Motion Compensation for 4D Digital Subtraction Angiography via Deep Autofocus and Implicit Neural Model

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Acknowledgments

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Adham Khalil (Johns Hopkins Radiology)

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Digital Subtraction Angiography (DSA)

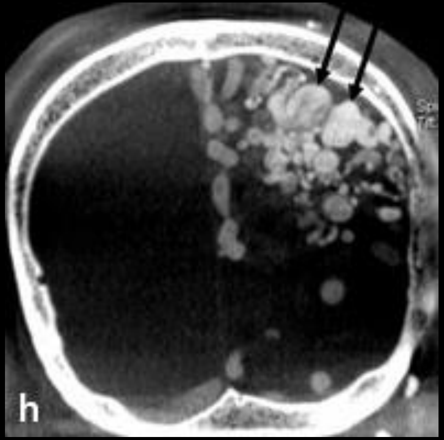
3D-DSA in Interventional Neuroradiology

<u>Critical to diagnosis and guidance of treatment</u>

- Subarachnoid hemorrhage (>27k per year in the US [1])
- Stroke (over 101 million worldwide [2])
- Arterial Vascular Malformation (AVM)

Relies on 2D-DSA for temporal information

→ Limited by vessel overlap [3]



DSA of Venous Aneurysm [7]

From 3D to 4D-DSA [4]

<u>Time-resolved 3D-DSA sequence</u>

- Volumetric visualization + flow quantification
- Complements 3D-DSA
    - Diagnosis of AVMs [5]
    - Treatment of Intracranial Aneurysms [6]

4D-DSA Flow Estimation [7]

[1] J. Brisman, et al, New England Journal of Medicine, 2006.
[2] Wolfe, C. D. A. The impact of stroke. Br Med Bull, 2000
[3] K.L. Ruedinger, et al, AJNR, 2021
[4] B.J. Davis, Implementation and Evaluation of 4D-DSA, 2023
[5] C. Sandoval-Garcia, et al,. AJNR, 2017
[6] K.L. Ruedinger, et al, AJNR, 2018
[7] C. Wu, et al. Clin Neuroradiol, 2015

Challenges to DSA Image Quality - Motion

3D/4D DSA Requirements

<u>Spatial alignment (Mask + Contrast)</u>

- No intra-scan inconsistent artifacts
- Perfect spatial registration

Challenges from Motion

Prevalent source of artifacts in 4D-DSA [1]

>82% CBCT (~6% severe) [2]

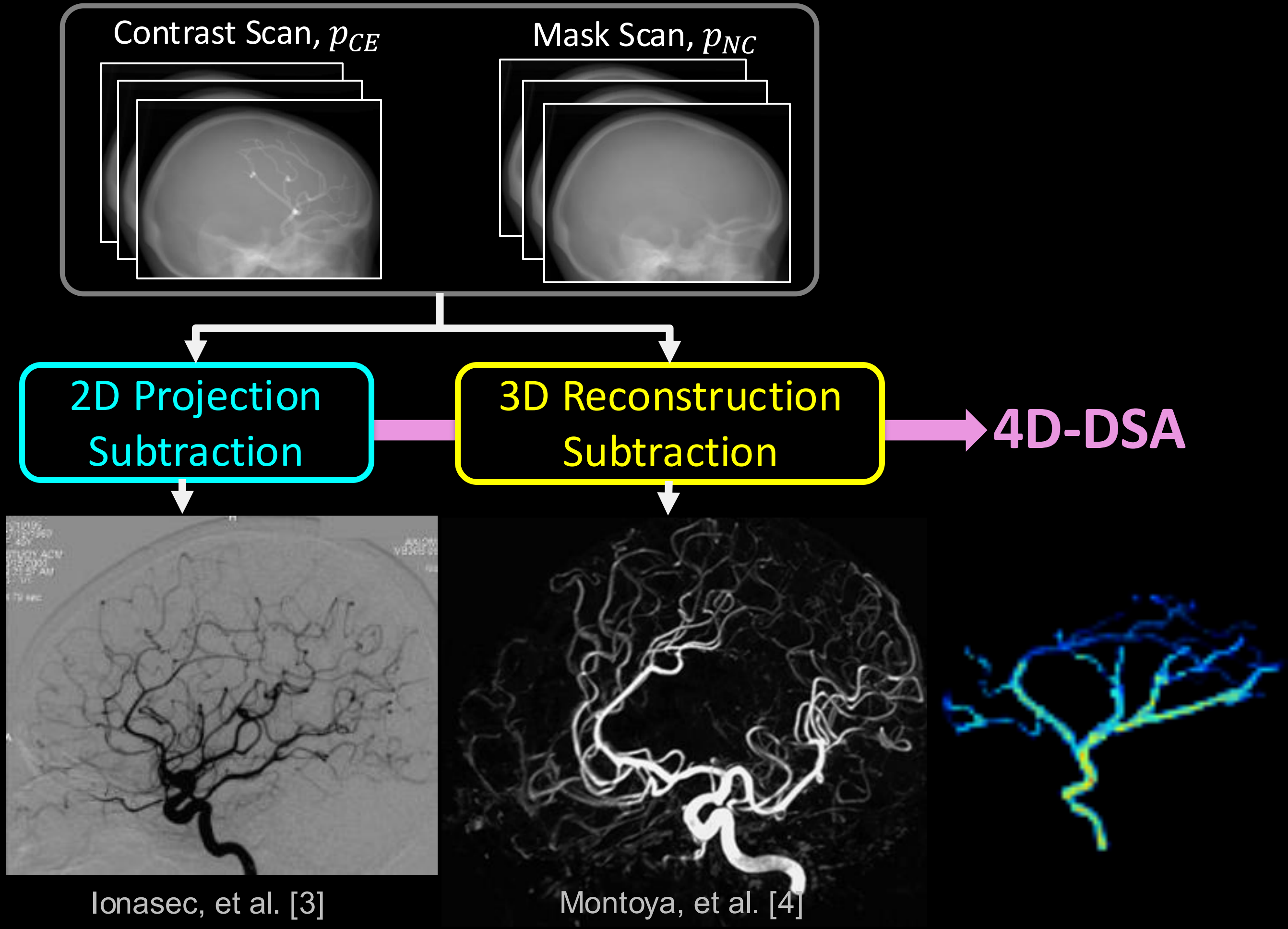
<u>Moderate acquisition time (4-20 s)</u>

- Intra-scan patient motion (trajectory)

<u>Two independent scans</u>

- Inter-scan misalignment (global pose)

→ Joint estimation of intra and inter-scan motion



[1] P.F. Samp, et al, ANJR. 2023
[2] R. Spin-Neto, A. Wenzel, Oral Surgery, Oral Medicine, 2016
[3] R.I. Ionasec, et al. *Computerized Medical Imaging and Graphics*, 33(4), 256, 2009
[4] J. Montoya, et al. *American Journal of Neuroradiology*, 39(5), 916, 2018

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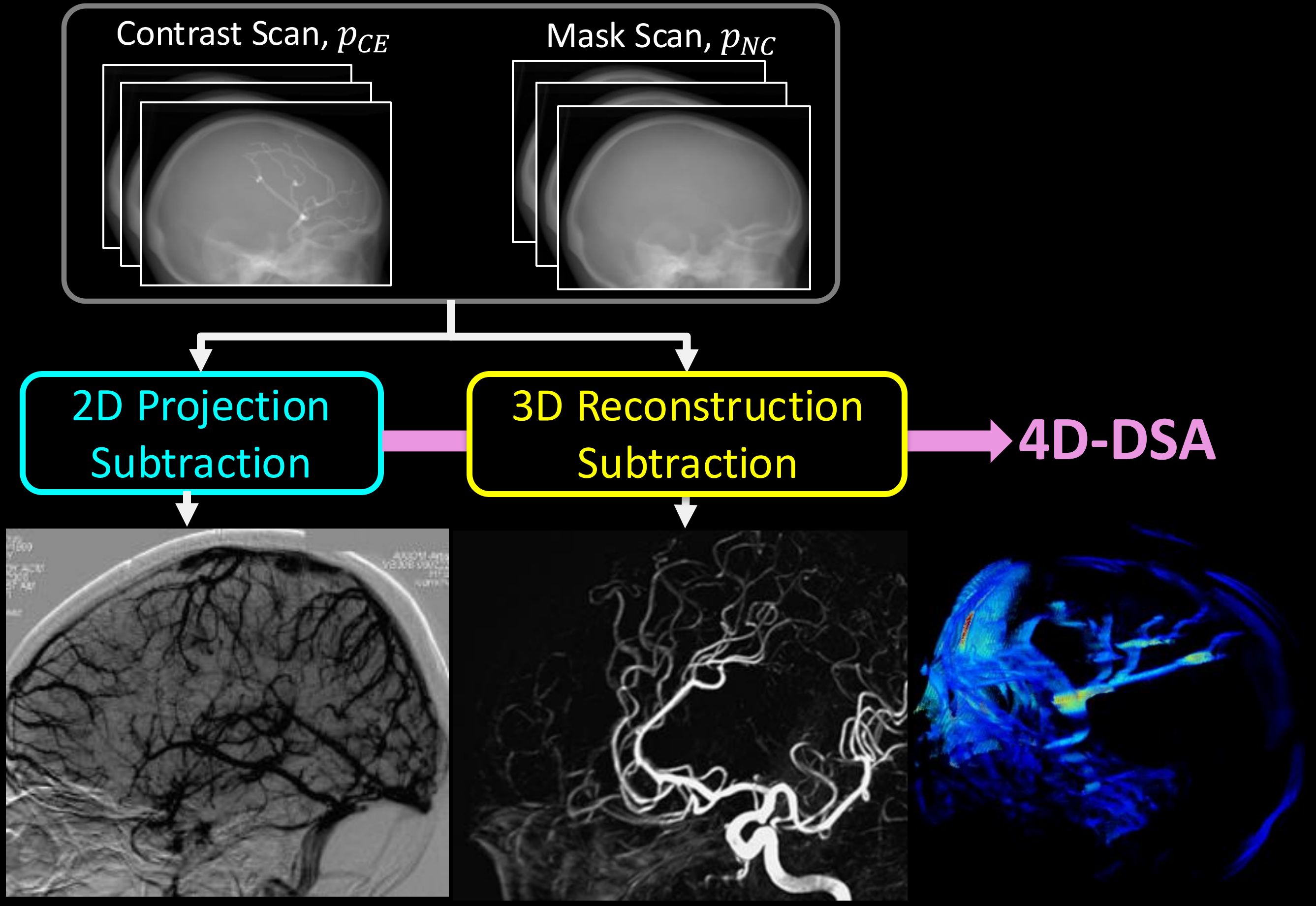

Ionasec, et al. [3] Montoya, et al. [4]

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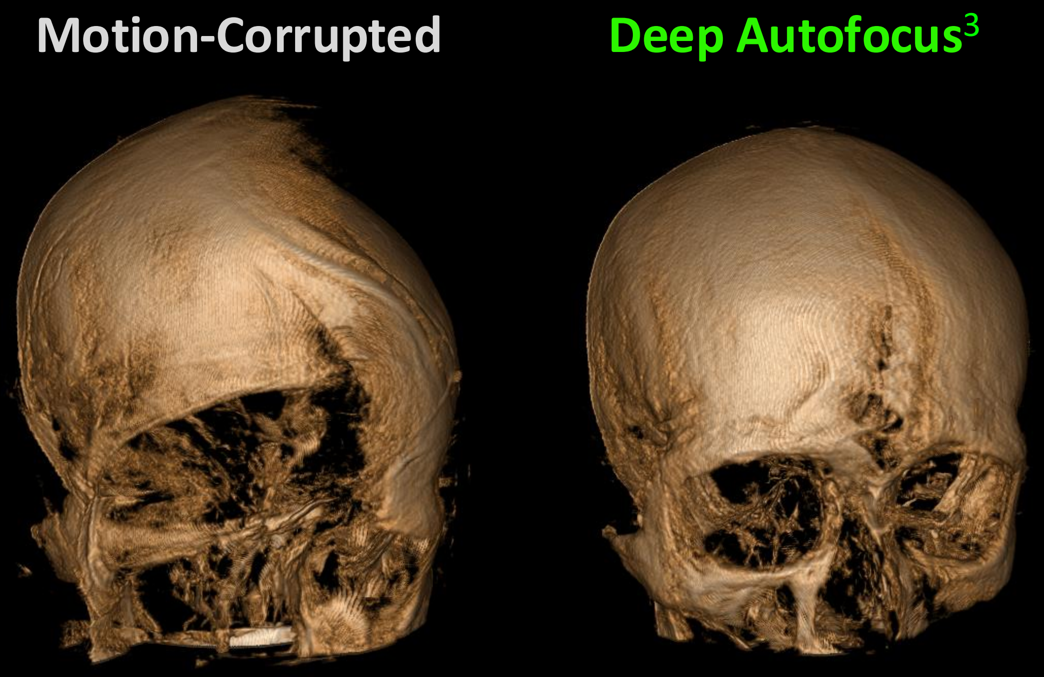
Deep Autofocus in Interventional CBCT

Motion Compensation in CBCT

Immobilization and breath-holding → Not sufficient
Fiducial markers → Fit poorly with interventional workflow
Gating → Difficult for long scan - only one motion source
Tracking of prior image → Prior unavailable

Deep Autofocus Motion Compensation

Rigid motion compensation[1,2,3] (extremity, brain/head)
Deformable motion compensation (abdomen) [4]
Learned deep autofocus metric
    Anatomy-aware learned metrics [5]
Adaptive Motion Models[6,7]
→ Applicable to 4-DSA



[1] J. Hahn, et al. *Med. Phys.* 44(11), 5795-5813, 2017.
[2] A. Sisniega, et al. *Phys. Med. Biol.* 62(9), 3712–3734, 2017
[3] H Huang et al 2022 Phys. Med. Biol. 67 125020
[4] S. Capostagno, et al. *Physics in Medicine and Biology*, 2020
[5] H Huang, et al. Medical Physics, 2024
[6] H Huang, et al., SPIE Medical Imaging, 2023
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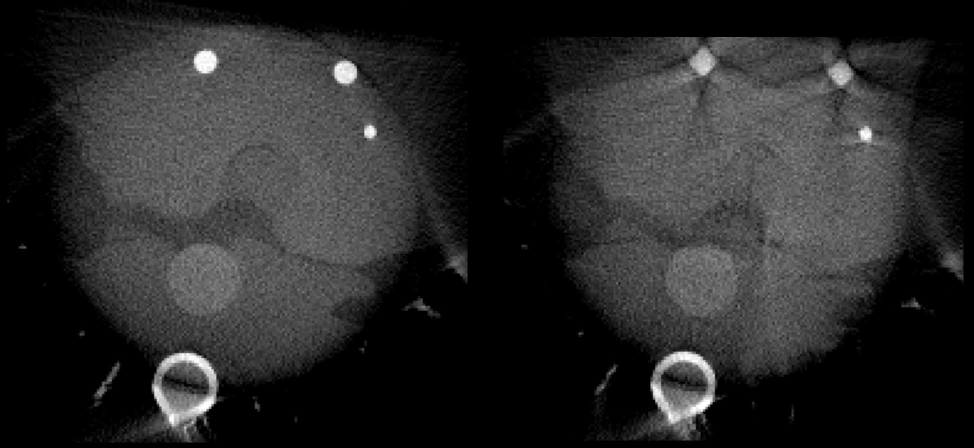

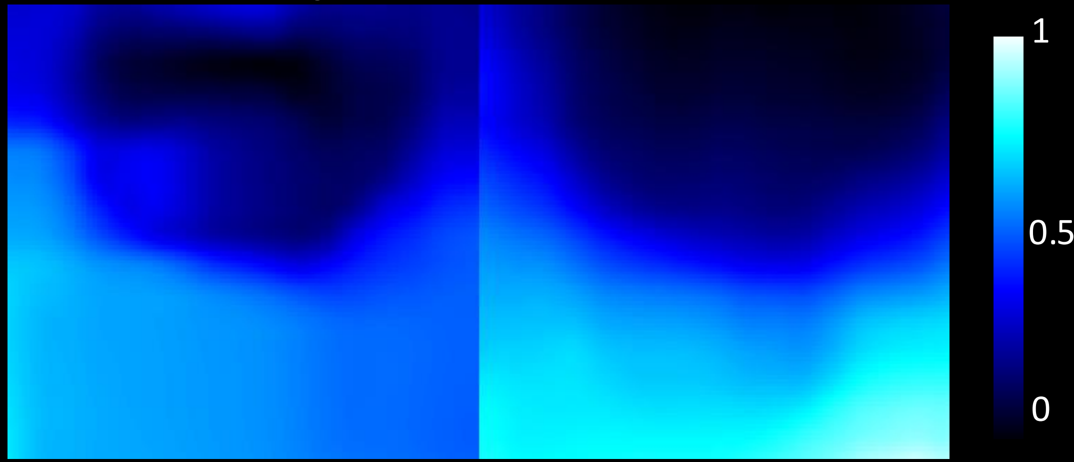

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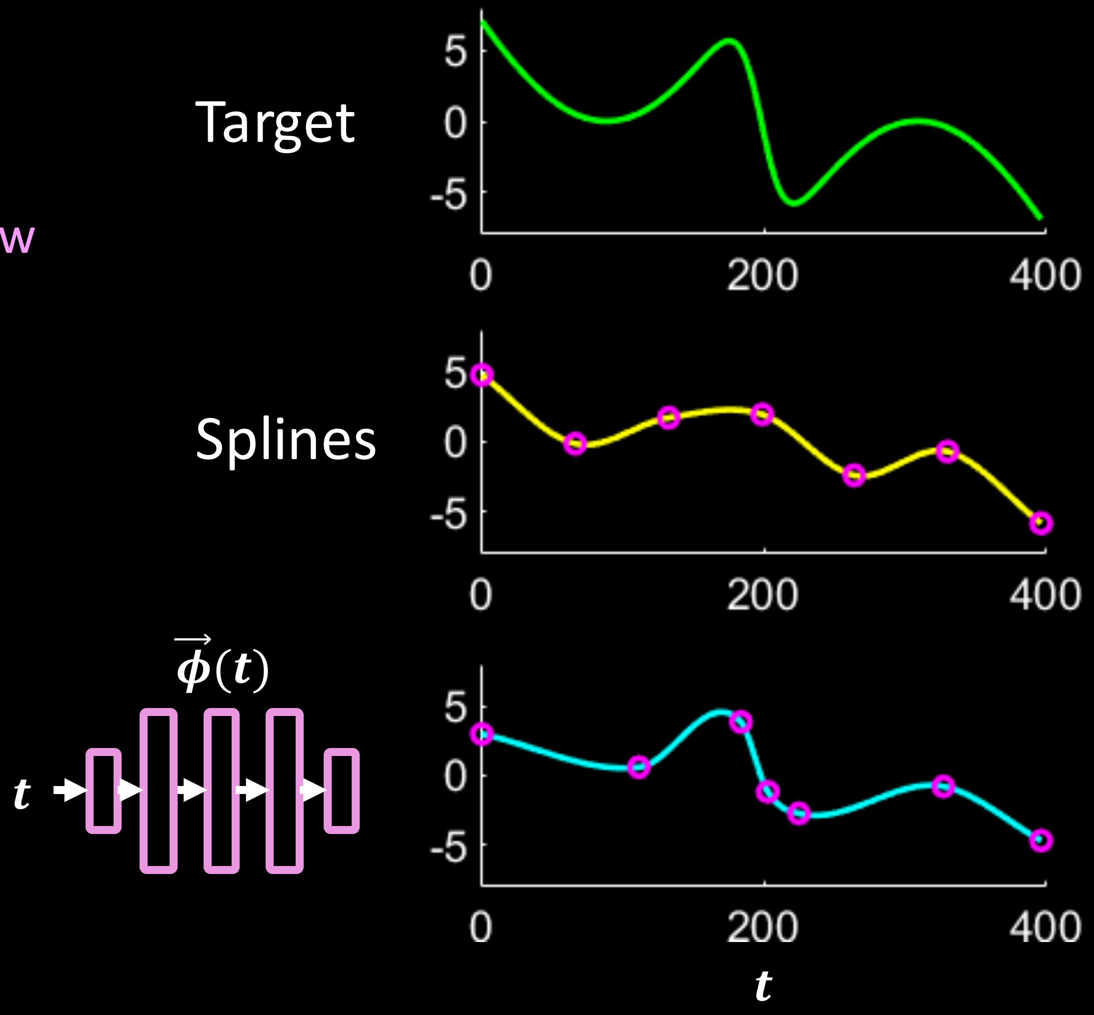

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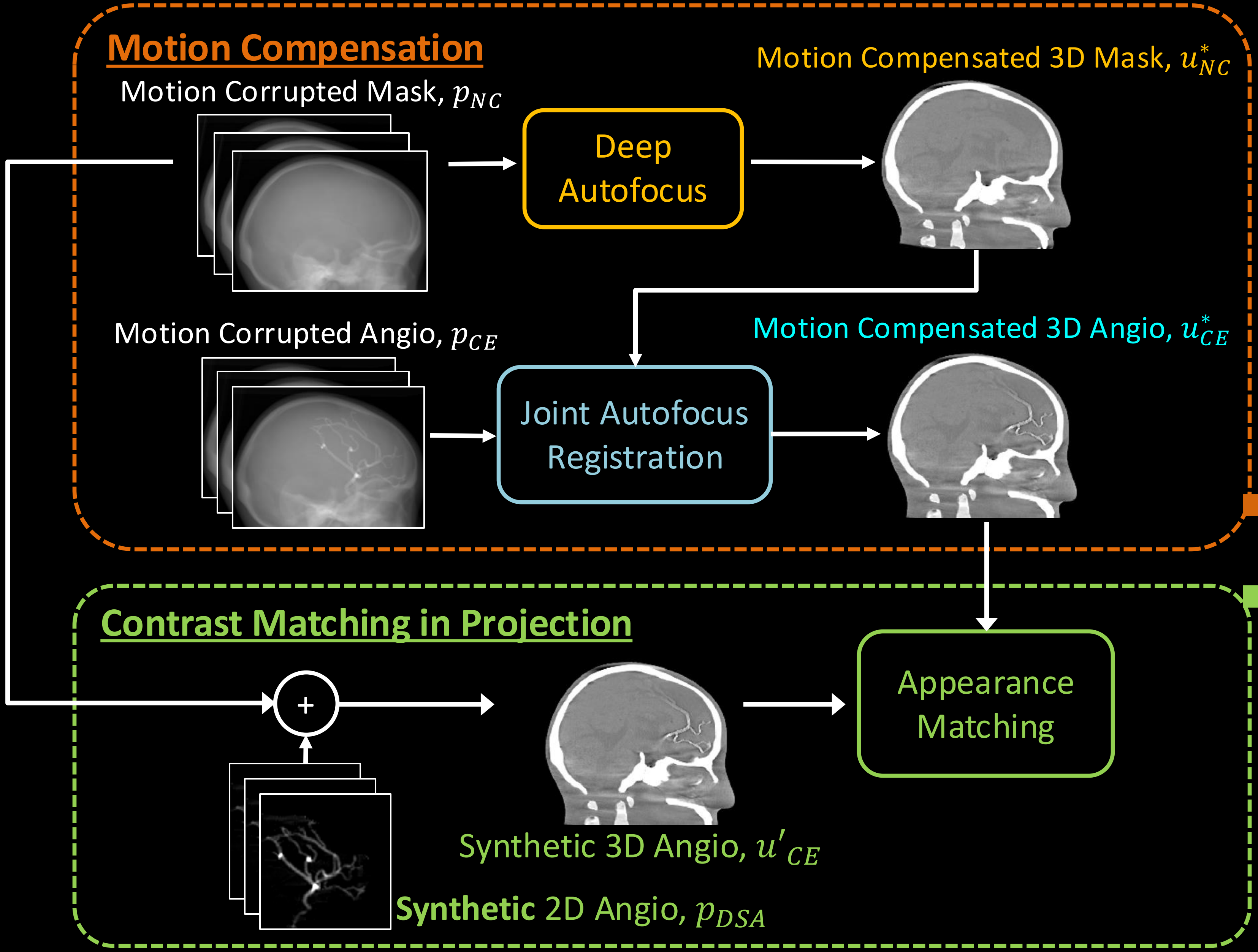
Framework for Motion Compensated 4D-DSA



Mask: Intra-Scan motion
- Rigid deep autofocus

Angio: Intra- and Inter-Scan Motion
- Joint autofocus and registration

→ Motion-Compensated 3D-DSA

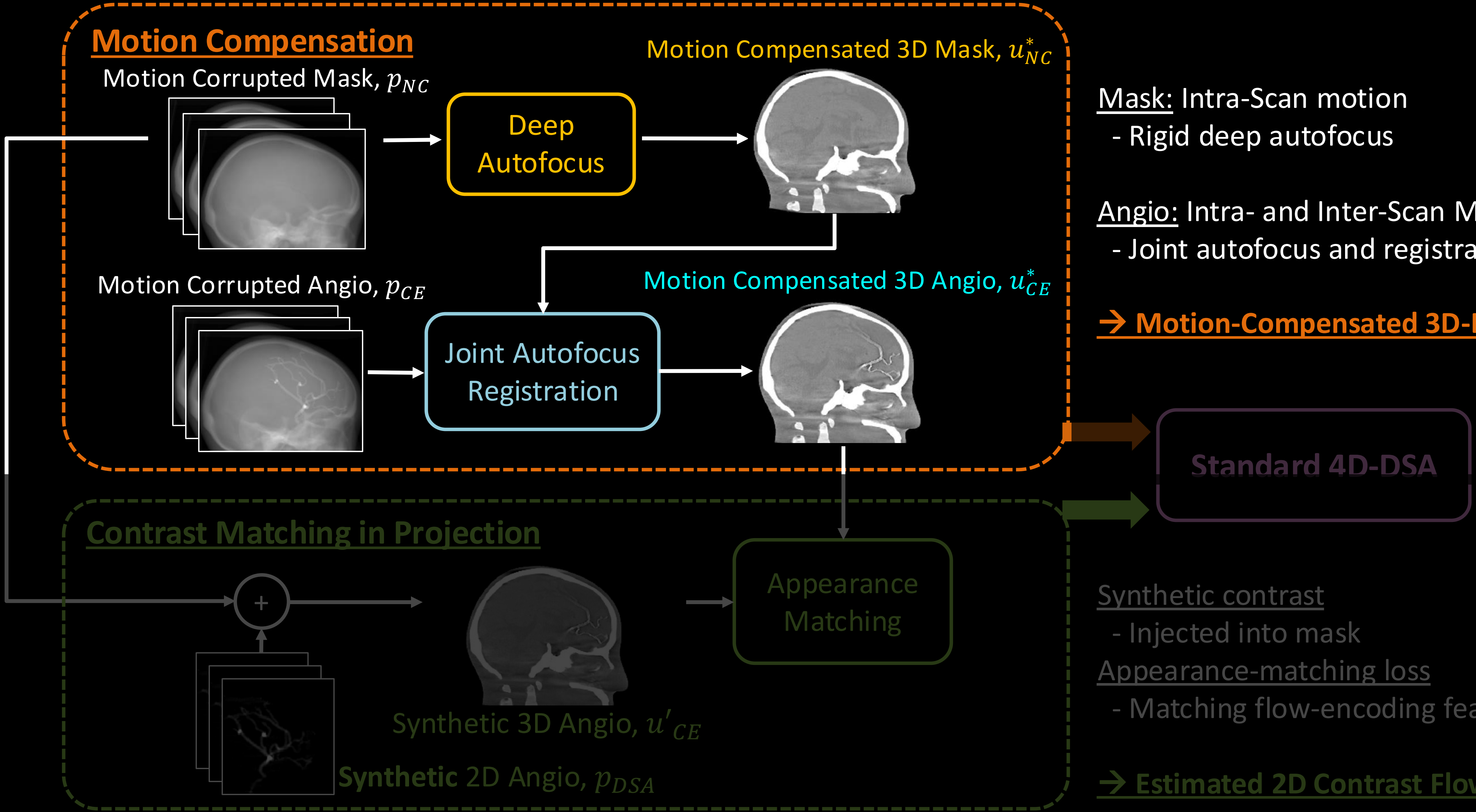
Standard 4D-DSA

Synthetic contrast
- Injected into mask

Appearance-matching loss
- Matching flow-encoding features

→ Estimated 2D Contrast Flow

Framework for Motion Compensated 4D-DSA



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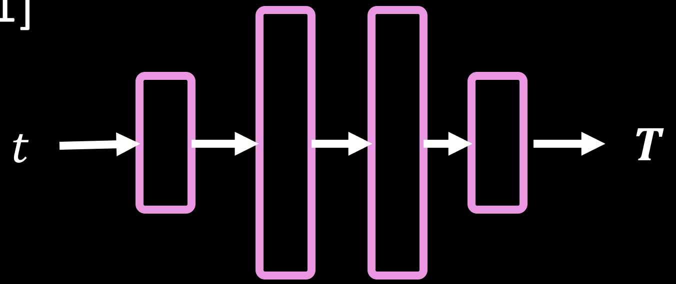
Intra-Scan Motion in Mask: Deep Autofocus

Deep Autofocus

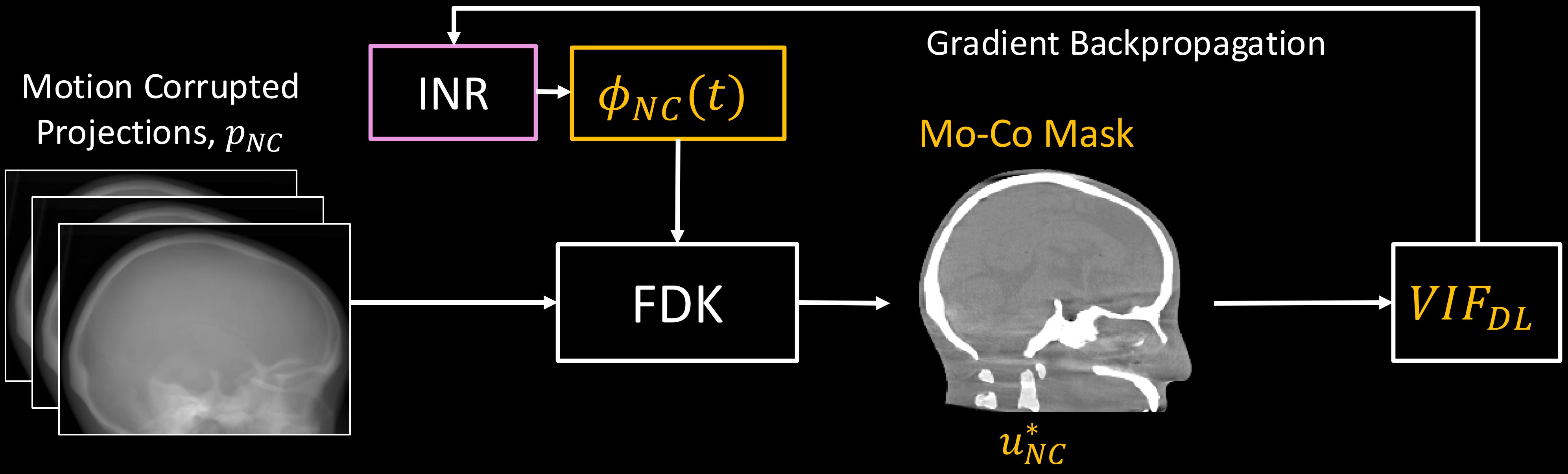
- Anatomy-aware learned metric VIF_{DL} [1]
- Differentiable motion model
  - Implicit Neural Representation (INR)
- Gradient-based optimization [2]

$T = \phi(t): \mathbb{R}^1 \mapsto \mathbb{R}^6$



Motion-Encoding INR

- Continuous function approximator
- $\boldsymbol{T} = \phi(t)$ - 6 DoF per projection
- Continuous input/output space
- Fully connected network
  3 hidden layers, 64 features each



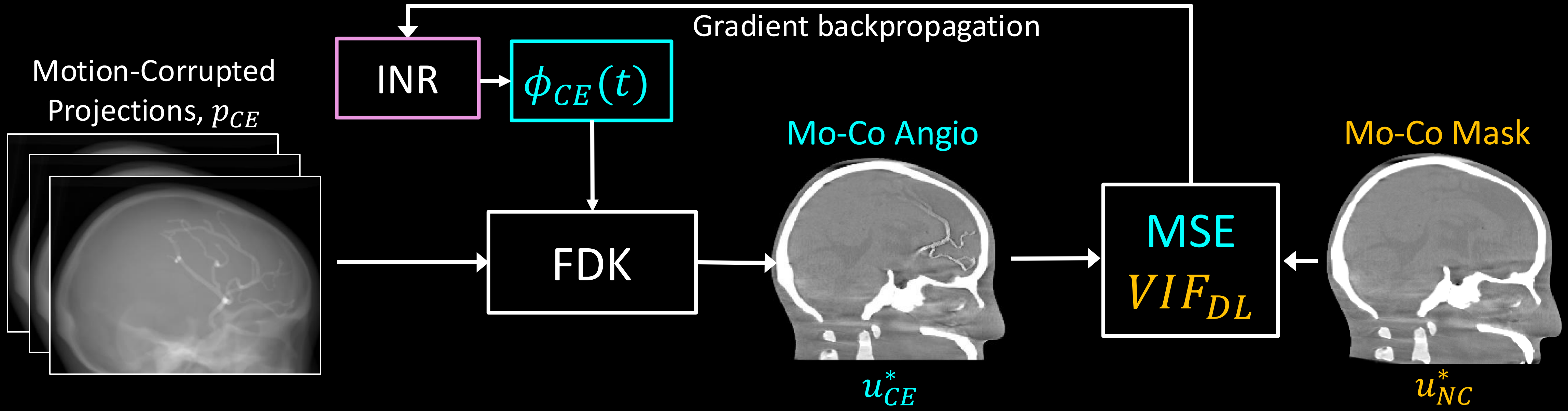
$$\boldsymbol{T}^*_{NC} = \underset{\boldsymbol{\phi}}{\operatorname{argmin}}\, \boldsymbol{VIF_{DL}}[FDK(p_{NC}, \boldsymbol{T})], \qquad \boldsymbol{u}^*_{NC} = FDK(p_{NC}, \boldsymbol{T}^*_{NC})$$

[1] H. Huang, et al. *Med. Phys. 2024*
[2] H. Huang, et al. SPIE Medical Imaging, 2023

Motion and Pose in Angio: Reference Autofocus

Joint Autofocus and Registration

- Motion compensated mask as reference
- Joint optimization:
  - Intra-scan motion with VIF_{DL}
  - Residual motion and registration with MSE vs reference



$$\boldsymbol{T}^*_{CE} = \underset{\boldsymbol{\phi}}{\operatorname{argmin}} \|\boldsymbol{u}^*_{NC} - FDK(p_{CE}, \boldsymbol{T})\|^2, \qquad \boldsymbol{u}^*_{CE} = FDK(p_{CE}, \boldsymbol{T}^*_{CE})$$

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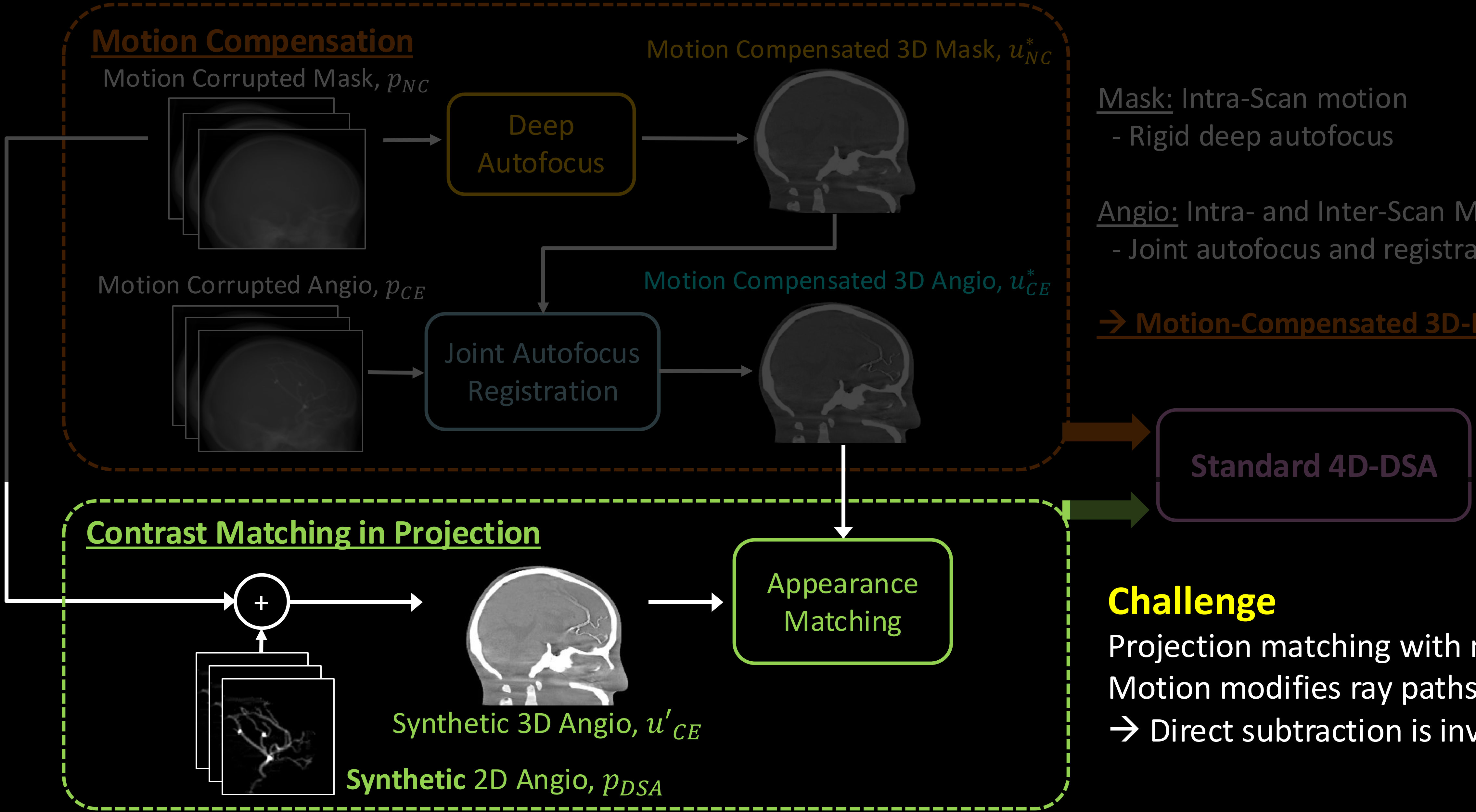
Framework for Motion Compensated 4D-DSA



Mask: Intra-Scan motion
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Angio: Intra- and Inter-Scan Motion
- Joint autofocus and registration

→ Motion-Compensated 3D-DSA

Challenge

Projection matching with motion

Motion modifies ray paths

→ Direct subtraction is invalid

Contrast Projection Estimation

INR for Contrast Synthesis

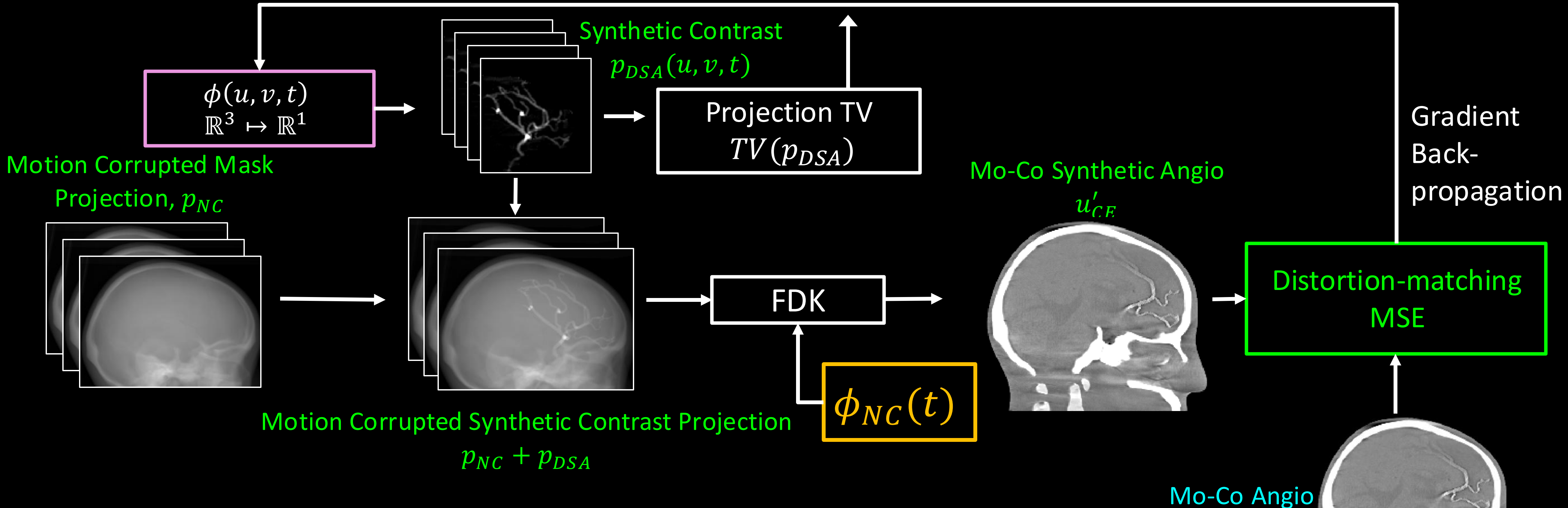
Map time-dependent pixel location to line integral values

→ Continuous multi-resolution transition

Distortion Matching Loss

Time-dependent contrast creates unique image features

→ Matching reconstruction "distortion" provides temporal information



$$p^*_{DSA} = \underset{p_{DSA}}{\operatorname{argmin}} \| \boldsymbol{u}^*_{CE} - FDK(p_{NC} + p_{DSA}, \phi_{NC}(t)) \|^2 + \beta \cdot TV(p_{DSA})$$

Validation Study

Simulation Phantom

CT scan of Kagaku phantom (Kyoto Kagaku, Japan)
- Contrast-enhanced vascularity:
  - Left-anterior and left-middle cerebral arteries
  - Internal carotid artery

Contrast Flow

Laminar Flow (2 cm/s during 12s scan)

Time-concentration modeled using gamma function [1]

Acquisition Geometry

Angle: 0° - 215° (304 projections)

Detector: 580x440 pixels (0.616x0.616 mm)

SAD: 750 mm SDD: 1200 mm

Motion Pattern

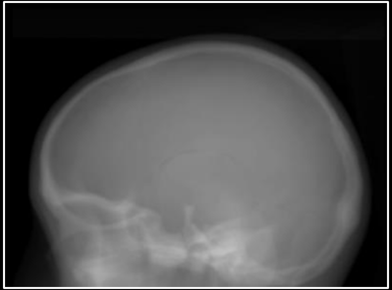
Amplitude: 2 – 6 mm

Frequency: 2 – 4 periods per scan

Inter-Scan Phase Shift: ~90 degrees (random)

Kagaku Phantom

Simulated Contrast Flow



Motion Corrupted Mask Projections

Motion Corrupted Contrast Projections

Evaluation

Motion Compensation Fidelity

<u>Intra-scan Motion Compensation</u>

SSIM of Mask and Angio volumes

<u>Vascular Tree Integrity</u>

DICE score of 3D-DSA

Contrast Projection Estimation Accuracy

<u>Vasculature Detection</u>

Precision and recall

<u>Contrast Flow Accuracy</u>

Pixel-wise mean average error (MAE)

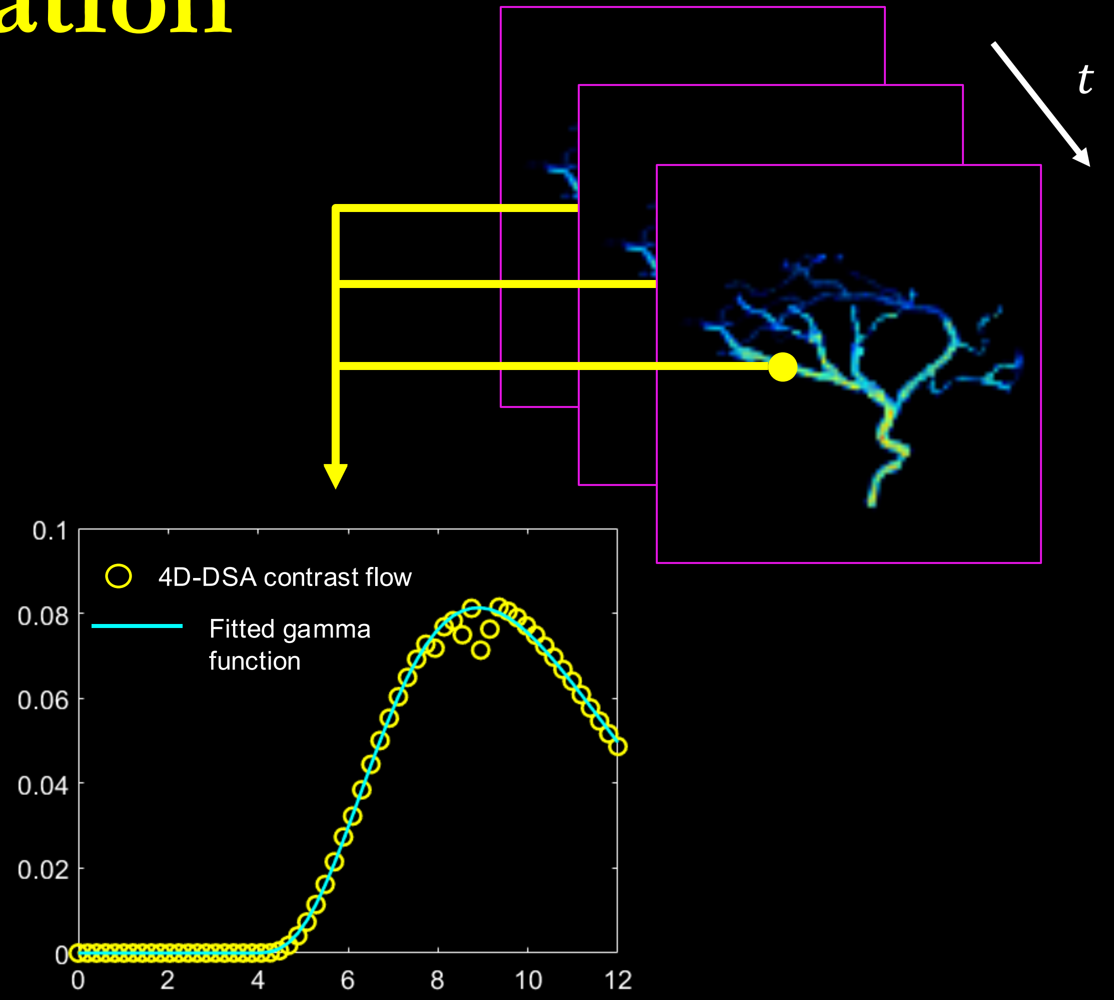
4D-DSA Quality

<u>Contrast Flow Quantification</u>

MAE of 4D-DSA

<u>Contrast Time of arrival (TOA)</u>

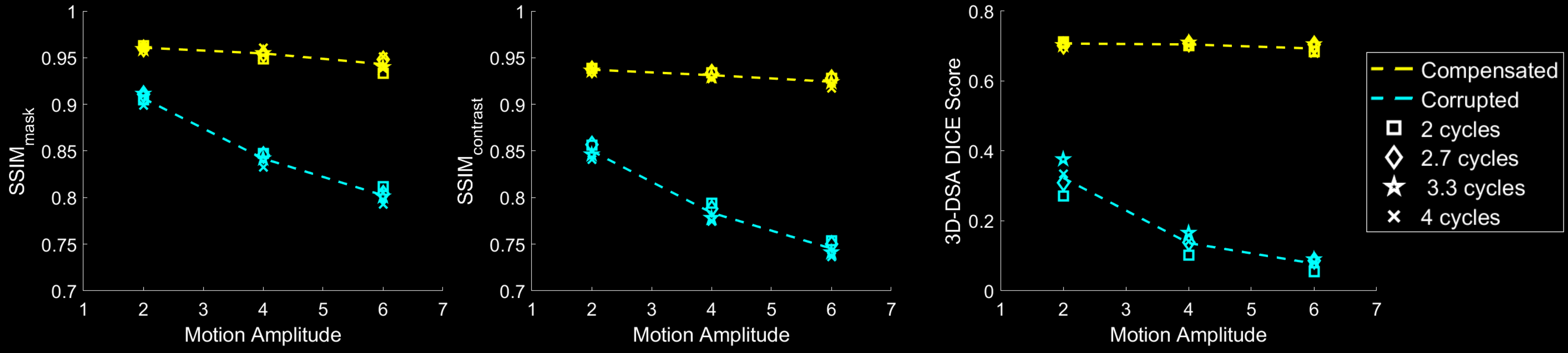
Fitting 4D-DSA to gamma function



$$\mu(t) = \frac{A}{(\alpha\beta \exp(-1))^{\alpha}} \tau^{\alpha} \exp\left(-\frac{\tau}{\beta}\right) \mathrm{H}(\tau)$$

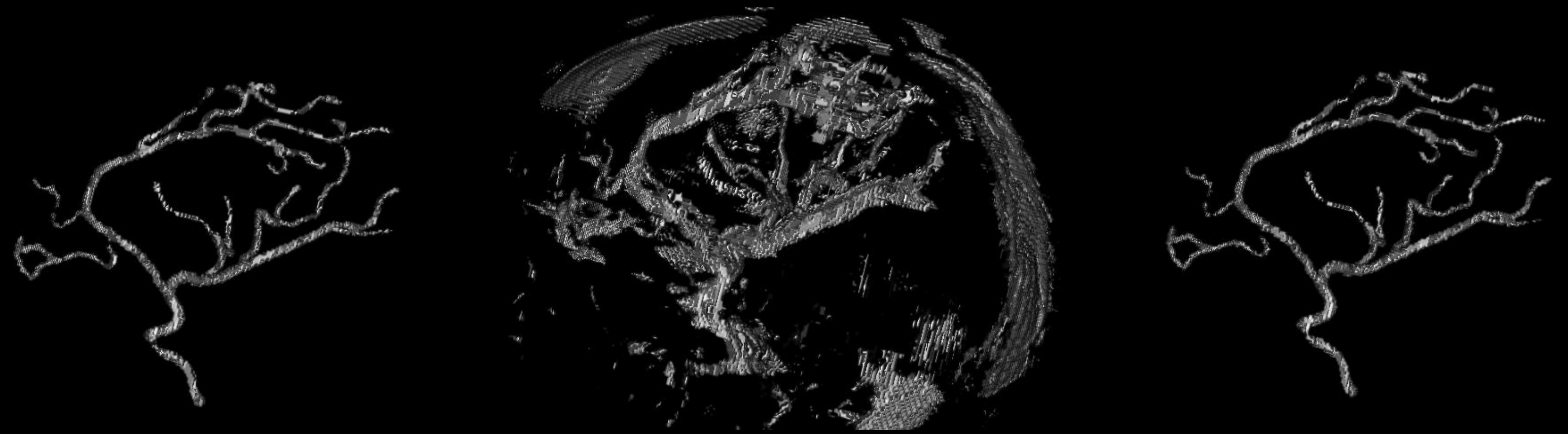
$\tau(t) = (t - \boldsymbol{t_0})/\eta$, where $\boldsymbol{t_0}$ is TOA

Motion Compensation Fidelity

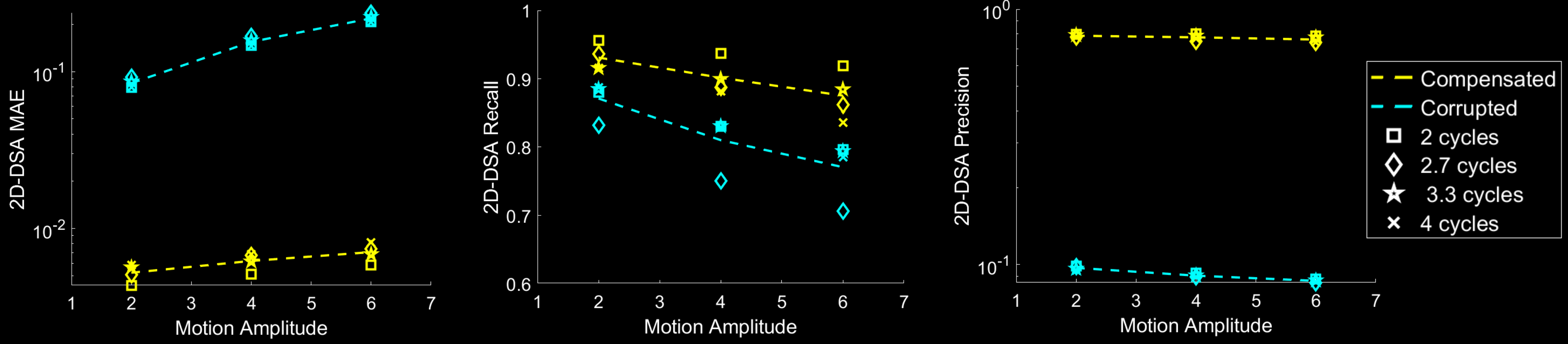


Moderate Motion (4mm, 2.6 cycles per scan)

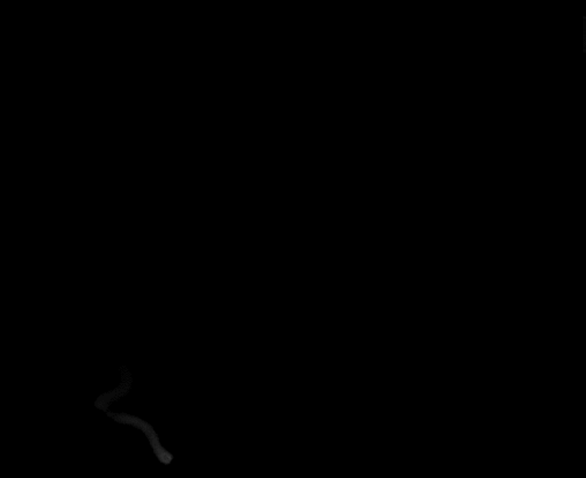
Ground truth | Motion-corrupted | Motion-Compensated



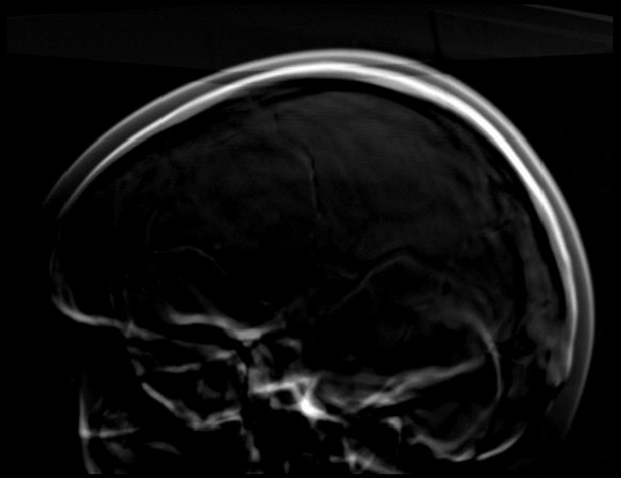
Contrast Projection Estimation Accuracy



Ground truth



Motion-corrupted



Motion-Compensated

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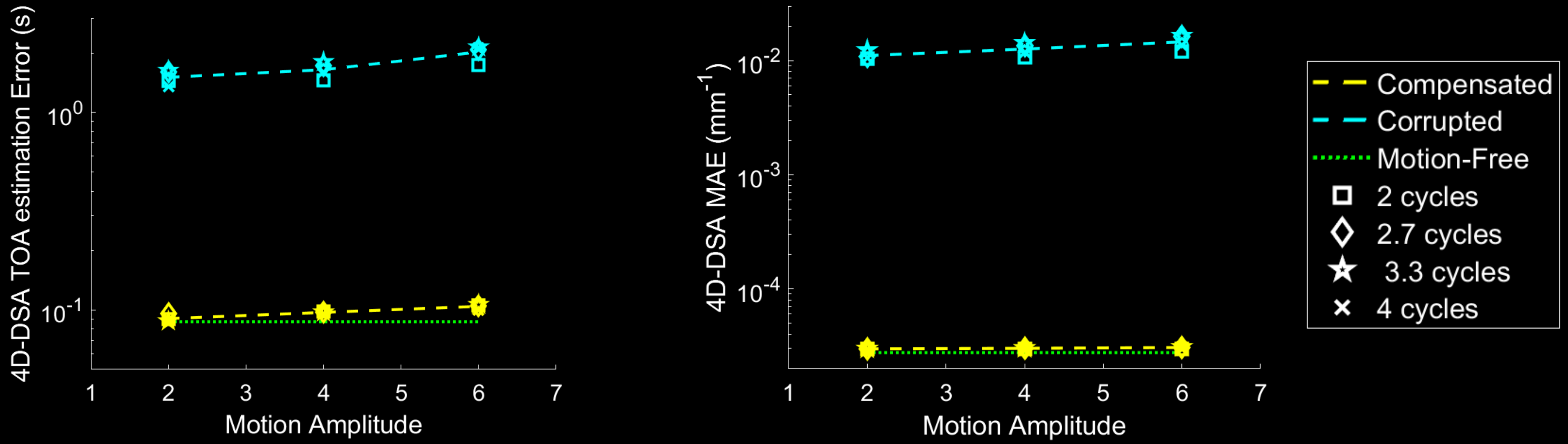
4D-DSA Quality



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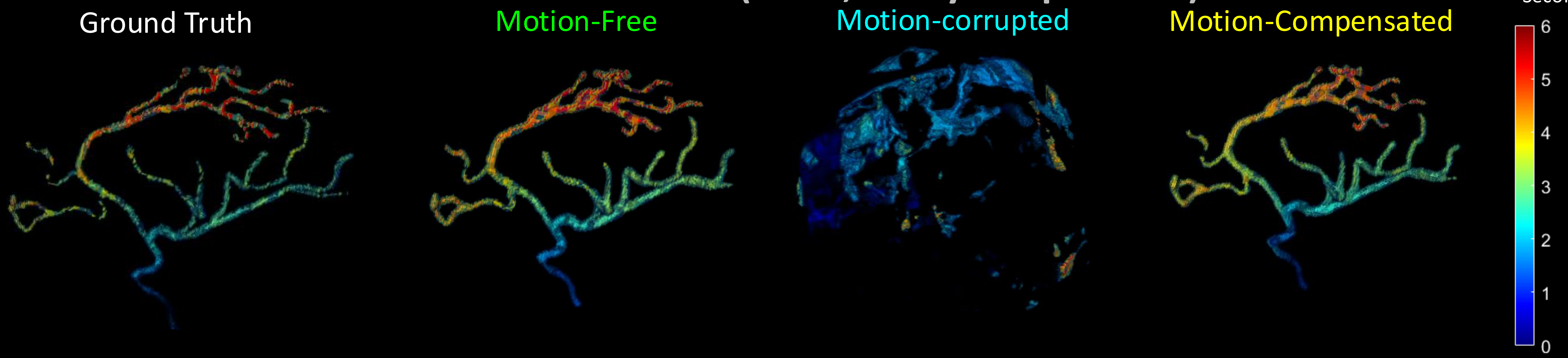


Conclusion

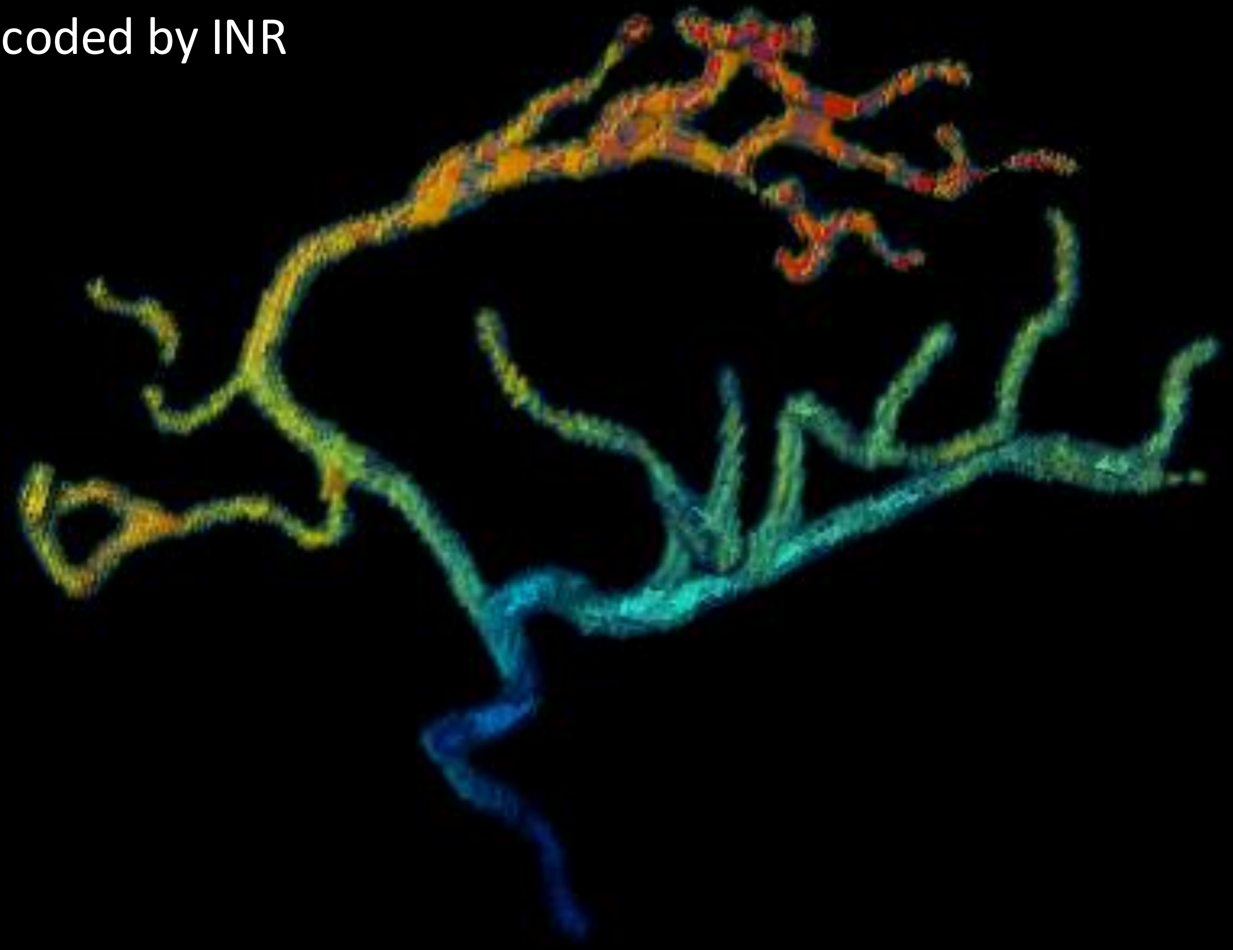
Motion Compensated 4D-DSA Framework

Joint Deep Autofocus & Registration:

Learning-based metric, INR of motion trajectory

Contrast Projection Synthesis:

Appearance-matching loss, projection intensity encoded by INR



Simulation Study

3D-DSA:

SSIM increase: 11.8%

DICE score increase: ~3 times higher

Contrast Projection Estimation:

MAE reduction: 93.3%

False detection reduction: 88.2%

4D-DSA:

Estimated TOA error reduction: 94.8%

Ongoing Work

Application to clinical data