CBCT with Single-View Temporal Resolution

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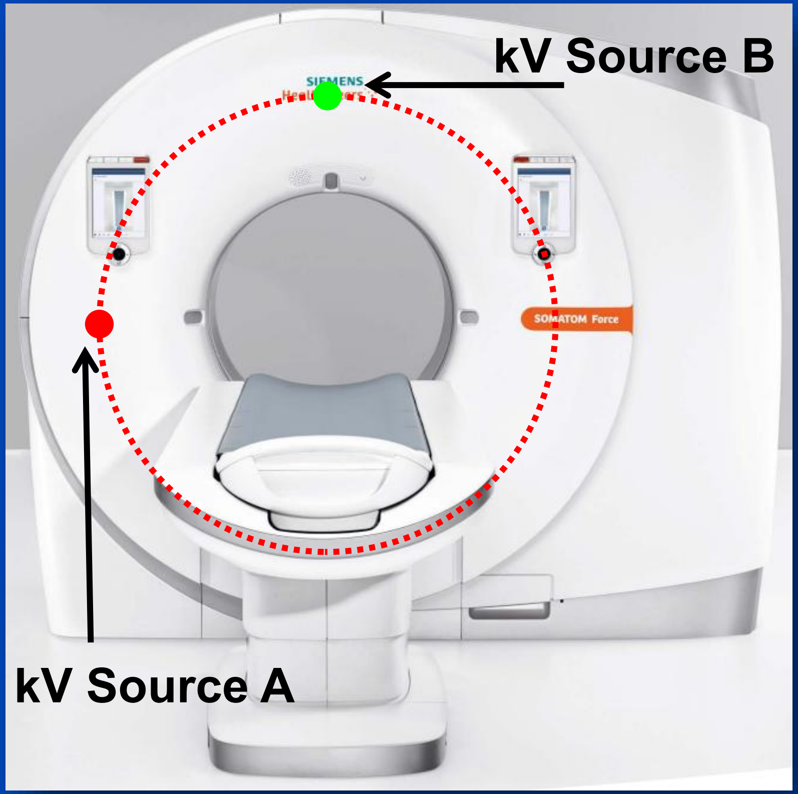
BRIEF GENERAL INTRODUCTION

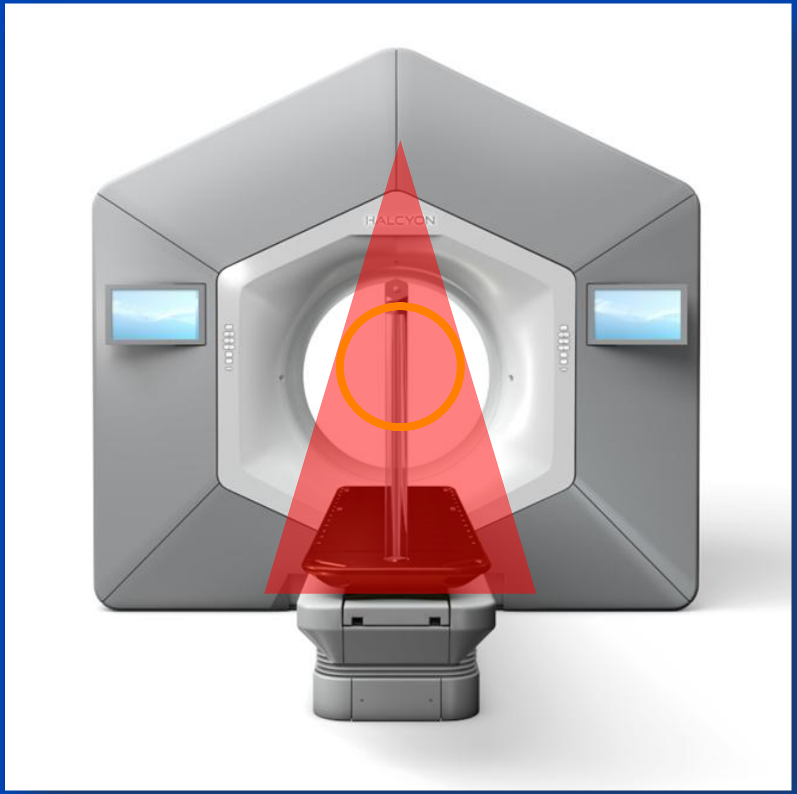
CT vs. CBCT

Clinical CT



Rotation time T_{rot}: down to 0.23 s

CBCT in IGRT



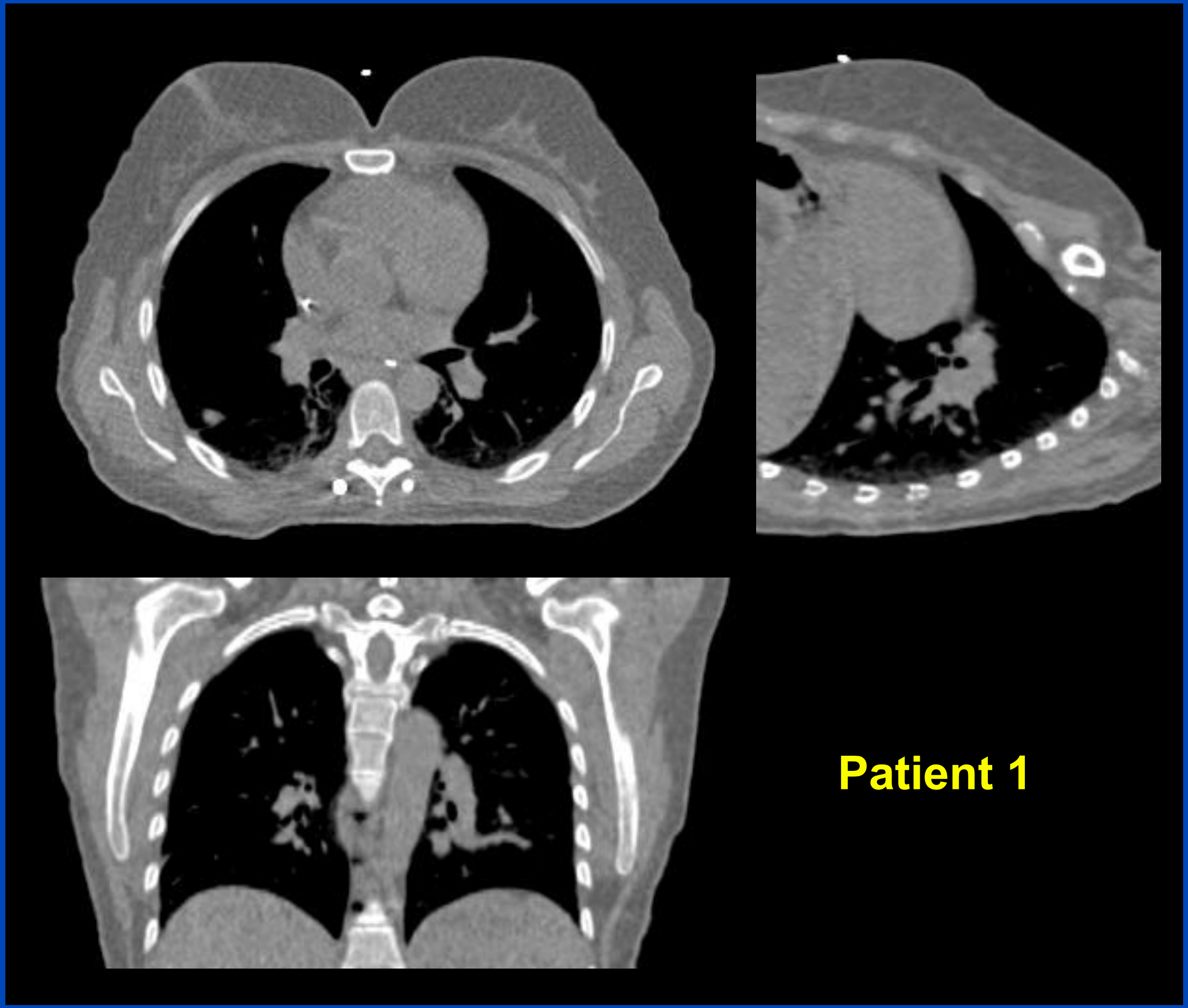
Rotation time T_{rot} : ~ 10 s

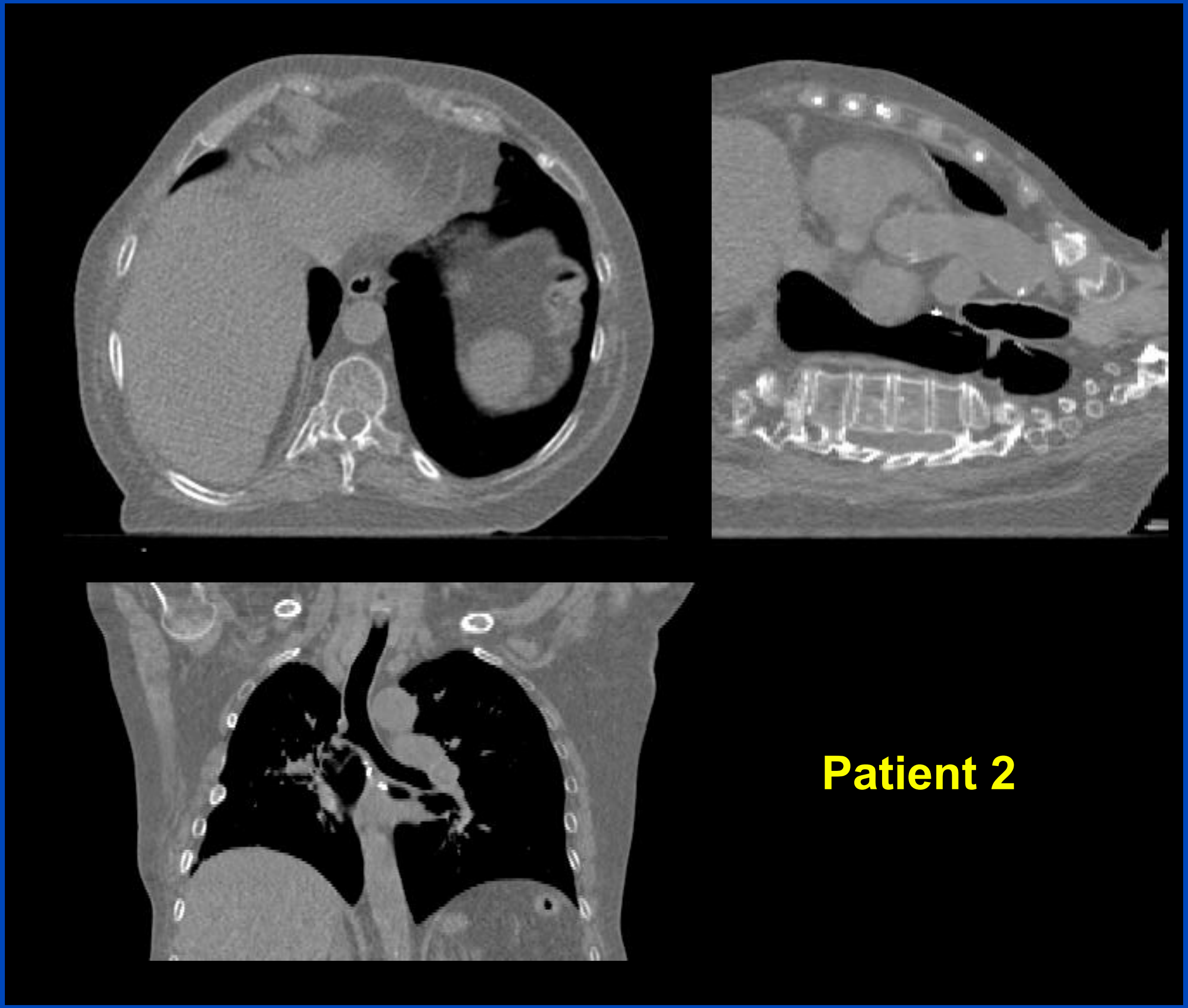
Temporal resolution: 0.5 × T_{rot} (single source), 0.25 × T_{rot} (dual source)

Faster, Equal or Slower Gantry Rotation than Motion Cycle – Which is Best for Cyclic 4D?

- Much faster ☺
  - Always good, since motion is (nearly) frozen.
  - Requires fast scanners with very high tube power and very high detector frame rates.
  - Not possible in CBCT.
- Much slower 😐
  - Allows for gating, if motion is quasi-periodic.
  - Gating results in sparseness artifacts (sparse angular sampling).
  - The slower the better: more motion cycles mean less pronounced sparseness artifacts.
- Close to equal ☹
  - For each view angle the patient is seen in a different motion state.
  - Weird artifacts may occur.
- Exception
  - Single breath-hold scan, if scan is fast enough (e.g. less than 10 s).
  - However, organ motion can no longer be resolved.

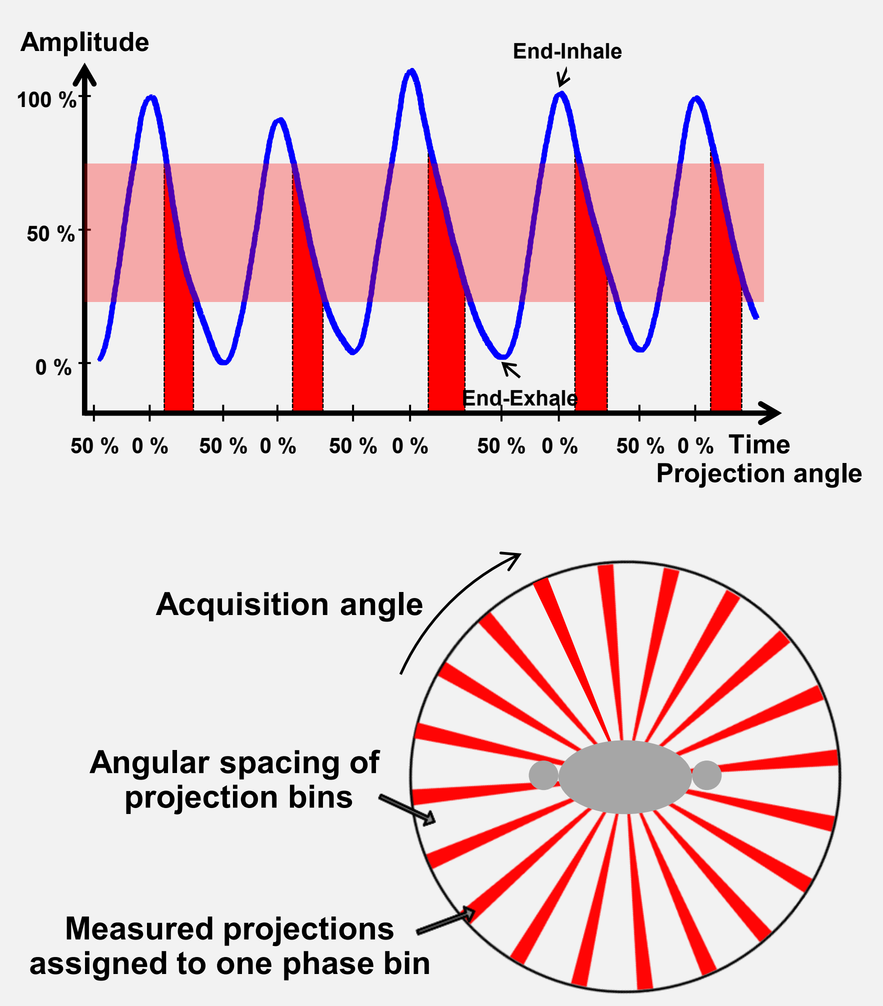
Much Faster: 4D CT





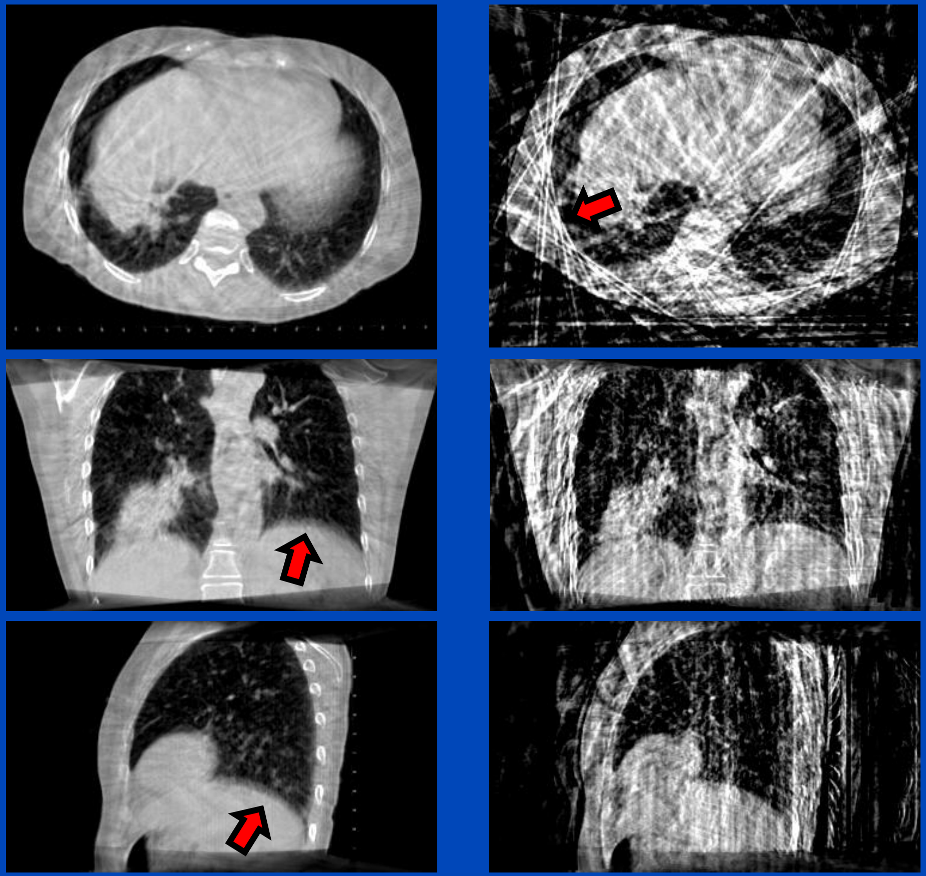
C = 0 HU, *W* = 1000 HU

Much Slower: 4D CBCT Scan

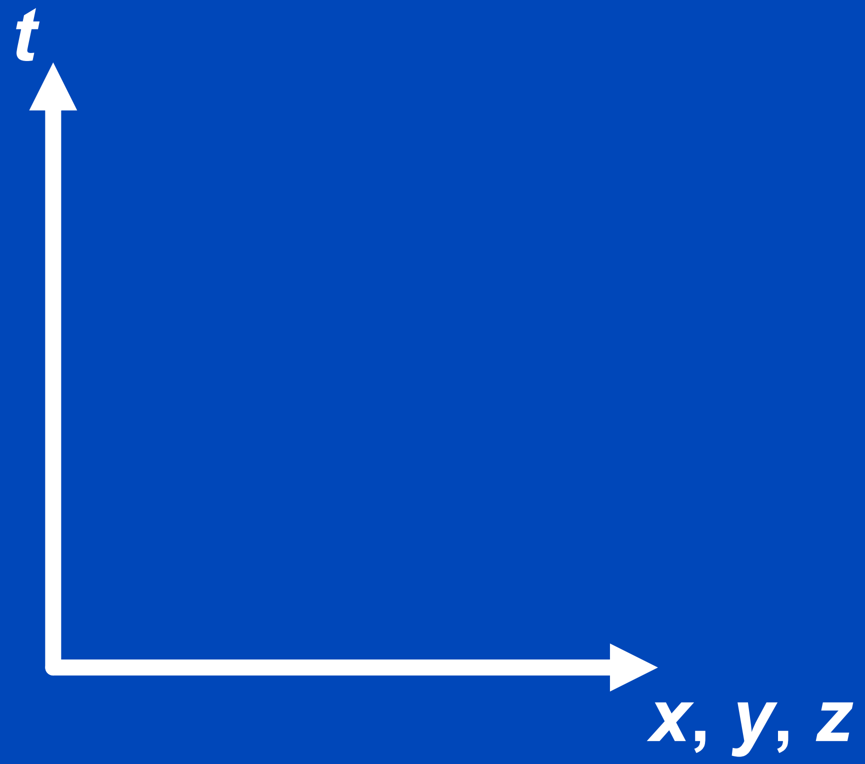


Without gating (3D): Motion artifacts

With gating (4D): Sparse-view artifacts



What is 4D?



What is 4D?

Cyclic 4D

Assumes periodic motion

Needs breathing signal

Today‘s 4D CT and 4D CBCT

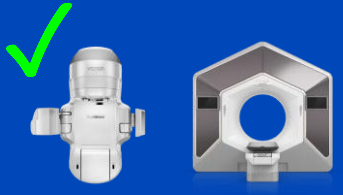
~ 500 ms temp. res.

~ 10 time points

Only before treatment

t

x, y, z



True 4D

t

Any kind of motion

No motion surrogate needed

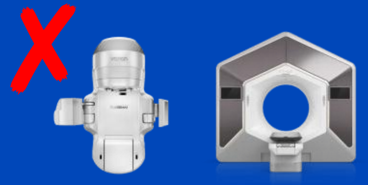
Not available clinically

~ 10 ms temp. res.

> 500 time points

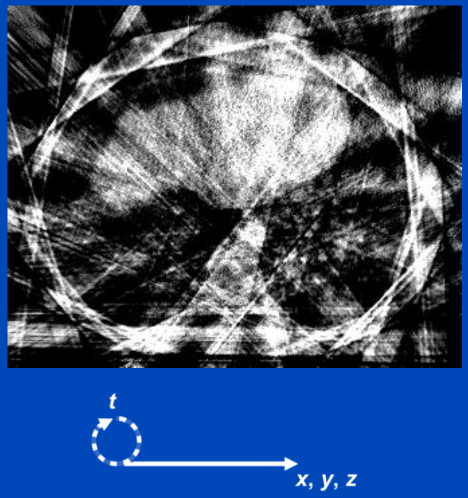
Also during treatment! → Tracking

x, y, z

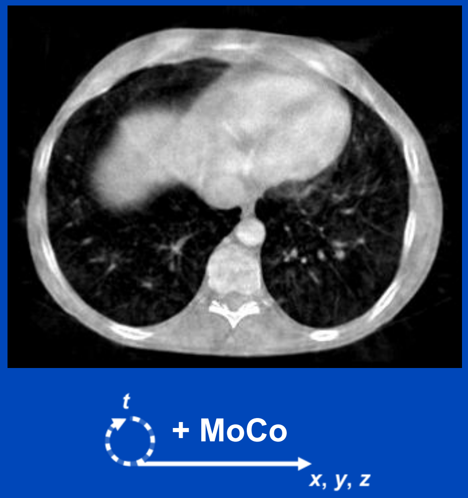


→ this presentation

Motion Compensation (MoCo)
Let the Voxels Move!



MoCo

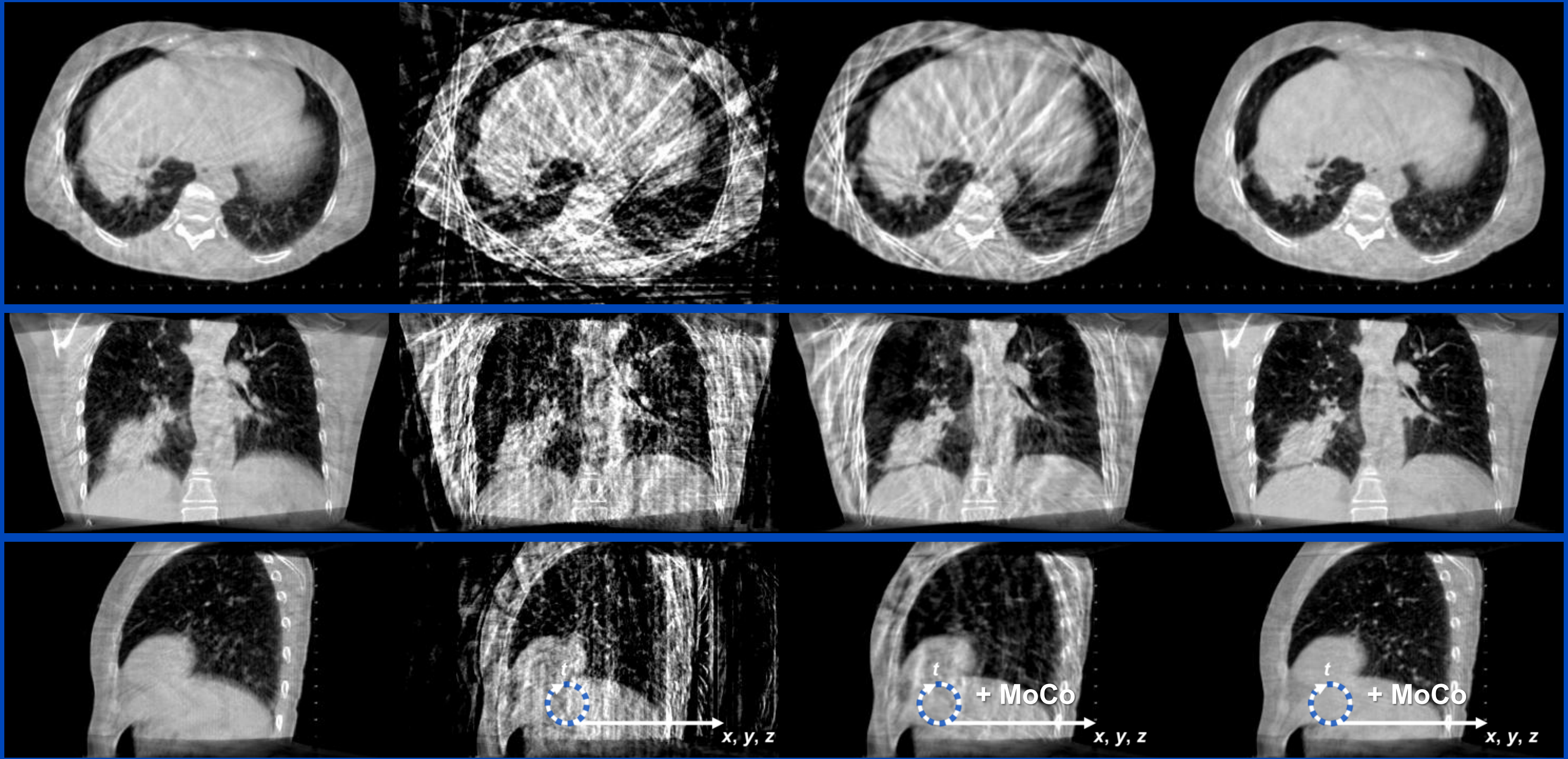


State-of-the-art

CYCLIC 4D

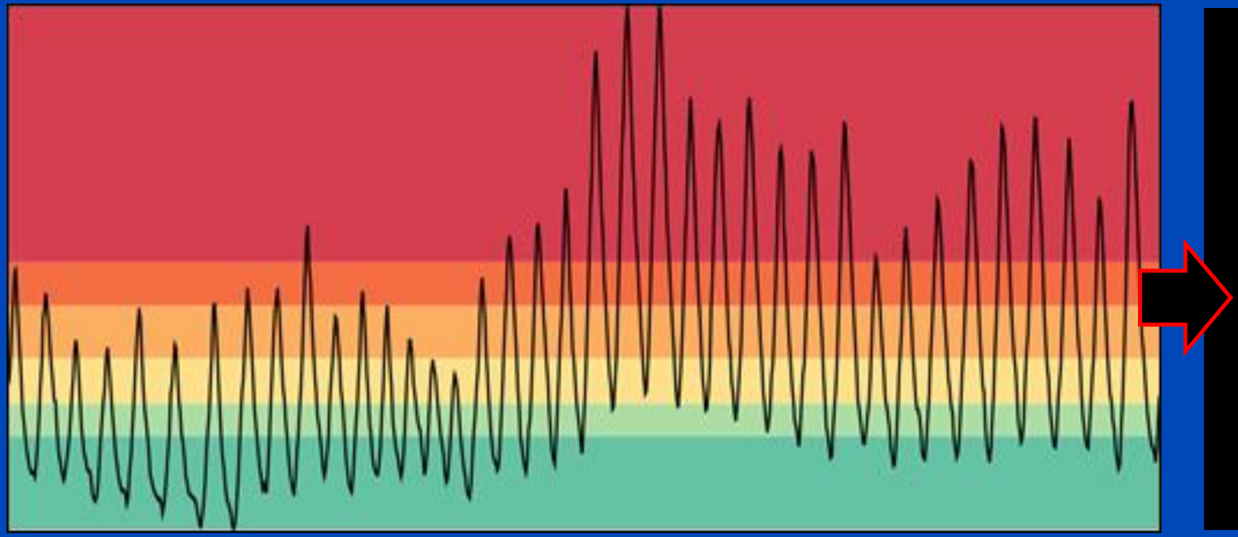
4D – University of Erlangen (2011 – 2014)

3D CBCT	4D gated CBCT	sMoCo	acMoCo
Standard	Conventional Phase-Correlated	Standard Motion Compensation	Artifact Model-Based Motion Compensation

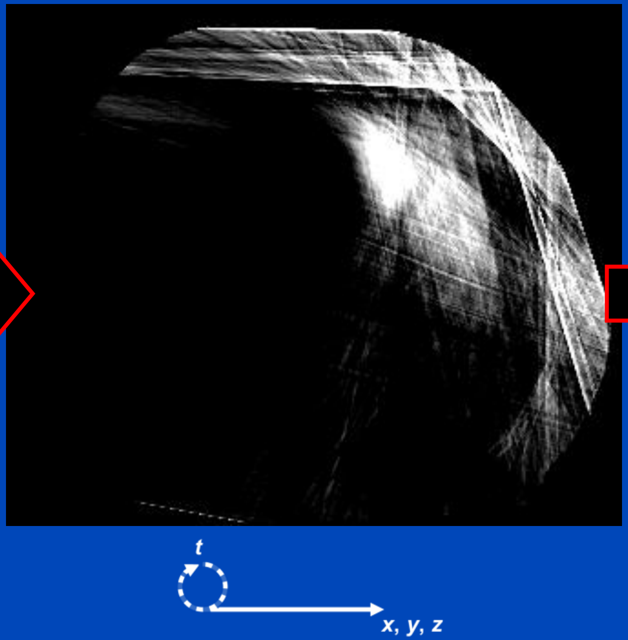


sMoCo: Li, Koong, and Xing, "Enhanced 4D cone–beam CT with inter–phase motion model," Med. Phys. 51(9), 3688–3695, 2007.
cMoCo: Brehm, Paysan, Oelhafen, Kunz, and Kachelrieß, "Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy," Med. Phys. 39(12):7603-7618, 2012.
acMoCo: Brehm, Paysan, Oelhafen, and Kachelrieß, "Artifact-resistant motion estimation with a patient-specific artifact model for motion-compensated cone-beam CT" Med. Phys. 40(10):101913, 2013.

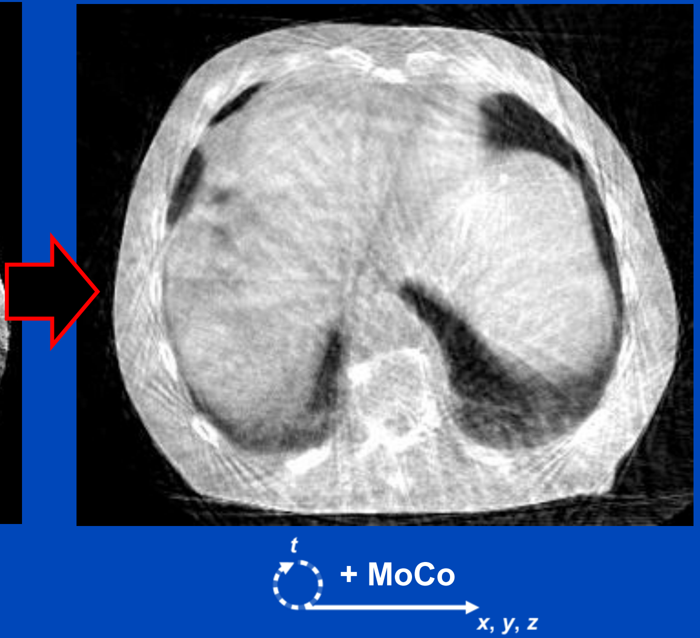
Gating Fails on Irregular Breathing!



Gating = bad



Gating + MoCo = still bad



Future

TRUE 4D

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RESEARCH ARTICLE

MEDICAL PHYSICS

Deep learning-based cone-beam CT motion compensation with single-view temporal resolution (Deep SAMoCo)

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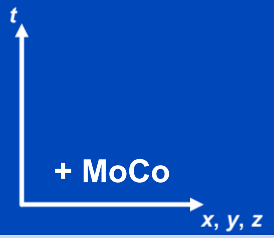
Abstract

Background: Cone-beam CT (CBCT) scans that are affected by motion often require motion compensation to reduce artifacts or to reconstruct 4D (3D+time) representations of the patient. To do so, most existing strategies rely on some sort of gating strategy that sorts the acquired projections into motion bins. Subsequently, these bins can be reconstructed individually before further post-processing may be applied to improve image quality. While this concept is useful for periodic motion patterns, it fails in case of non-periodic motion as observed, for example, in irregularly breathing patients.

Purpose: To address this issue and to increase temporal resolution, we propose the deep single angle-based motion compensation (SAMoCo).

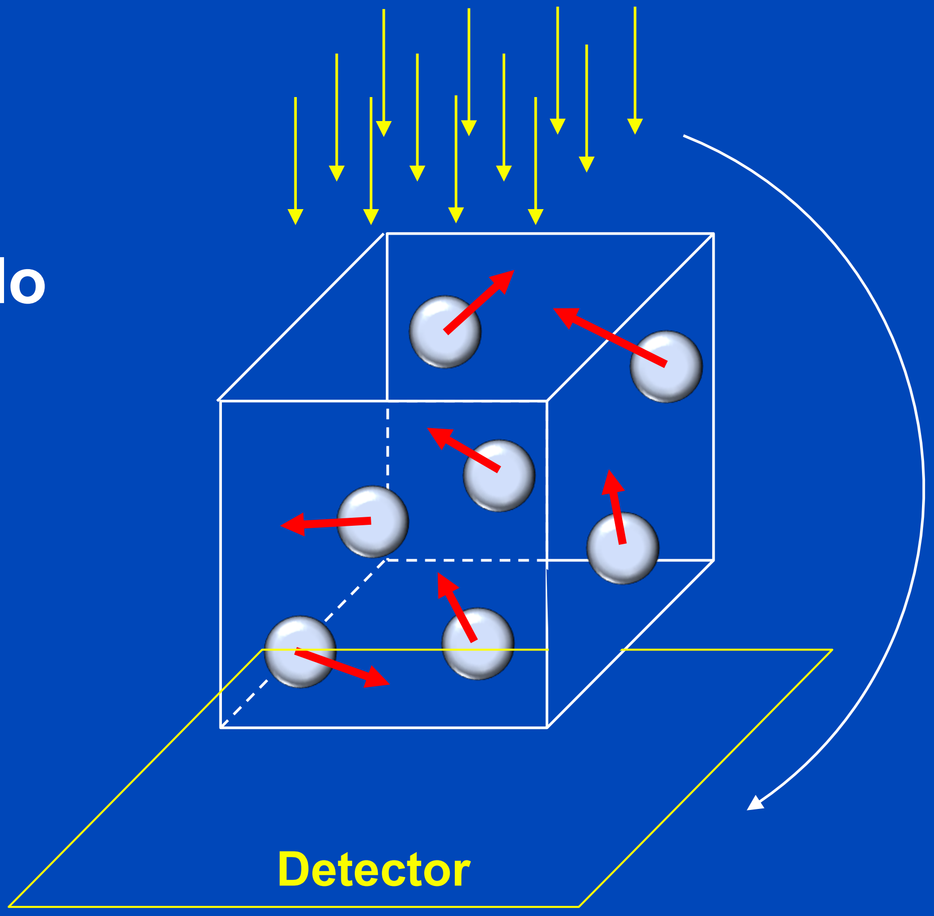
Methods: To avoid gating, and therefore its downsides, the deep SAMoCo trains

Deep SAMoCo = True 4D

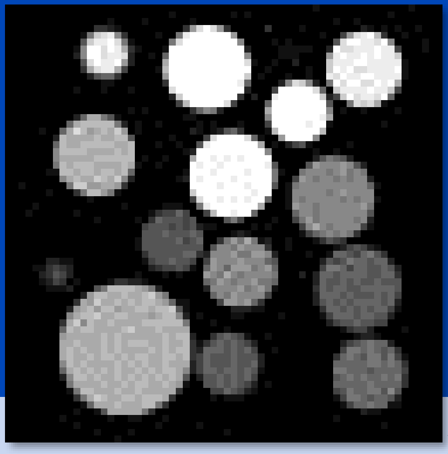


Bouncing Spheres

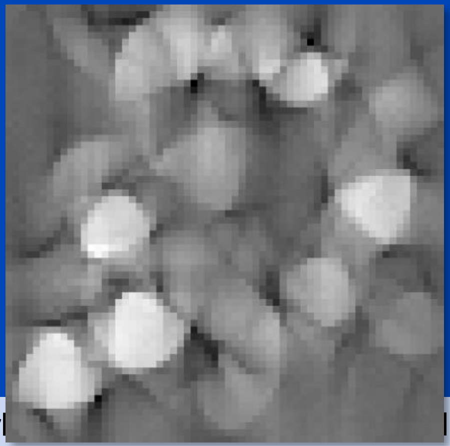
- Spheres with random velocity and random density in a box.
- Elastic collisions with other spheres and walls are elastic.
- 180° scan (180 projections) using a pseudo parallel-beam geometry.
- FDK reconstruction (64×64×32) of single views → 180 PARs.



Slice of prior volume



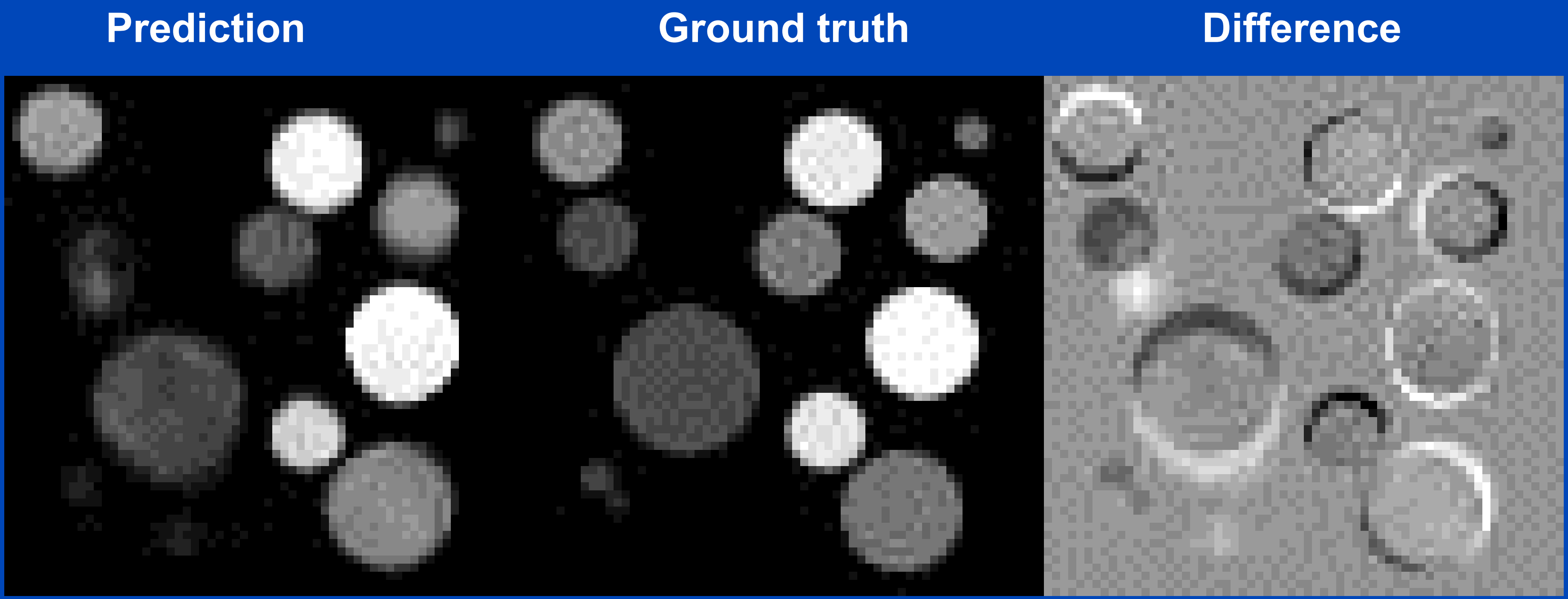
3D reconstruction



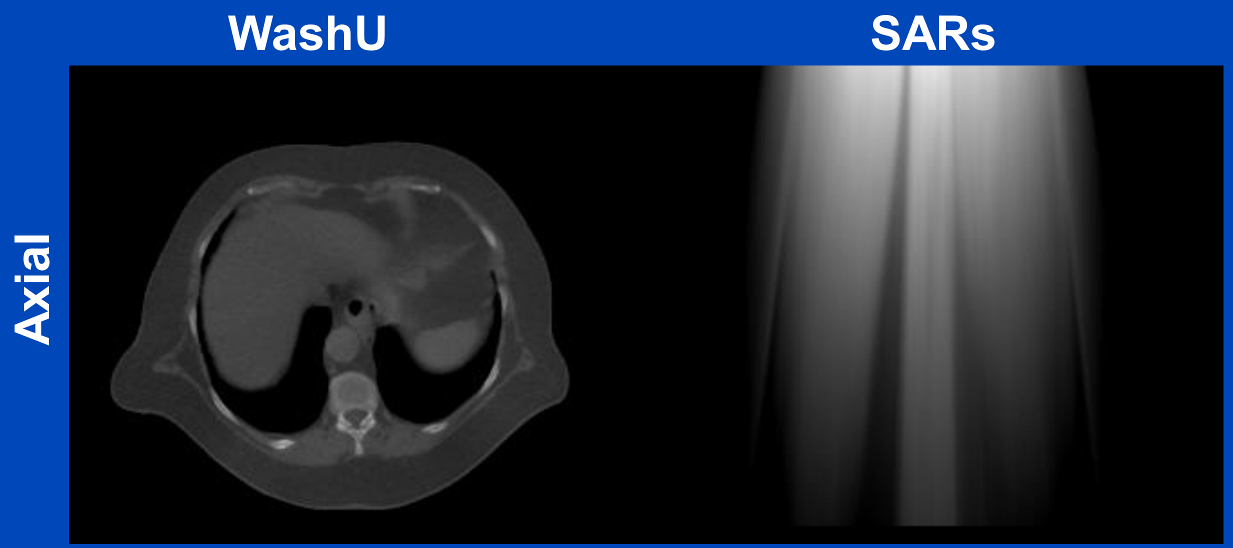
Ar[...]rieß. Deep learning-based cone-beam CT motion compensation with single-view temporal resolution. Med. Phys. 52(7):e17911, July 2025.

Results

Spheres



Single Angle Reconstructions (SARs)



84 4D CT scans (no artifacts, high temporal resolution)

- 10 respiratory phases each (WashU/Colorado dataset)
- 10·10 combinations of phase *A* and *B* possible (including *A*=*B*)
- 84·10·10 displacement vector fields (DVFs) known
- 720 CBCT projections[1] simulated for each CT scan (each phase)
- 84·10·720·10·720 = 6.5 billion projection pairs with known DVF

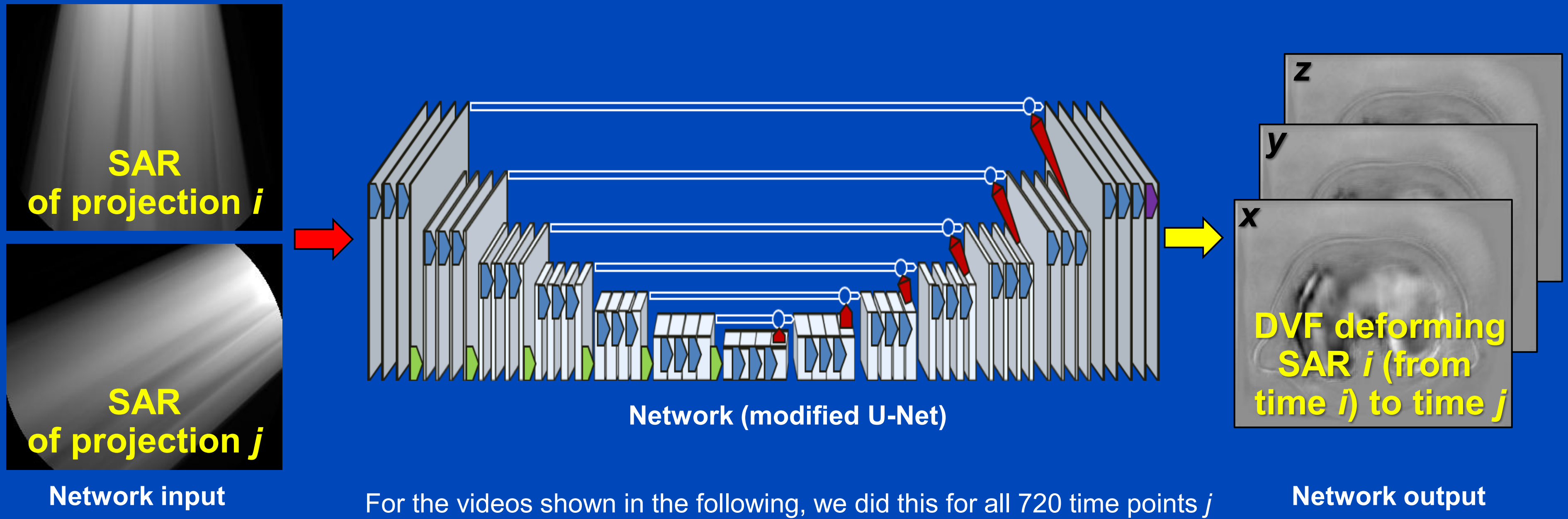
[1]The actual projection numbers are between 420 and 900 and depend on the scan mode.

J. Maier, S. Sawall, M. Arheit, P. Paysan and M. Kachelrieß. Deep learning-based cone-beam CT motion compensation with single-view temporal resolution. Med. Phys. 52(7):e17911, July 2025.

Inference Workflow of Deep SAMoCo

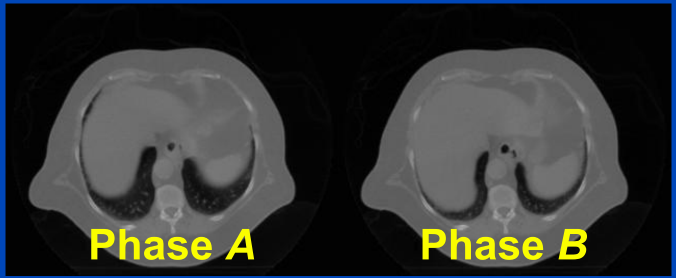
- For a new patient
  - decide for the desired time point *j*, e.g. the one from 1 millisecond ago
  - for all $i \neq j$ get the DVFs pointing from *i* to *j* from the neural network
  - deform SARs for all $i \neq j$ into time point *j*
  - add all the volumes

For all $i \neq j$ do



For the videos shown in the following, we did this for all 720 time points *j*

Training Workflow of Deep SAMoCo

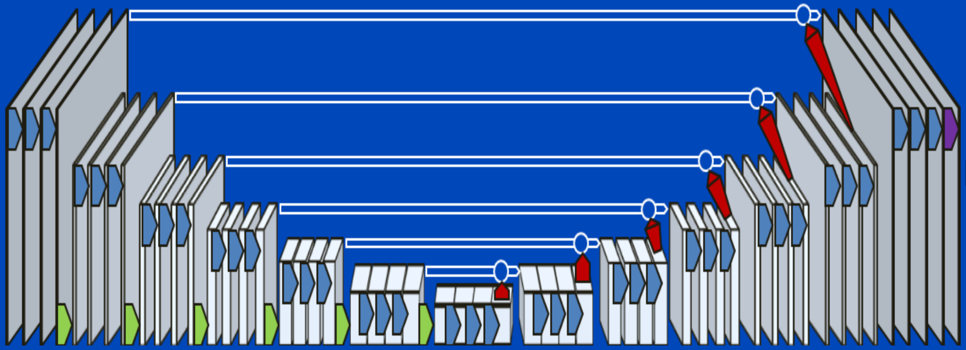


Random patient, random *A* and *B*

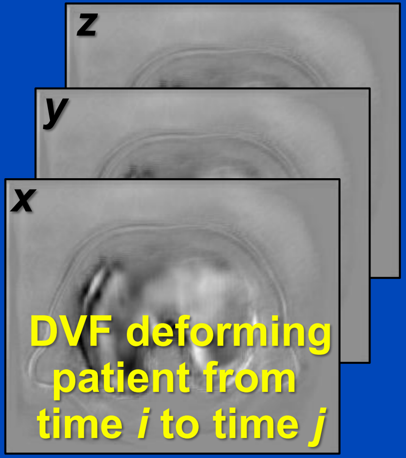
Randomly select
- projection *i* from *A*
- projection *j* from *B*
and backproject.

Calculate DVF from phase *A* to phase *B* (Demons, Deeds, VoxelMorph, …)

Network input



Network (modified U-Net)



Training labels

All images shown here are volumes of size 512^3.

varian

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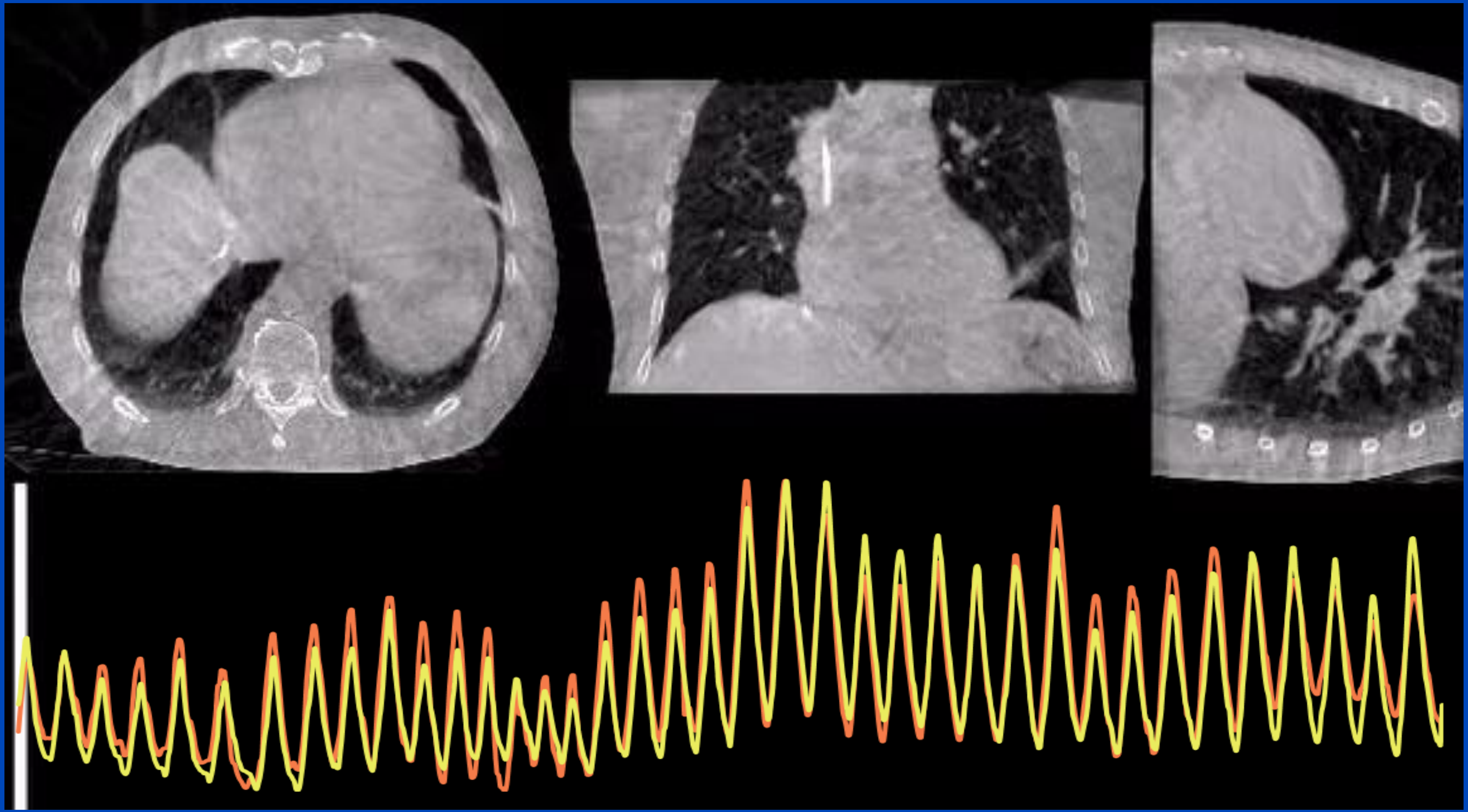
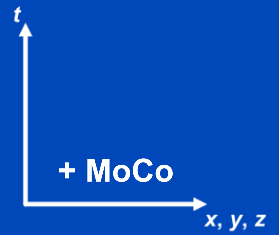
VUMC_4DThorax





Red: RPM signal (external signal – not used for recon)
Yellow: Diaphragm motion (intrinsic signal – from PAMoCo recon)

varian

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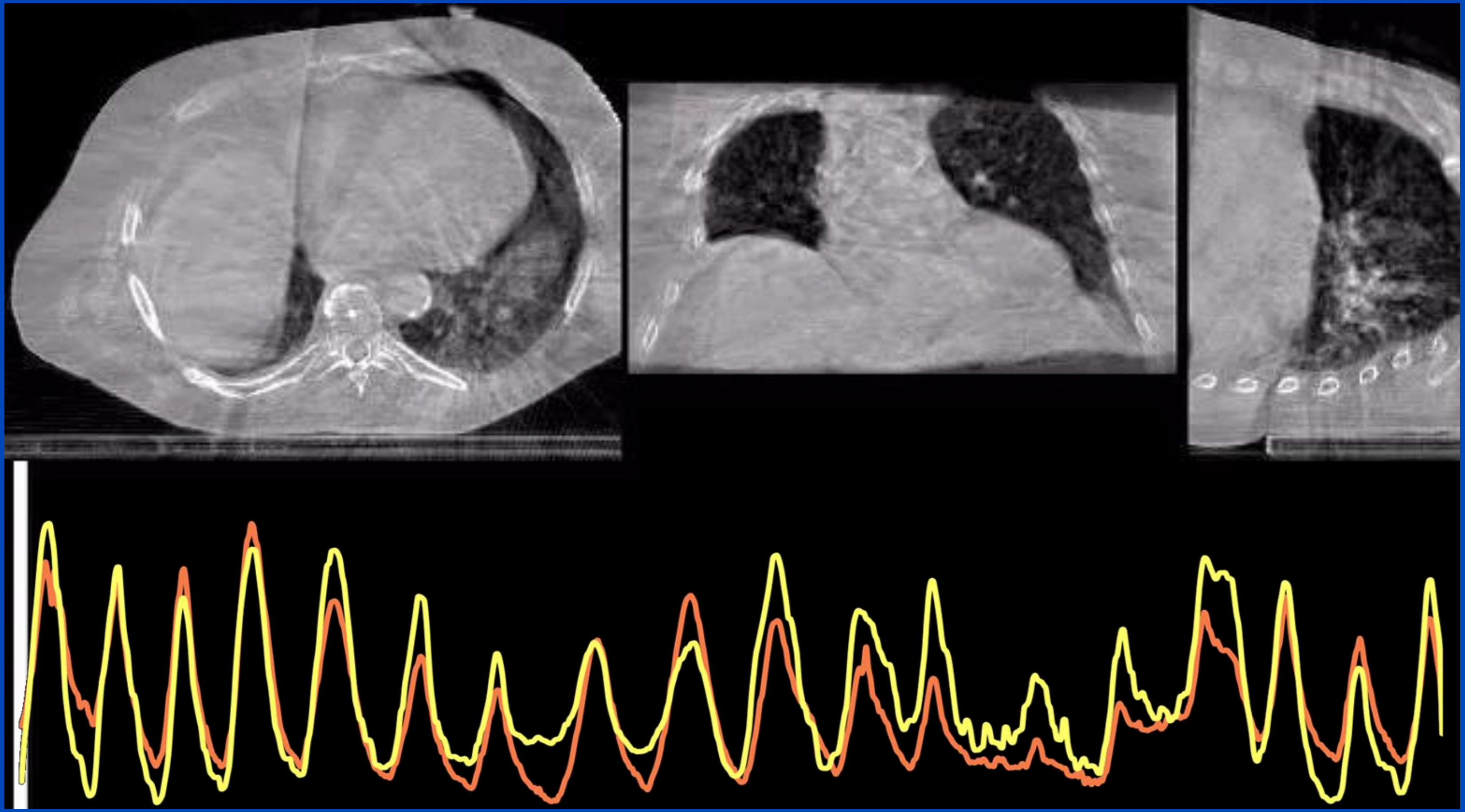
MSK 1



Red: RPM signal (external signal – not used for recon)
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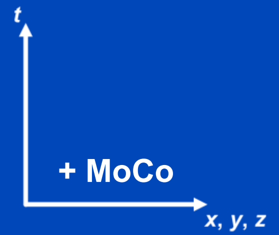
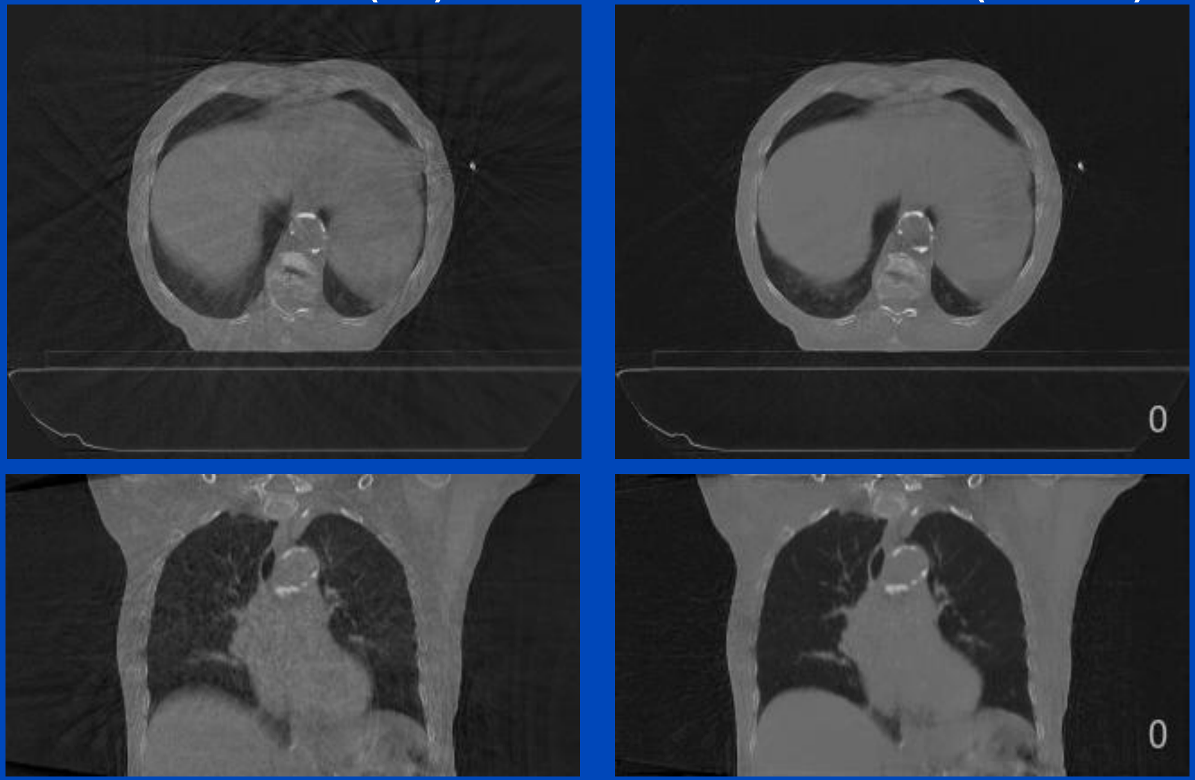


Hypersight Patient Example

60 s Scan

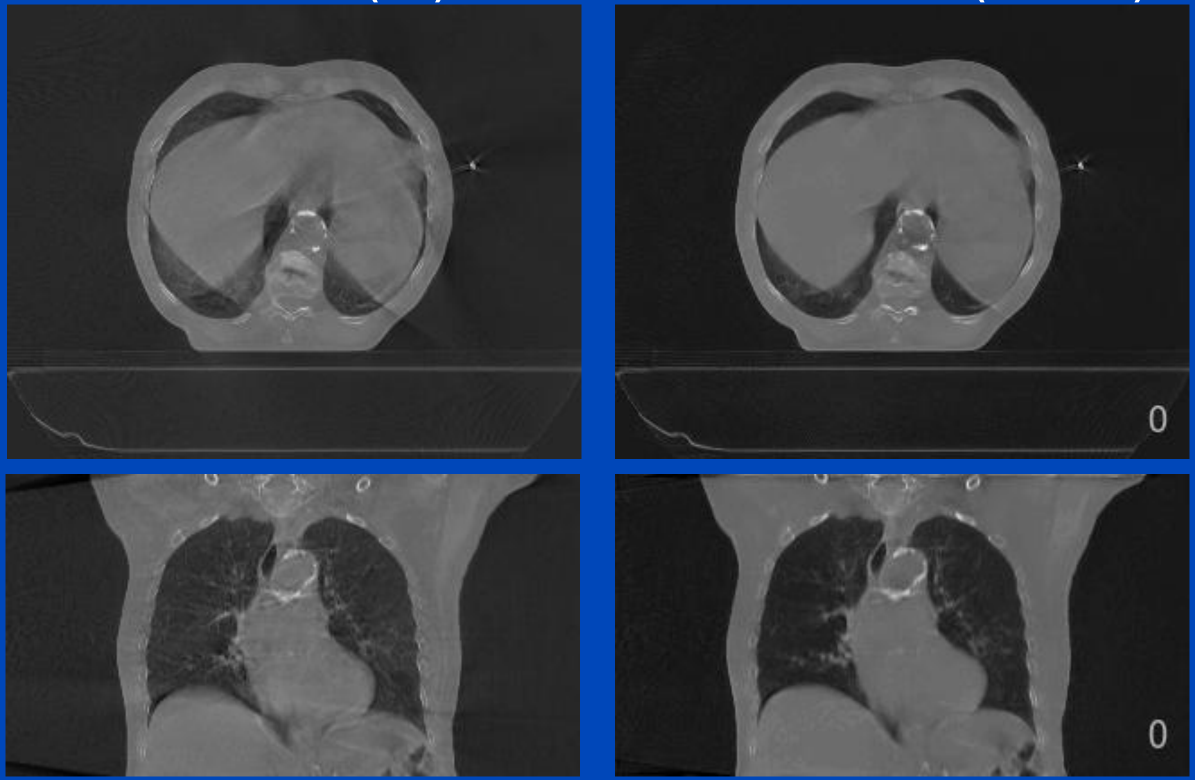
FDK recon (3D) | **SAMoCo recon (true 4D)**



60 s, 200° short scan, 867 projections, MA_53_Lung_60s.
Displayed are 434 time points with 140 ms increment at 10 fps.

6 s Scan

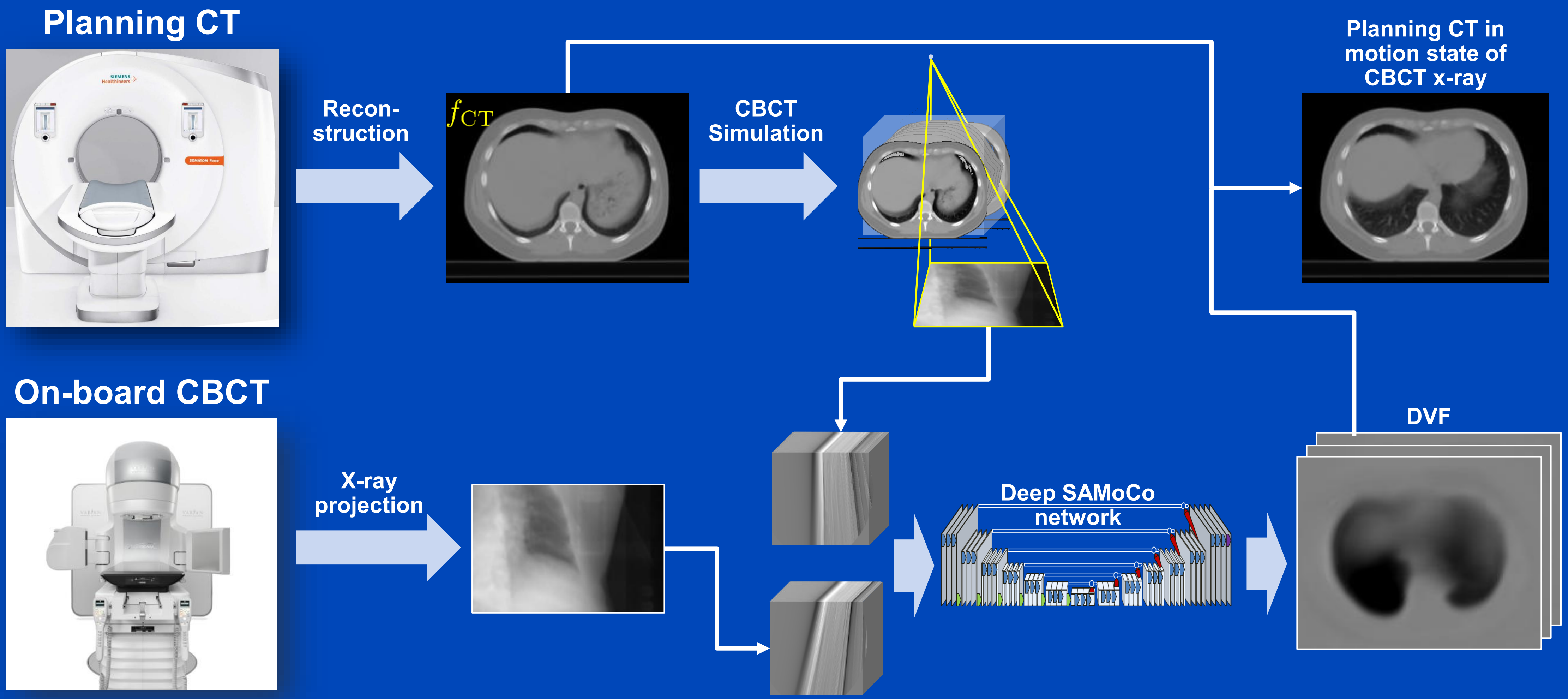
FDK recon (3D) | **SAMoCo recon (true 4D)**

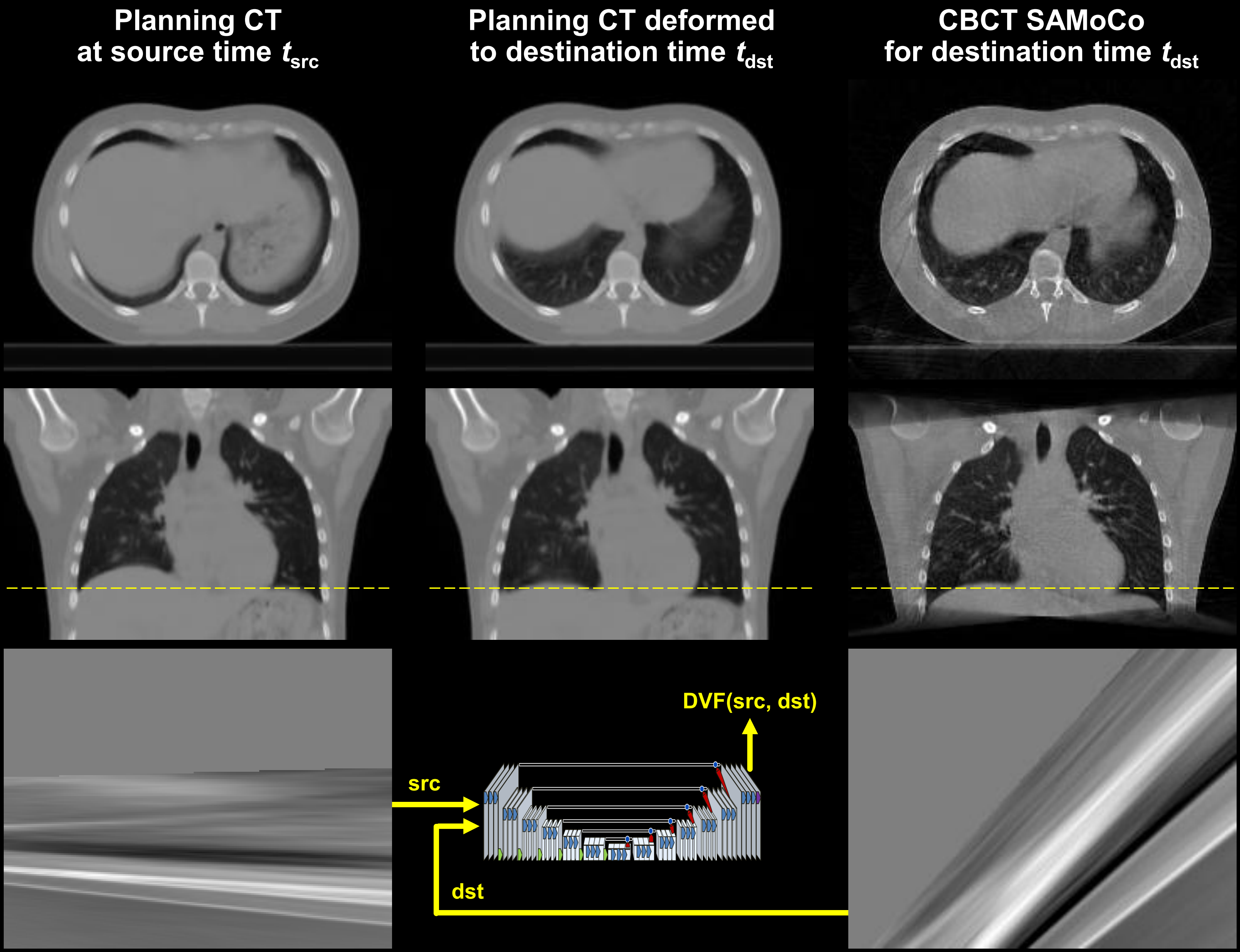


6 s, 200° short scan, 406 projections, MA_53_Lung_BH_6s
Displayed are 41 time points with 140 ms increment at 10 fps.

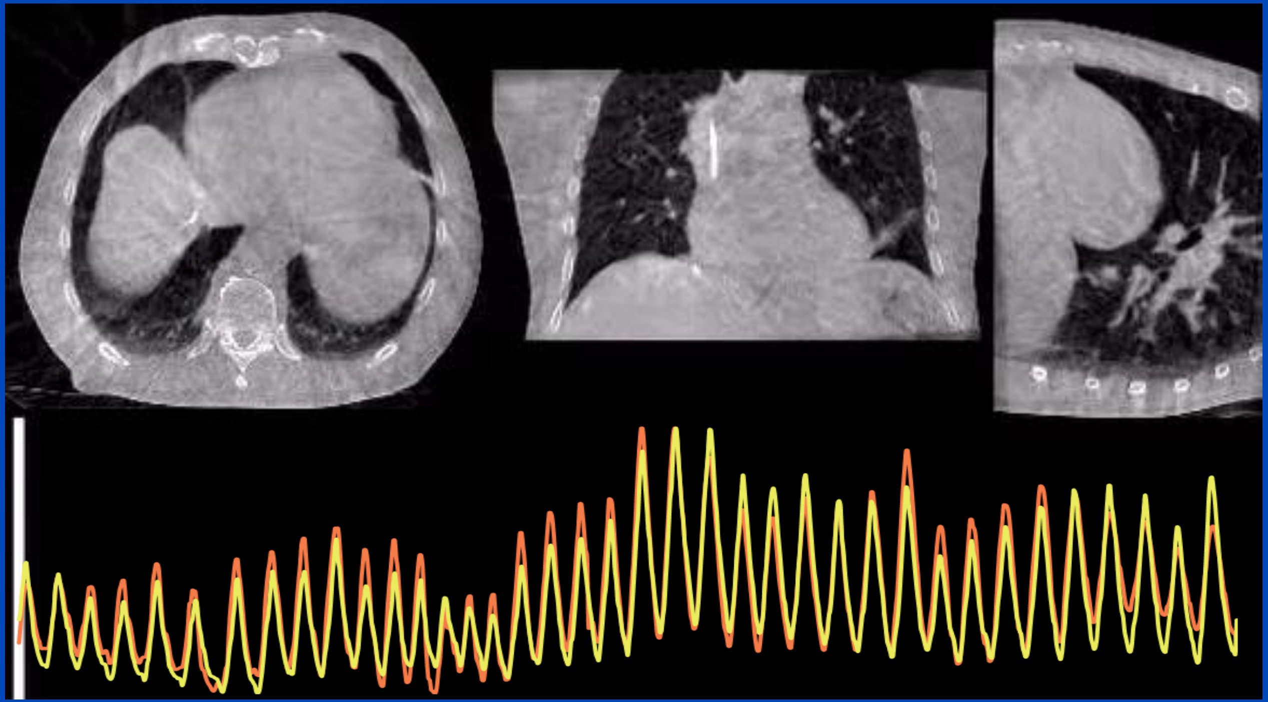
Numbers show frame numbers and not projection numbers

Experiment: Deform Planning CT





Planning CT
at source time t_{src}
Planning CT deformed
to destination time t_{dst}
CBCT SAMoCo
for destination time t_{dst}
DVF(src, dst)
src
dst



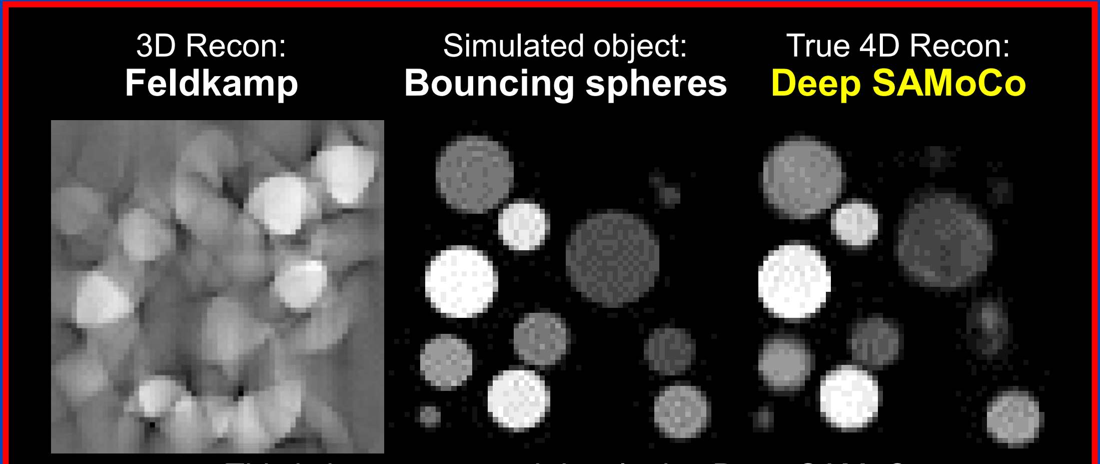
Imaging ($t < 0$)

Treatment ($t > 0$)

t

Conclusions and Outlook

- Conventional 4D (cyclic 4D) collapses time onto a periodic phase.
- Deep SAMoCo 4D (true 4D) reconstructs time as a true dimension.
  - Motion does not need to be periodic.
  - Rotation speed does not matter.
- Deep SAMoCo allows to track structures in 3D, given x-ray images during treatment.
  - However: Single view x-ray data during treatment currently not available to us.



This is how we started developing Deep SAMoCo.

Thank You!

This presentation will soon be available at www.dkfz.de/ct.

Job opportunities through marc.kachelriess@dkfz.de or through DKFZ's international PhD or Postdoctoral Fellowship programs.

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.