High dynamic range magnetic resonance flow imaging

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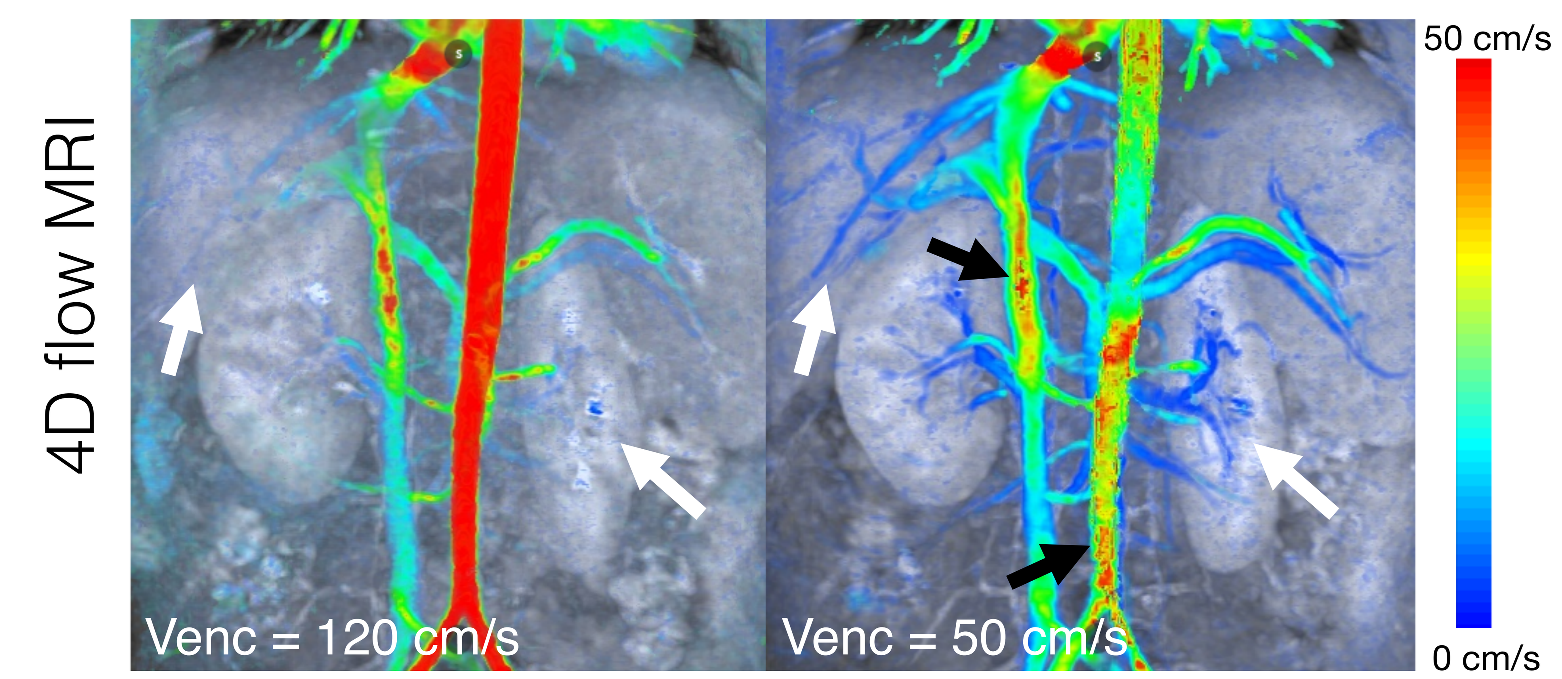
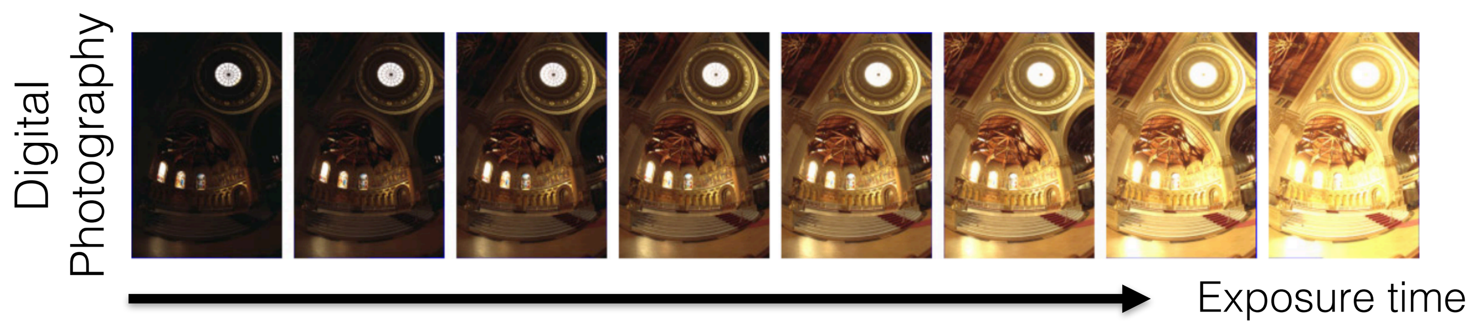
Objectives

- Apply high dynamic range (HDR) processing techniques[1] to magnetic resonance flow imaging to allow simultaneous assessment of arterial (fast) and venous (slow) blood flow
- Evaluate HDR flow technique both qualitatively and quantitatively, compare to clinical standard

Motivation

- Time-resolved, volumetric phase-contrast (4D flow) MRI is a medical imaging technique that allows comprehensive assessment of cardiovascular anatomy, flow, and function[2]
- 4D flow MRI has limited dynamic range: tissue velocity information is encoded into the principal value phase of the complex MRI signal, causing there to be a maximum encodable velocity (Venc)
- If one wants to directly measure both slow and fast hemodynamics, two or more separate scans (multi-venc acquisition[3]) are necessary – how to combine this data? Similar to HDR problem





Methodology

- Combine multiple LDR datasets by minimizing weighted HDR cost function using ADMM[4] (ρ=1, 25 iterations, 100 L-S iterations) Assign higher weights to high SNR measurements, and lower weights to aliased measurements

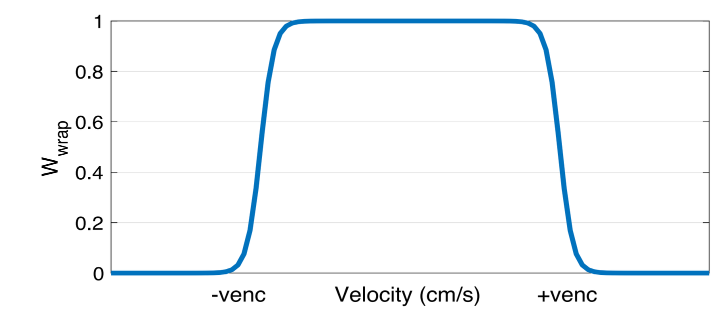
$$\underset{\hat{V}}{\text{minimize}} \sum_{i=1}^{n} ||W_i^{\mathsf{T}}(V_i - \hat{V})||_2^2 + \lambda ||\Psi(\hat{V})||_1$$

$$W_{ij} = w_{\text{SNR}}\, w_{\text{wrap}}$$

- Weights:

$$w_{\text{SNR}} = \frac{\text{SNR}_{ij}}{\text{venc}_i}$$

$$w_{\text{wrap}} = 1 - \text{sigmoid}(|v_{ij}| - \text{venc}_i)$$

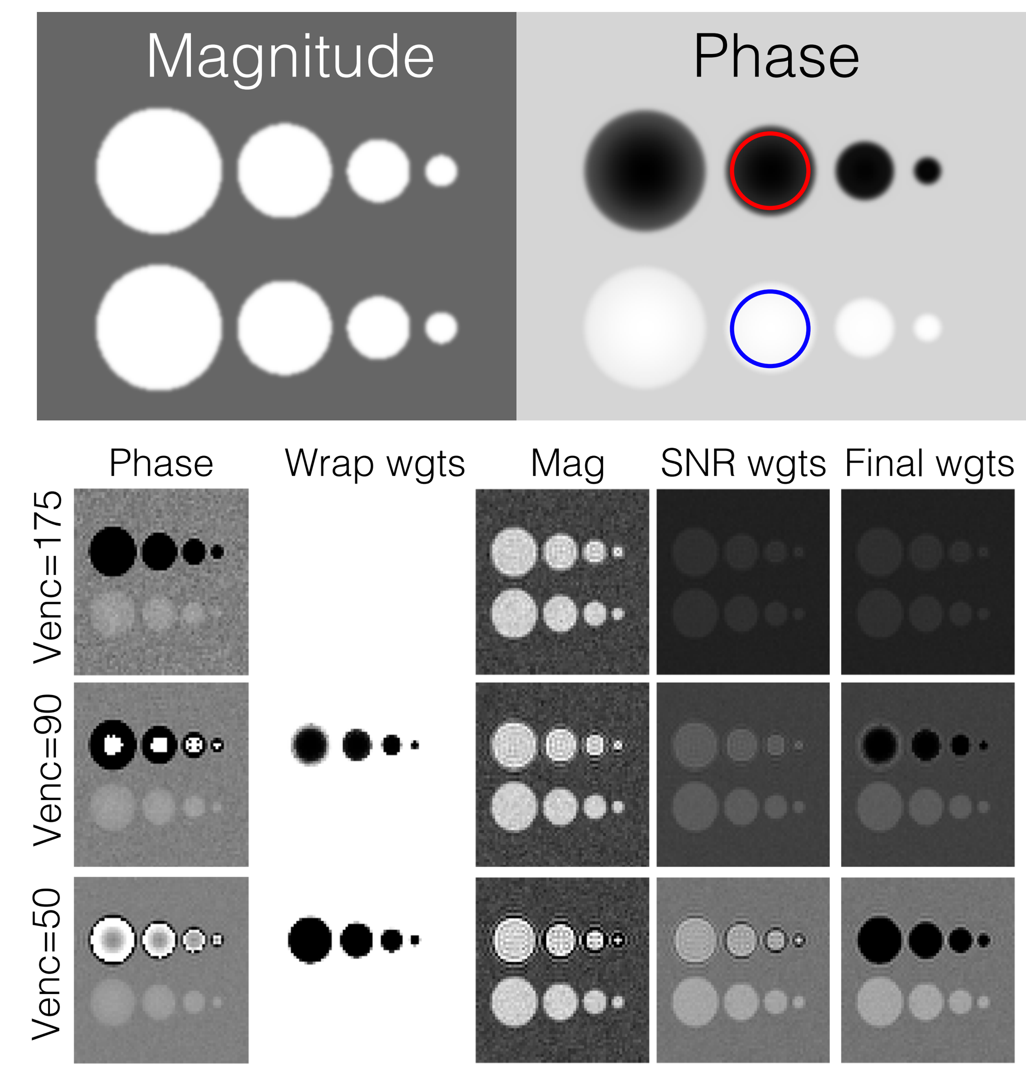


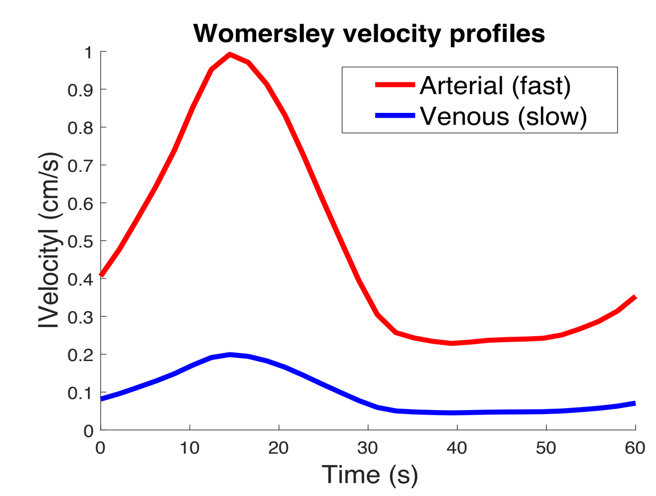
- Flow field priors (smoothness & divergence-free):

$$\Psi_{\text{TV}}(\hat{V}) = \begin{pmatrix} \nabla_x \\ \nabla_y \\ \nabla_z \\ \nabla_t \end{pmatrix} \hat{V} \qquad \Psi_{\text{div}}(\hat{V}) = \begin{pmatrix} \nabla_x & \nabla_y & \nabla_z \end{pmatrix} \begin{pmatrix} \hat{V}_x \\ \hat{V}_y \\ \hat{V}_z \end{pmatrix}$$

- Incorporate priors such as flow smoothness (TV) and divergence (Div) regularization[5] to denoise HDR images

- Synthetic MR flow simulations

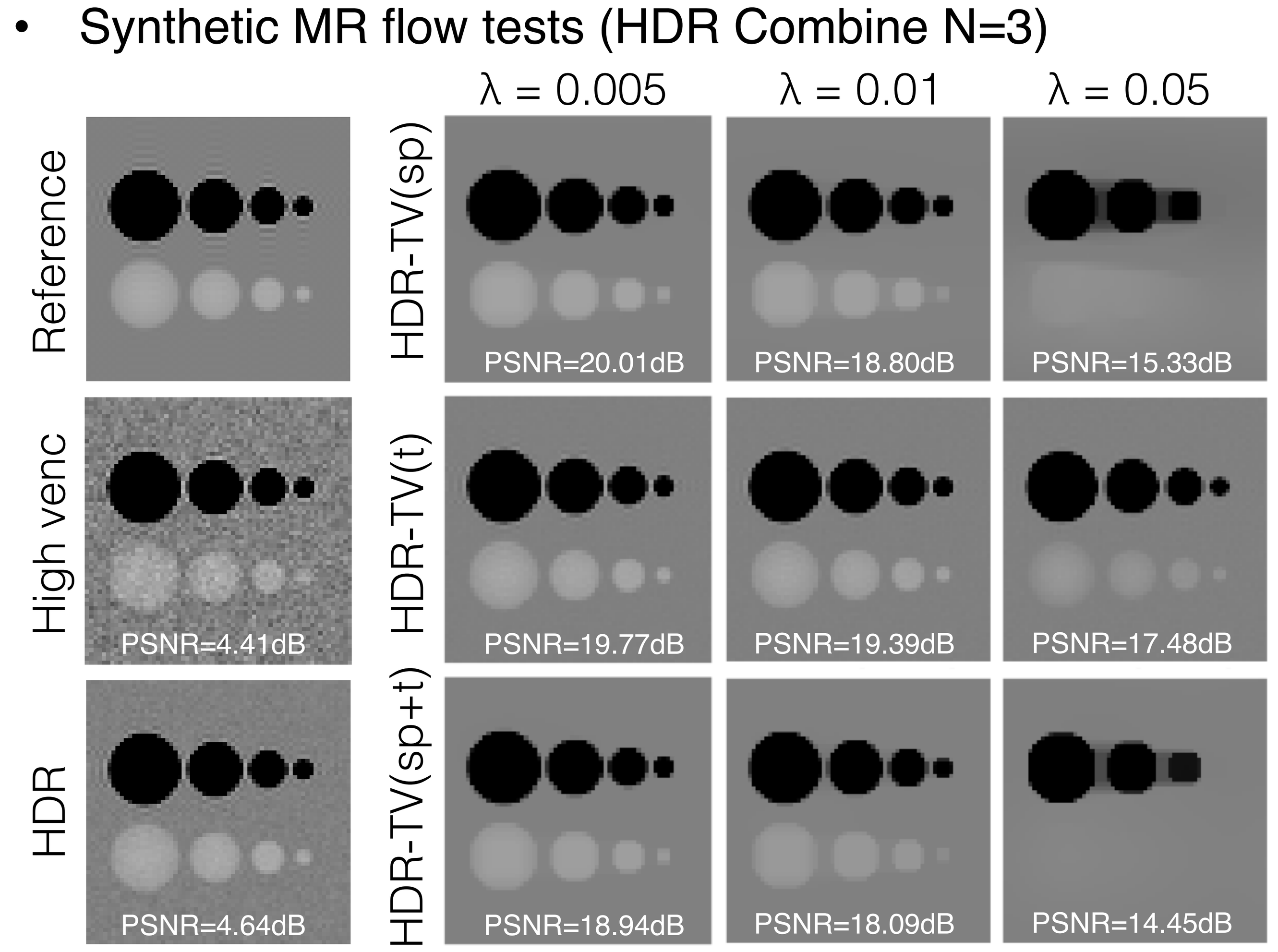




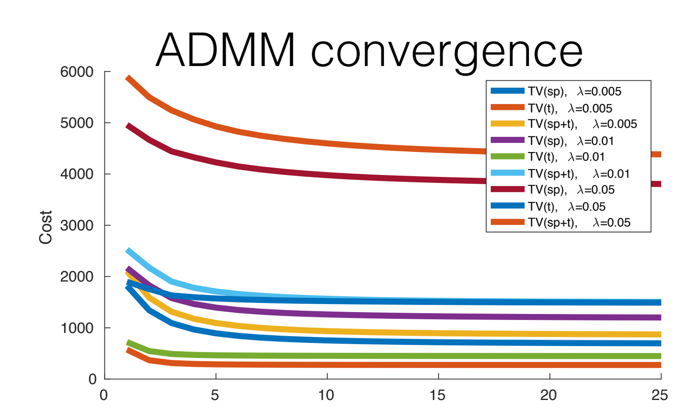
- Complex 4D flow MRI data of ideal arterial (red) and venous (blue) vessels of varying diameters is simulated using computational fluid dynamics model[6] + complex white noise model
- Apply weighted HDR-TV in space (sp), time (t), space+time (sp+t)

Results

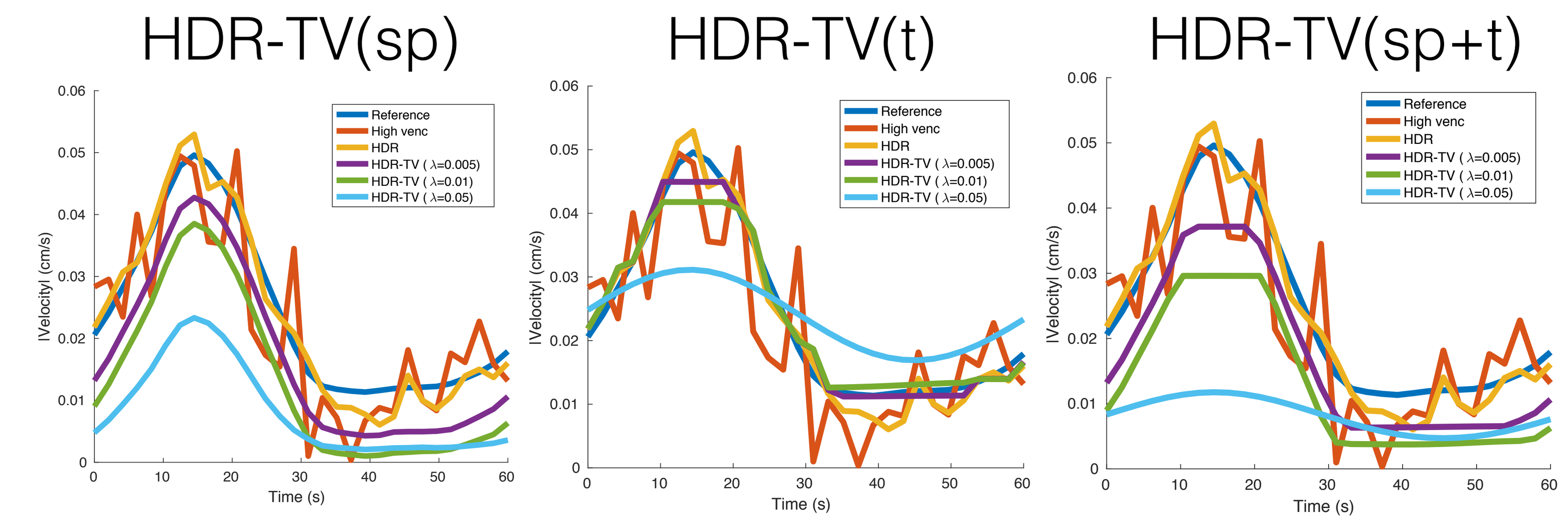
- Synthetic MR flow tests (HDR Combine N=3)



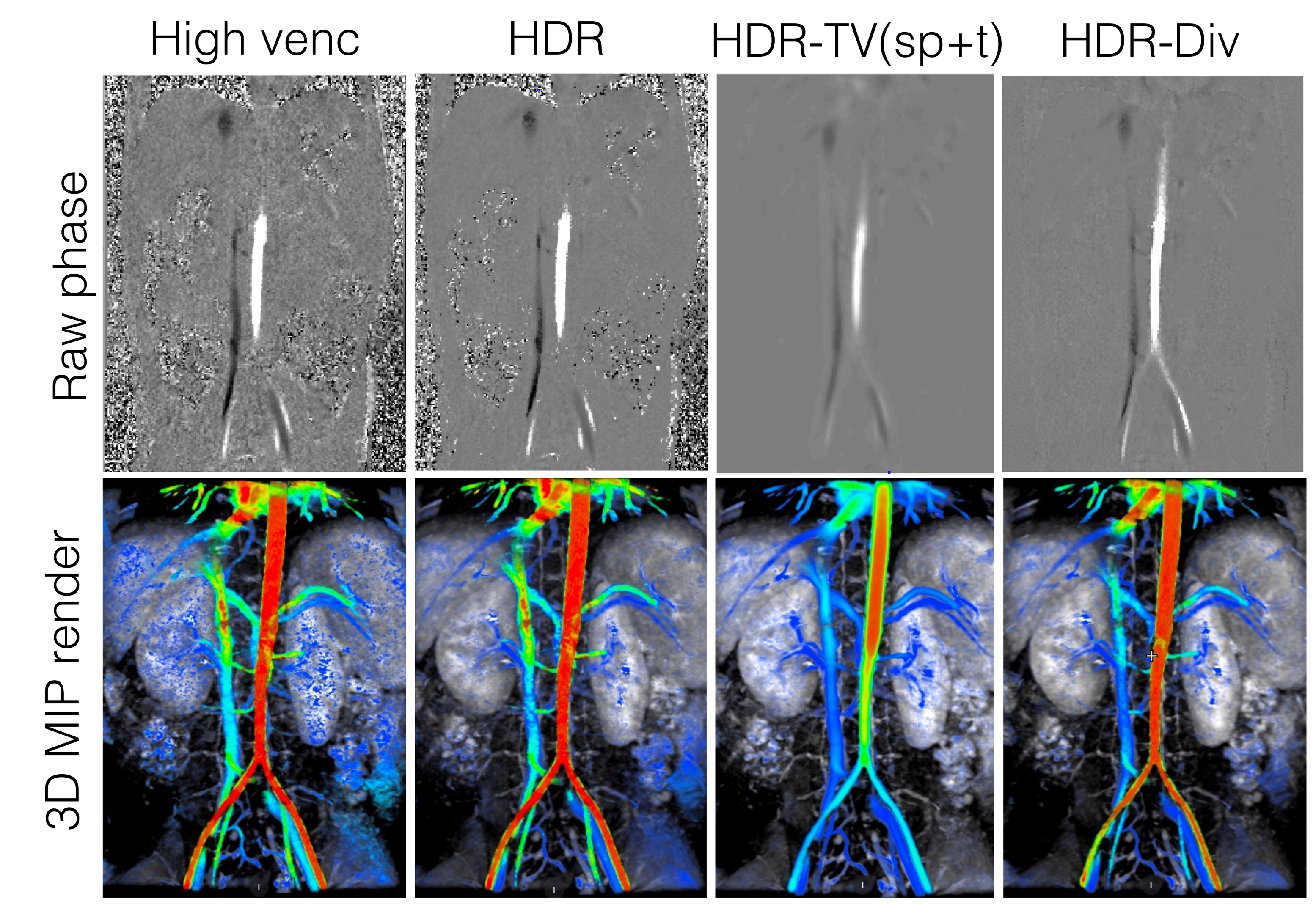
- Spatial TV is best w.r.t. PSNR, but biases global velocity values depending on distribution
- Temporal TV is best w.r.t. velocity quantitation, but biases peak velocity



- Synthetic MR flow tests (venous velocity profiles)



- In-vivo tests (HDR Combine N=2)



Conclusions

- HDR 4D flow allows simultaneous assessment of arterial and venous flow in the abdomen, however, data acquisition theoretically takes twice as long – use HDR and super-resolution approach to accelerate this
- Temporal TV and Divergence-free regularizations are most robust priors for HDR 4D flow data – combine into one cost function
- Further research required to quantify bias from regularization term

References

[1] PE Debevec & J Malik. Recovering high dynamic range radiance maps from photographs. SIGGRAPH 1997.
[2] M Markl, et al. Time-resolved three-dimensional phase-contrast MRI. JMRI 2003.
[3] S Schnell, et al. Accelerated dual-venc 4D flow MRI for neurovascular applications. JMRI 2017.
[4] S Boyd et al. Distributed optimization and statistical learning via the alternationg direction method of multipliers. FTML 2011.
[5] C Santelli et al. Accelerating 4D flow MRI by exploiting vector field divergence regularization. MRM 2016.
[6] JR Womersley. Method for calculation of velocity, rate of flow and viscous drag in arteries. J Physiol 1955.