

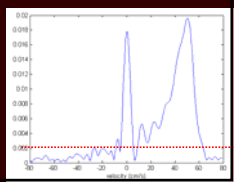


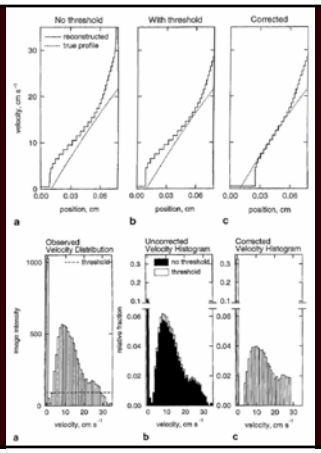
Frayne 1995
MRM 34:376

Required corrections

- Blood / arterial wall signal differences
  - Different even for static blood
- Flow enhancement
  - Rapid moving spins are brighter (less saturated)
- Noise



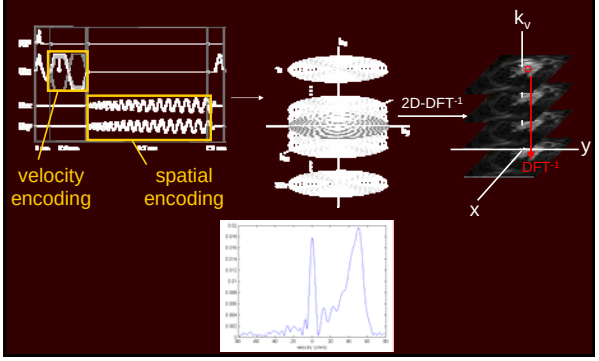




Frayne's shortcomings in 1995

- Scantime: 4.5 hours
  - Resolution: 0.8 mm, 1 cm/s
  - Very long TR: 500 ms
- No *in vivo* experiment was made (duh…)
- In practice
  - 1.5 mm, 5 cm/s resolution is sufficient
  - Short TR: 2-4 views/beat is ok
- 2DFT FVE: 7-14 minutes (per slice)
- Spiral FVE: 2 minutes (per slice)
- Both can be further reduced

Spiral FVE



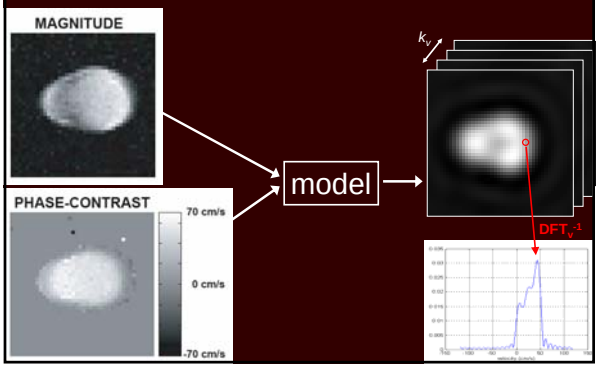
PC-FVE relationship

- Assuming hi-res PC with no distortions
  - partial volume, signal loss, low SNR, motion
- Can obtain FVE by blurring PC

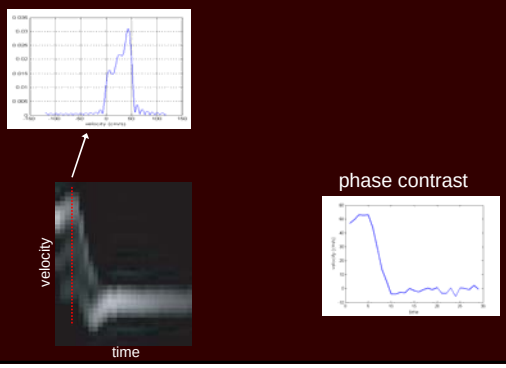
PC: m(x,y), v(x,y) —sinc(v), jinc(x,y)→ FVE: s(x,y,v)

$$s(x,y,v) = \left(m(x,y) \cdot \mathrm{sinc} \frac{v - v_{PC}(x,y)}{v_{res}} \right) * \mathrm{jinc} \frac{\sqrt{x^2 + y^2}}{xy_{res}}$$

PC-derived FVE

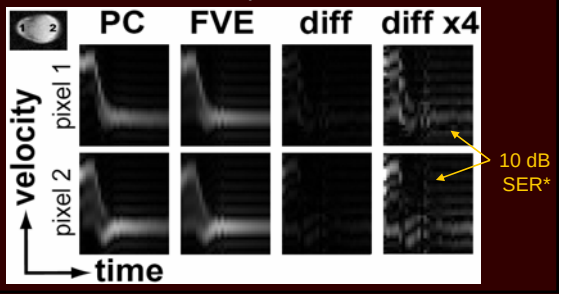


Time-velocity distribution



Spiral FVE - Validation

- Carotid flow phantom
- Exact same scan parameters



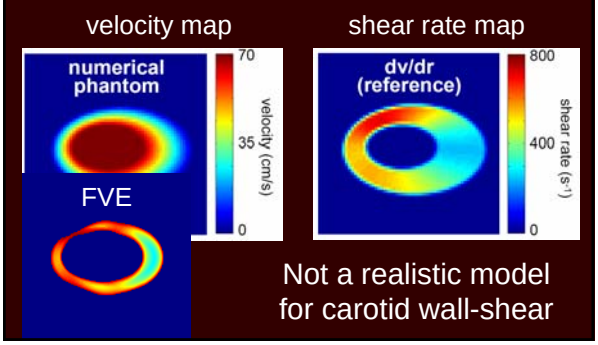
Important results

- Spiral FVE is accurately measuring the velocity distributions
- The proposed sinc/jinc method accurately models spiral FVE
  - FVE data from a hi-res velocity map
  - Can be used for simulations

Simulation: WSR w/ spiral FVE

- No gold standard for WSR
  - Impossible to validate *in vivo*
- Flow phantom
  - No signal from vessel wall
  - Can't use it for WSR validation
- Simulation
  - Reasonable reality check
  - Sinc/Jinc model has been validated
  - Need a hi-res carotid velocity map

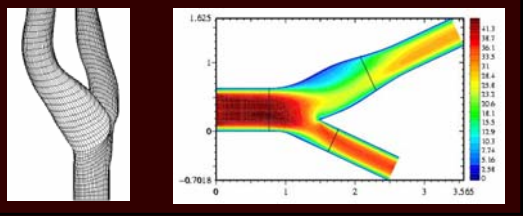
Shear rate numerical phantom

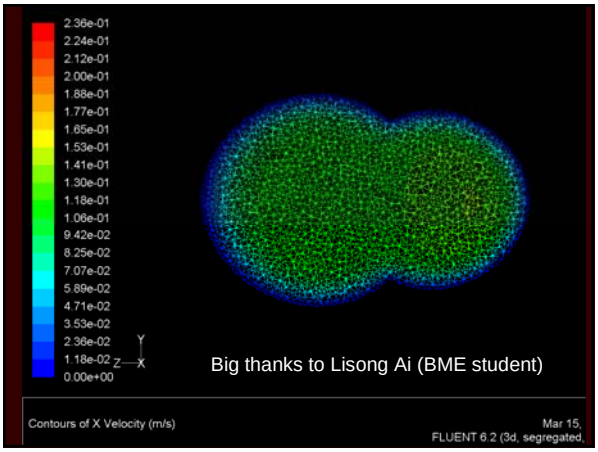


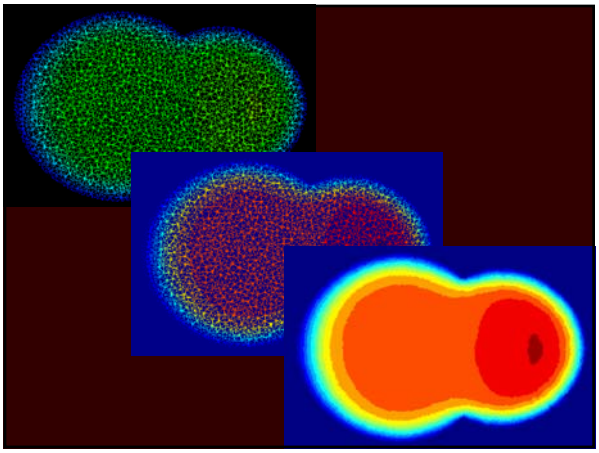
Not a realistic model for carotid wall-shear

CFD-based numerical phantom

- **Computational fluid dynamics (CFD)**
  - User provides: vessel geometry, input and output velocity profiles
  - CFD provides: velocities through the vessel







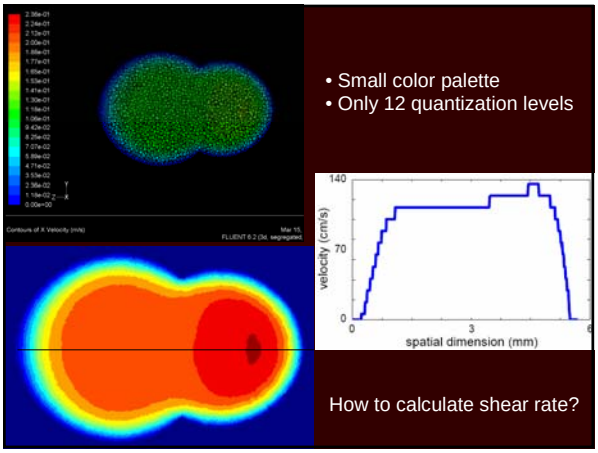
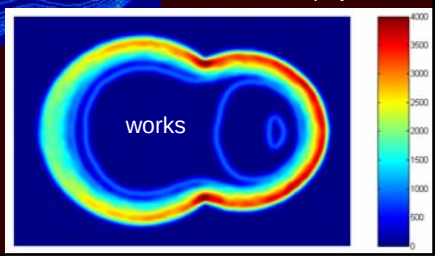


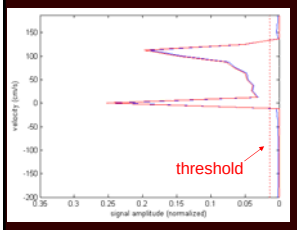
Image gradient (Sobel)

1st order 2D polynomial fit

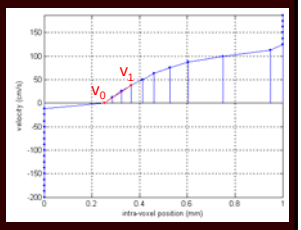


Simulation results

velocity distribution



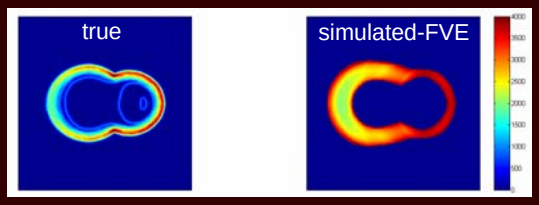
velocity profile

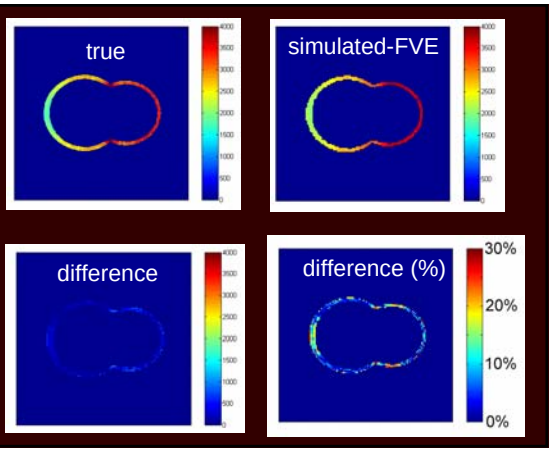


- No flow enhancement in this simulation
- No blood/vessel wall signal differences: magn(x,y) = 1

Simulation results

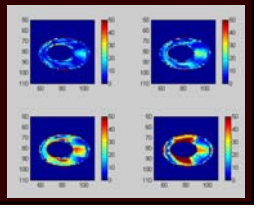
- Fixed threshold (2.5%)
- Fixed v_0-v_1 pair (0-30 cm/s)





To-do list

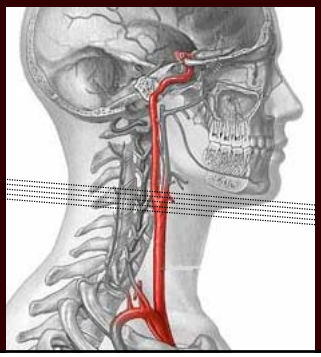
- Resolution requirements
  - Spatial resolution
  - Velocity resolution
- Off-resonance tolerance

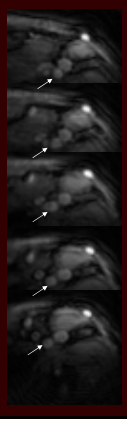


In vivo experiments

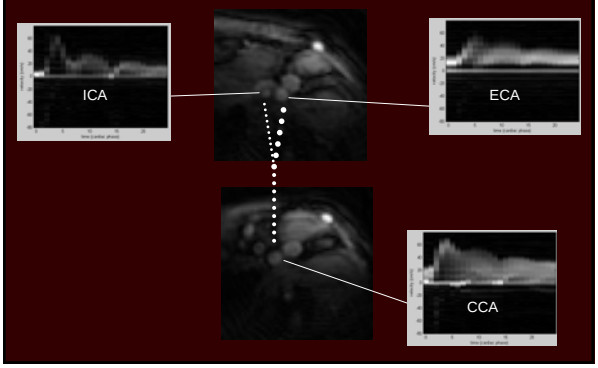
- Excitation: 30°, 5 mm
- TR:12 ms
- Variable density spirals:
  - 8 interleaves
  - 4 ms readout
  - FOV: 16~6.25 cm
- Resolution: 1.4 mm, 5 cm/s, 24 ms
- Velocity FOV: 160 cm/s (32 vencs)
- Scan time: 2 minutes per slice

Scan plane prescription

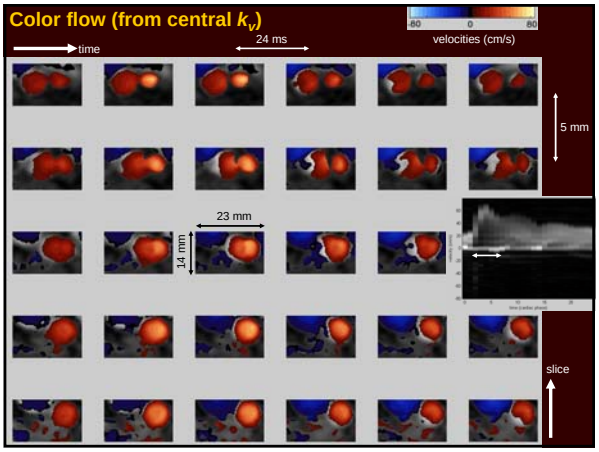




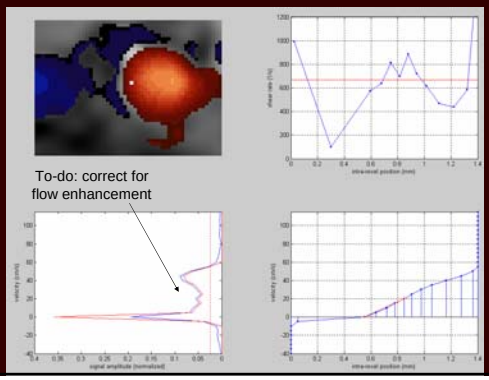
Time-velocity distributions



Color flow (from central k_y)

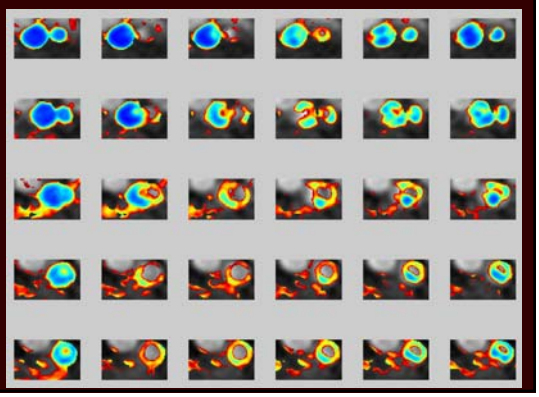


WSR: *in vivo* results



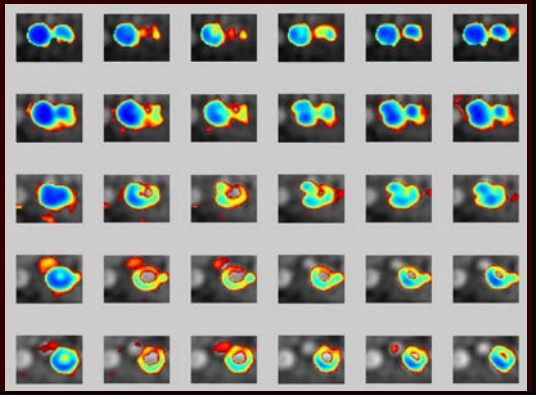
- Fixed threshold (2.5%)
- Fixed v0-v1 pair (0-30 cm/s)

volunteer 1



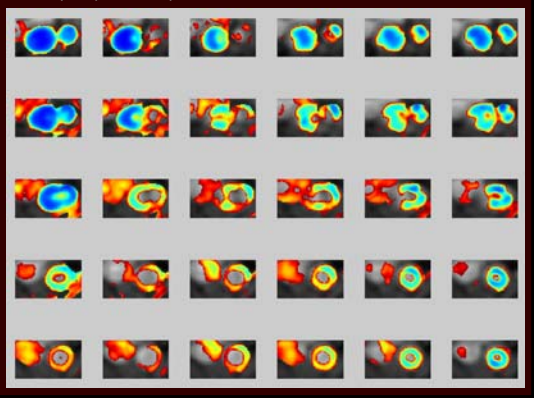
- Fixed threshold (2.5%)
- Fixed v0-v1 pair (0-30 cm/s)

volunteer 2



- Fixed threshold (2.5%)
- Fixed v0-v1 pair (0-30 cm/s)

volunteer 3



Discussion

- Through-plane velocities (v_z) only
- Slice not perpendicular to vessel wall:
  - Correction is needed
  - Geometry is usually known
- 3D FVE should have higher SNR than multi-slice FVE
- Scan time (2 min/slice) can be drastically reduced

Conclusion

- Spiral FVE was validated against ultra-hi-res 2DFT phase-contrast
- A model for deriving FVE data from PC was proposed & validated
- Spiral FVE can measure WSR in clinically practical scan time
  - Demonstrated in vivo
  - Validated on a realistic (CFD-based) numerical phantom
- To-do: re-evaluate resolution requirements & off-resonance tolerance

Obrigado

(thank you)

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