

Multi-layer Spectral Analysis for Tensor Structure Encoding of 4D Deformation Field Data

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Disclosure

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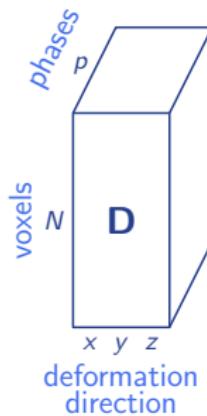
Introduction: respiratory motion modeling

4D-CT (XCAT phantom¹)

showing DVF + registration errors

deformable
registration

deformation vector fields (DVF)



multiple dimensions:

directional

$(D_x, D_y, D_z|t)$



temporal

(i, j, k)

spatial

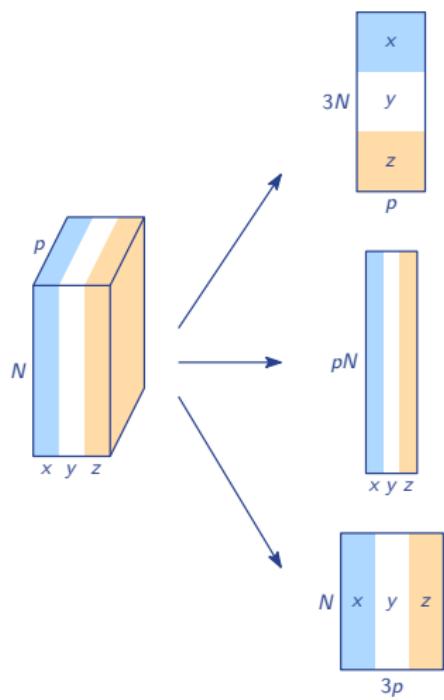
- DVF → patient-specific model of respiratory motion
- applications^{2,3}: reconstruction, registration, prediction, ...

¹Segars et al, *Med Phys*, 2008

²Zhang et al, *Med Phys*, 2013

³Ruan & Keall, *Phys Med Bio*, 2010

Introduction: PCA-based modeling & limitations

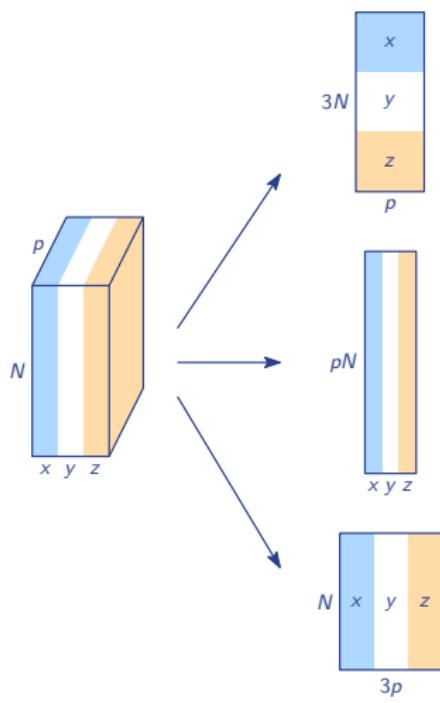


PCA limitations

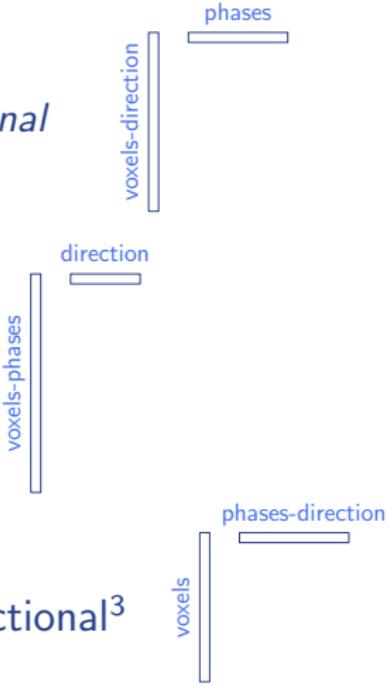
- two-way coupling & analysis
- linear correlations

Introduction: PCA-based modeling & limitations

two-way analysis of DVF motion



- temporal^{1,2}
 - *conventional approach*
- directional
- temporal-directional³



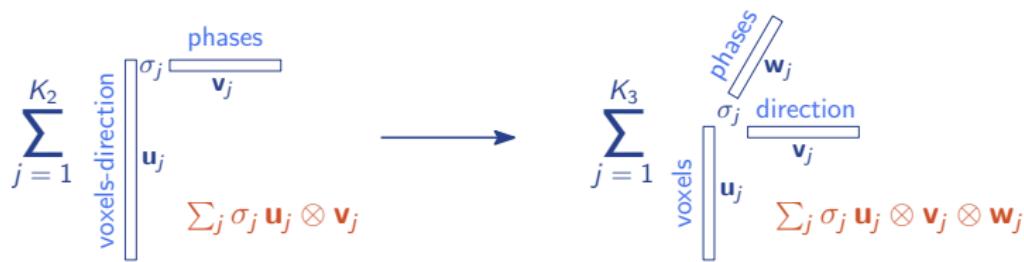
¹Zhang et al, *Med Phys*, 2007

²Li et al, *Phys Med Bio*, 2011

³Ruan & Keall, *Phys Med Bio*, 2010

Purpose: beyond two-way, linear models

- multi-dimensional motion: spatial, directional, temporal
 - linear/non-linear variations¹
- tensor: multi-way extension of two-way relations
 - e.g. voxels \otimes direction \otimes phases



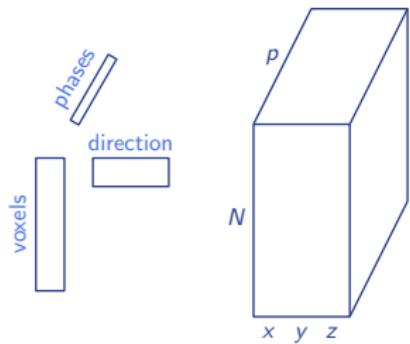
- multi-linear analysis^{2,3}
 - layered two-way spectral approach

¹Boldea et al, *Med Phys*, 2008

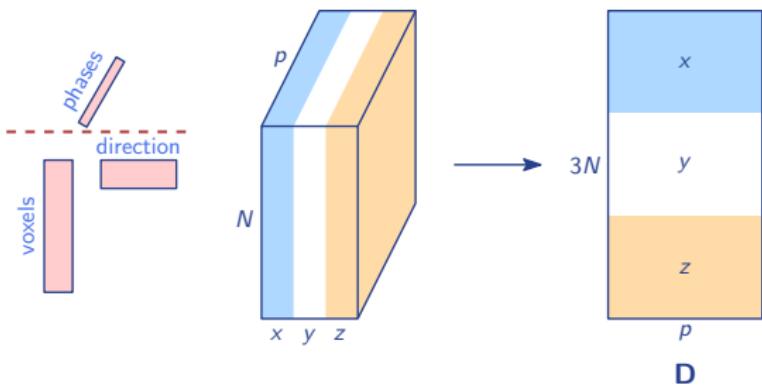
²Tucker, *Contrib Math Psych*, 1964

³Acar & Yener, *IEEE TKDE*, 2008

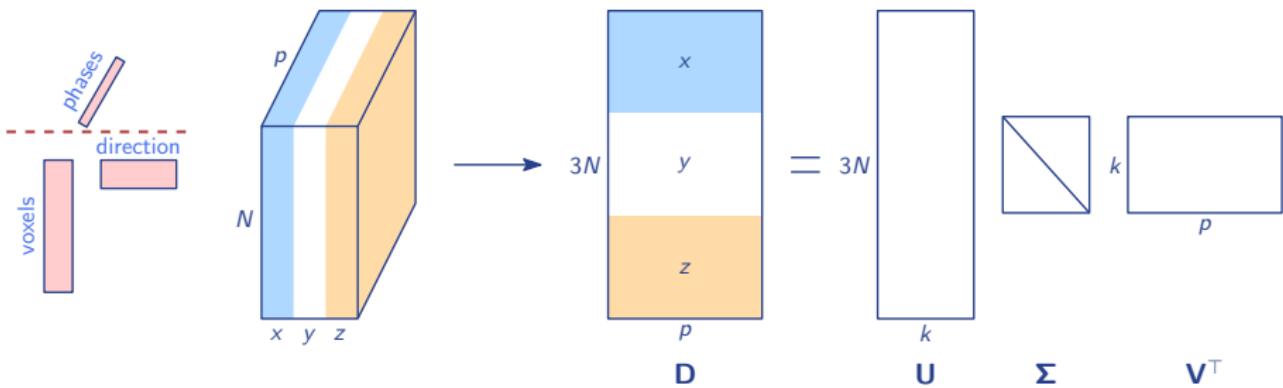
Layered method: components & sub-components



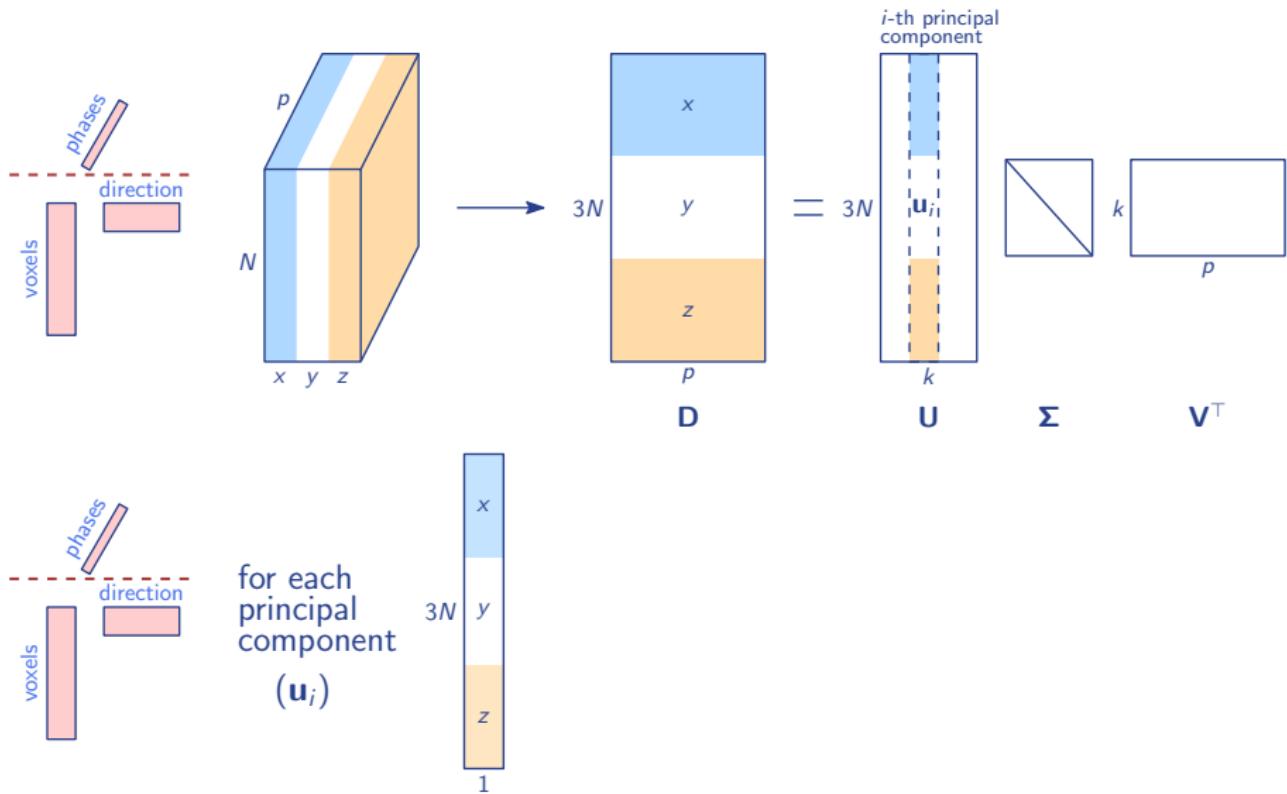
Layered method: components & sub-components



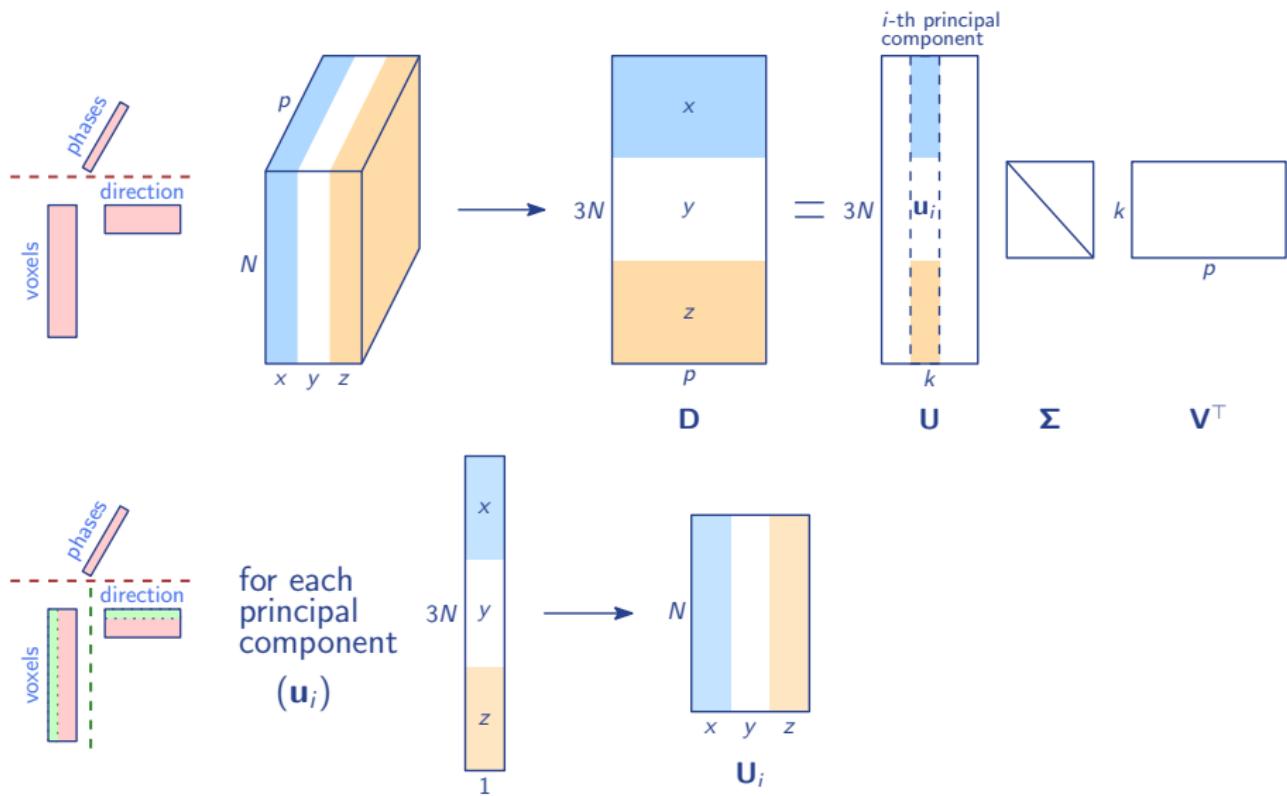
Layered method: components & sub-components



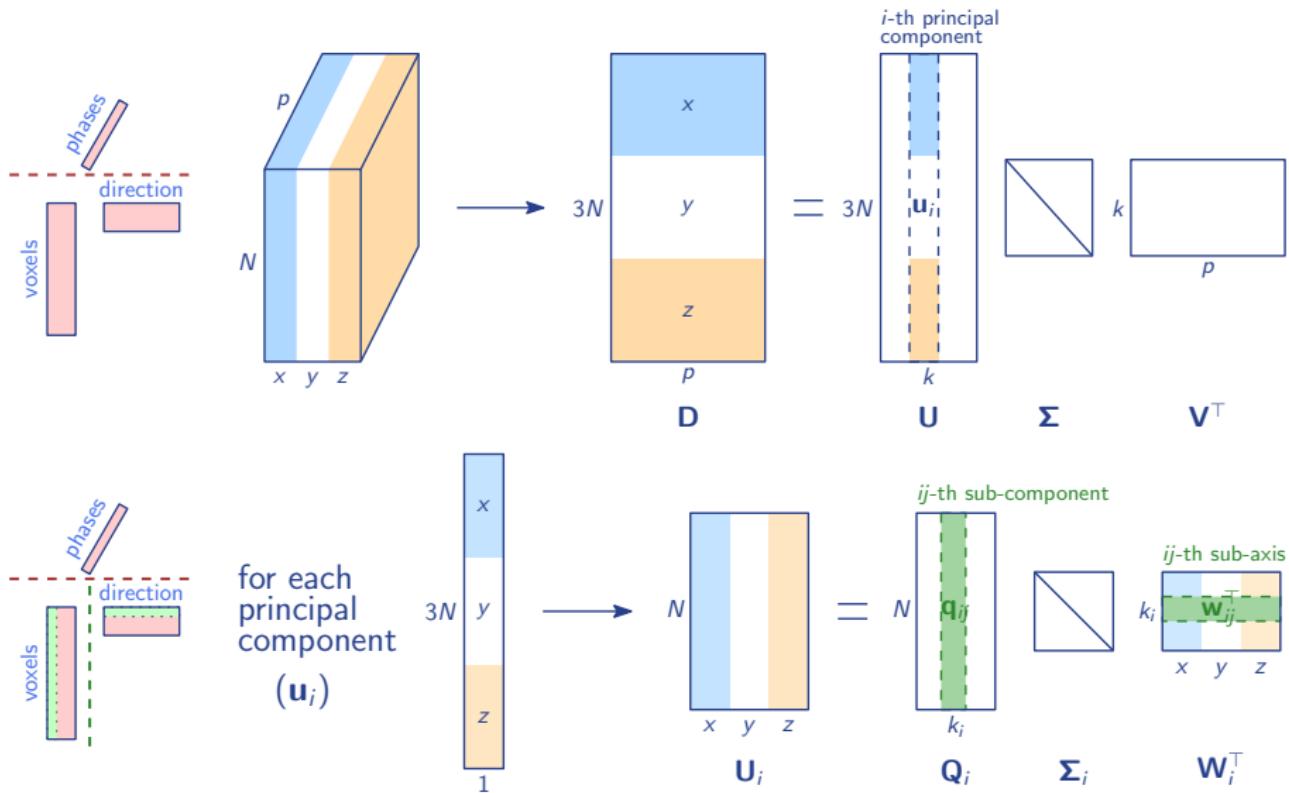
Layered method: components & sub-components



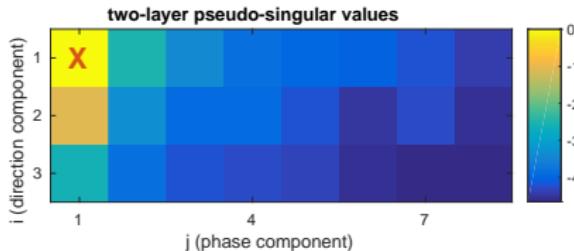
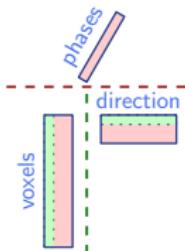
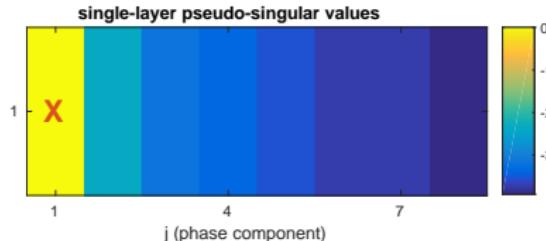
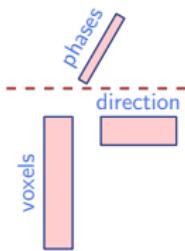
Layered method: components & sub-components



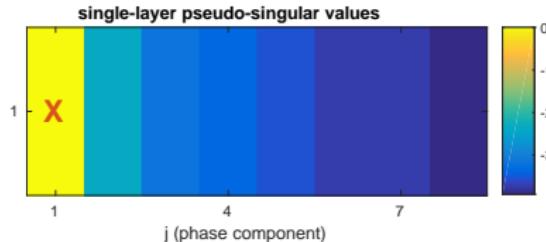
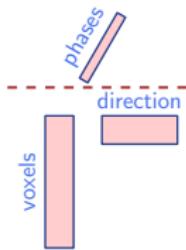
Layered method: components & sub-components



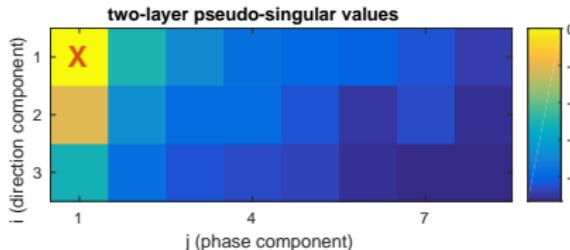
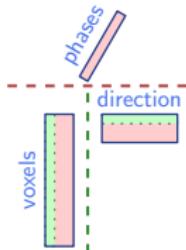
Layered method: components & sub-components



Layered method: components & sub-components

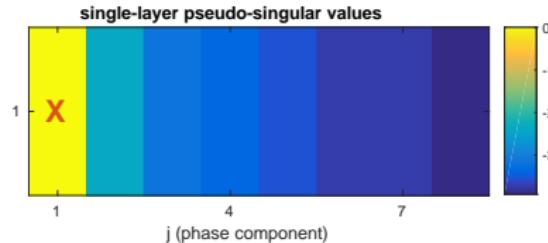
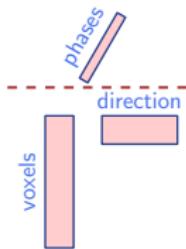


captured variance: 92.3%

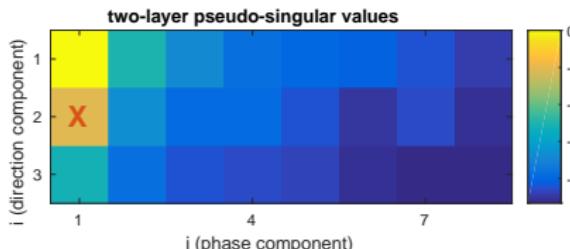
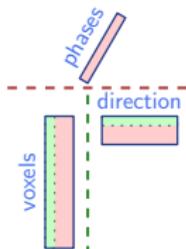


captured variance: 73.6%

Layered method: components & sub-components

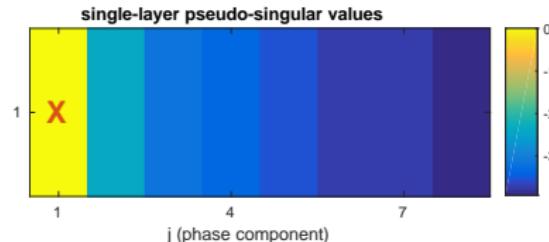
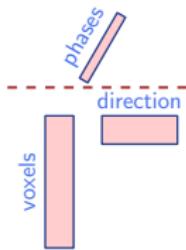


captured variance: 92.3%

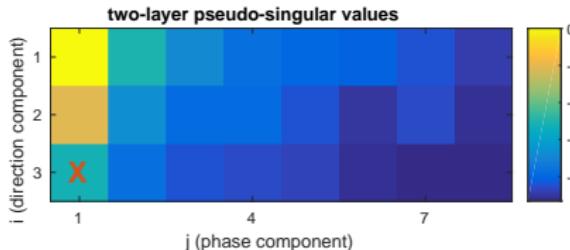
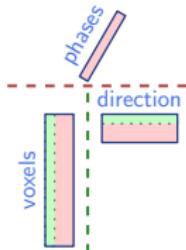


captured variance: 16.7%

Layered method: components & sub-components

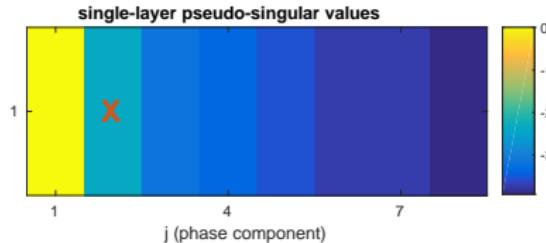
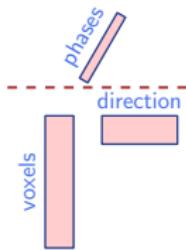


captured variance: 92.3%

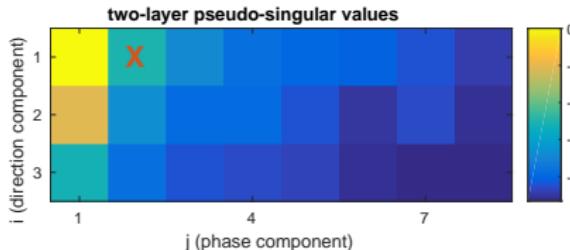
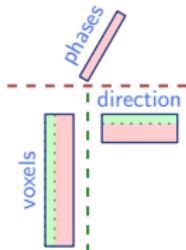


captured variance: 2.0%

Layered method: components & sub-components

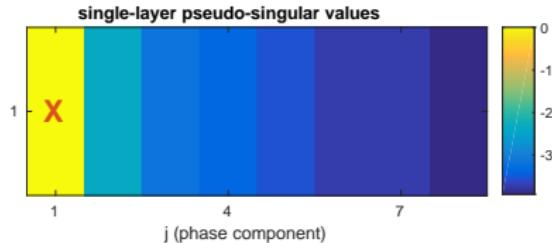
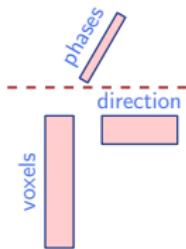


captured variance: 3.5%

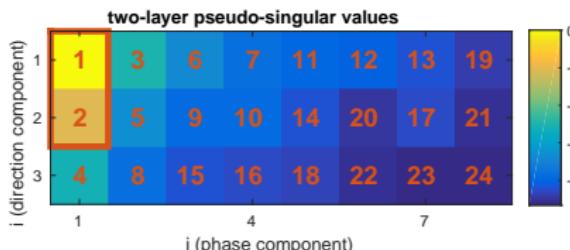
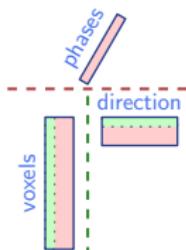


captured variance: 2.4%

Layered method: components & sub-components

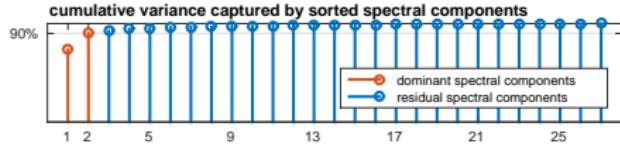
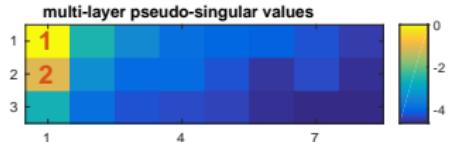
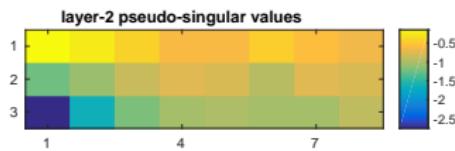
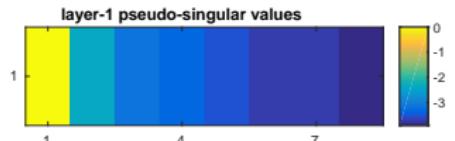
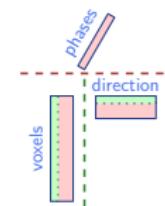


captured variance: 92.3%

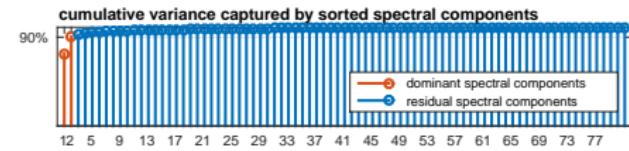
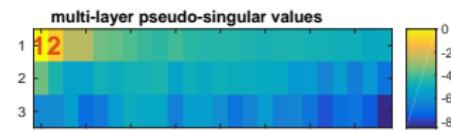
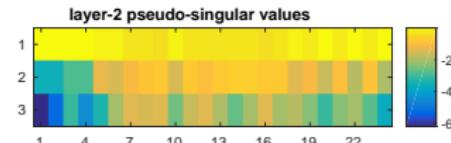
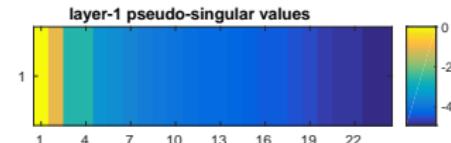
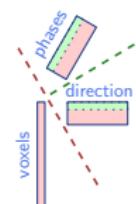
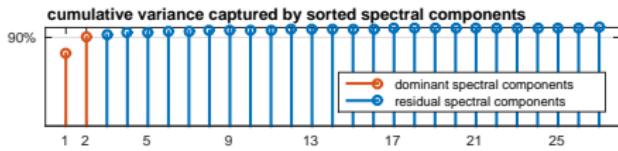
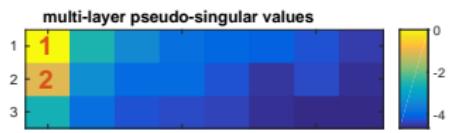
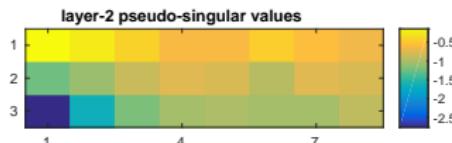
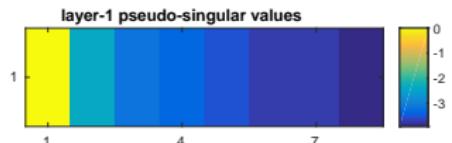
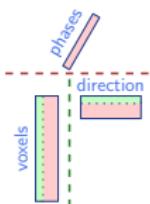


captured variance: 90.3%

XCAT 4D-DVF: dominant spectral components

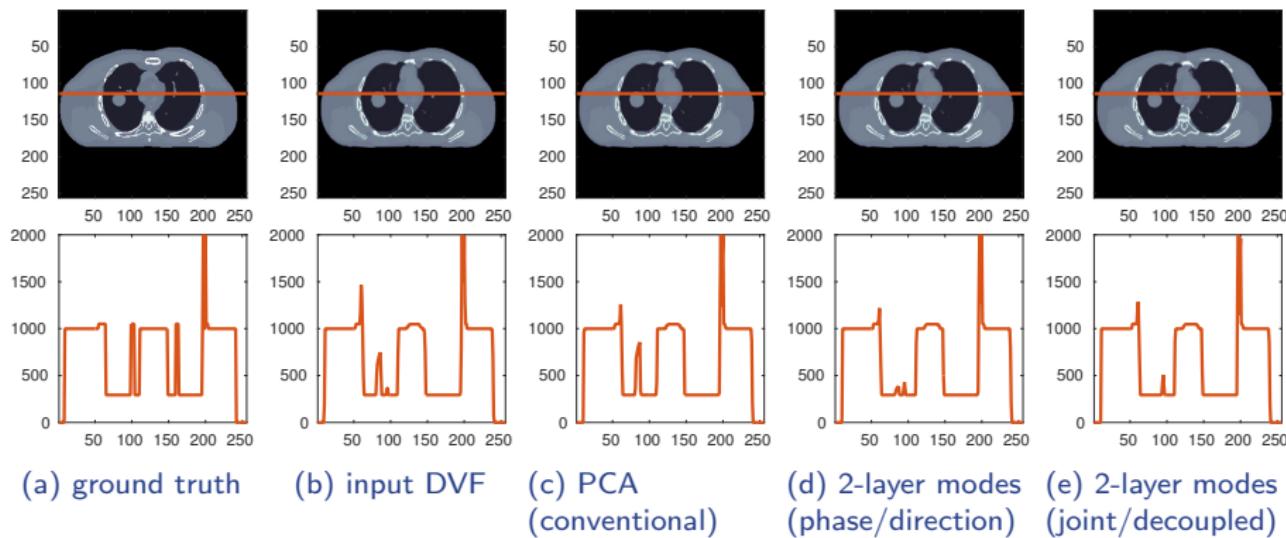


XCAT 4D-DVF: dominant spectral components



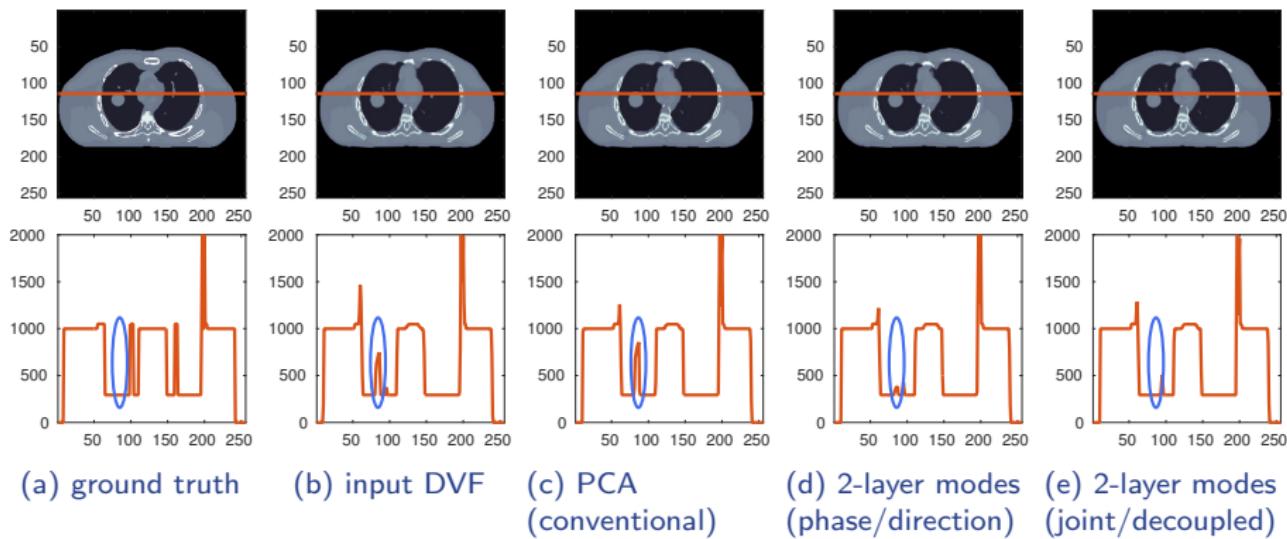
Early test: XCAT 4D-DVF motion

- DVF motion recovery: phase 0 (EE) → phase 5 (EI)
 - motion representation
 - registration denoising



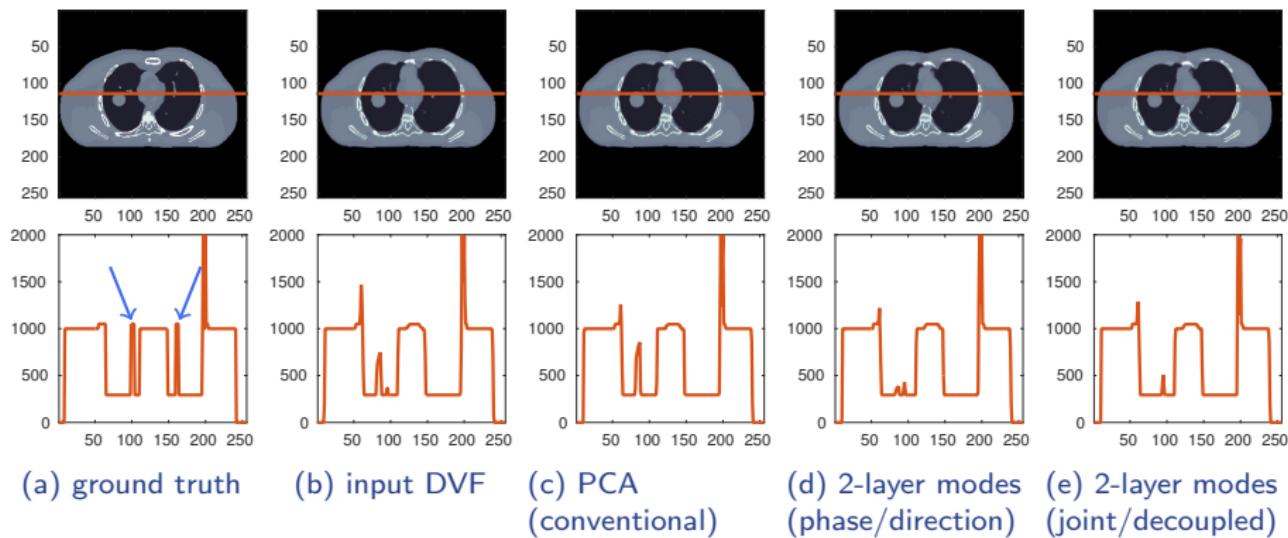
Early test: XCAT 4D-DVF motion

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Early test: XCAT 4D-DVF motion

- DVF motion recovery: phase 0 (EE) → phase 5 (EI)
 - motion representation
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Conclusion

- multi-linear analysis of multi-dimensional DVF data
 - beyond 3-way, e.g. multiple respiratory cycles
- systematic, layered approach
 - successively decoupled dimensions
 - fine control over component selection
- potential impact
 - motion modeling, deformable registration, tracking
 - *experimentation in progress*

Thank you!

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References I

- [1] E. Acar and B. Yener. Unsupervised multiway data analysis: a literature survey. *IEEE Transactions on Knowledge and Data Engineering*, 21(1):6–20, Jan. 2009.
- [2] V. Boldea, G. C. Sharp, S. B. Jiang, and D. Sarrut. 4d-CT lung motion estimation with deformable registration: quantification of motion nonlinearity and hysteresis. *Medical Physics*, 35(3):1008–1018, 2008.
- [3] J. Eom, X. G. Xu, S. De, and C. Shi. Predictive modeling of lung motion over the entire respiratory cycle using measured pressure-volume data, 4dct images, and finite-element analysis. *Medical Physics*, 37(8):4389, 2010.
- [4] H. Gao, J.-F. Cai, Z. Shen, and H. Zhao. Robust principal component analysis-based four-dimensional computed tomography. *Physics in Medicine and Biology*, 56(11):3181–3198, June 2011.
- [5] R. Li, J. H. Lewis, X. Jia, T. Zhao, W. Liu, S. Wuenschel, J. Lamb, D. Yang, D. A. Low, and S. B. Jiang. On a PCA-based lung motion model. *Physics in Medicine and Biology*, 56(18):6009–6030, Sept. 2011.

References II

- [6] D. Ruan and P. Keall. Online prediction of respiratory motion: multidimensional processing with low-dimensional feature learning. *Physics in Medicine and Biology*, 55(11):3011–3025, June 2010.
- [7] W. P. Segars, M. Mahesh, T. J. Beck, E. C. Frey, and B. M. W. Tsui. Realistic CT simulation using the 4d XCAT phantom. *Medical Physics*, 35(8):3800, 2008.
- [8] D. Staub, A. Docef, R. S. Brock, C. Vaman, and M. J. Murphy. 4d Cone-beam CT reconstruction using a motion model based on principal component analysis. *Medical Physics*, 38(12):6697–6709, Dec. 2011.
- [9] Y. Suh, S. Dieterich, B. Cho, and P. J. Keall. An analysis of thoracic and abdominal tumour motion for stereotactic body radiotherapy patients. *Physics in Medicine and Biology*, 53(13):3623–3640, July 2008.
- [10] L. R. Tucker. The extension of factor analysis to three-dimensional matrices. In *Contributions to Mathematical Psychology*, pages 110–182. Holt, Rinehard and Wilson, New York, NY, USA, 1964.

References III

- [11] Q. Zhang, Y.-C. Hu, F. Liu, K. Goodman, K. E. Rosenzweig, and G. S. Mageras. Correction of motion artifacts in cone-beam CT using a patient-specific respiratory motion model. *Medical Physics*, 37(6):2901–2909, June 2010.
- [12] Y. Zhang, F.-F. Yin, W. P. Segars, and L. Ren. A technique for estimating 4D-CBCT using prior knowledge and limited-angle projections. *Medical Physics*, 40(12):121701, Nov. 2013.