Motion Vector Field Upsampling with Joint Phase and Amplitude Binning for Motion-Compensated 4D Cone-Beam CT Image Reconstruction

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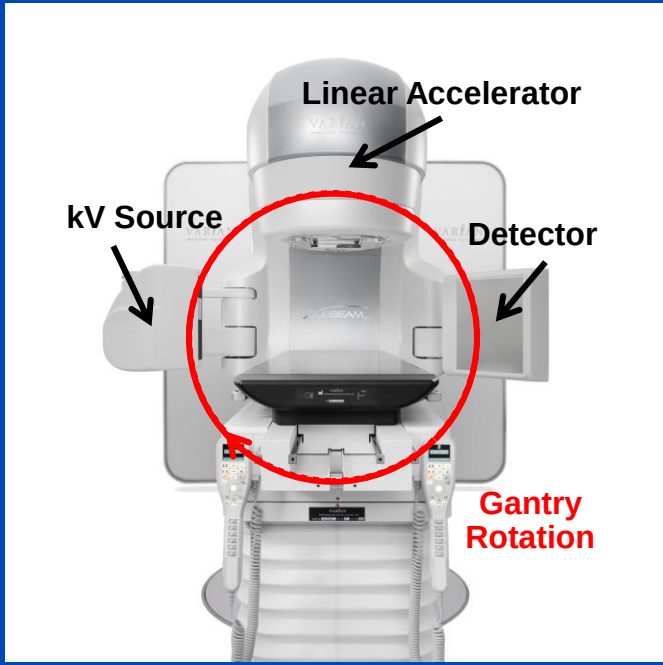
Slowly Rotating CBCT Devices

- Image-guided radiation therapy (IGRT)
  - Cone-beam CT (CBCT) imaging unit mounted on gantry of a LINAC treatment system
  - Accurate information about patient motion required for radiation therapy
- Slow gantry rotation speed of 3° or 6° per second
  - Much slower than clinical CT devices
- Breathing about 10 to 30 respiration cycles per minute (and thus per scan)
- Heartbeat about 50 to 80 beats per minute
- Acquire breathing signal during acquisition

Account for patient motion!

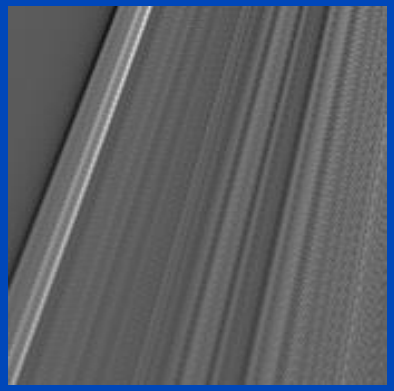


*Brehm, Sawall, Maier, and Kachelrieß, "Cardio-respiratory motion-compensated micro-CT image reconstruction using an artifact model-based motion estimation" Med. Phys. 42(4):1948-1958, 2015.

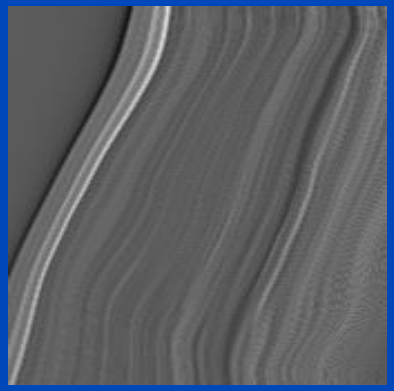
Motion Compensation (MoCo)

- **Use all projection data for each phase to be reconstructed**
  - Even those of other respiratory phase bins (100 % dose usage)
  - Compensate for motion applying motion vector fields (MVFs)
  - In our case MVFs are estimated from conventional gated reconstructions
- **Use MVFs during image reconstruction**
  - Backproject sparse data along straight lines, then warp with respect to the MVFs
  - Computational efficiency
    - » Corresponds to backprojection along deformed lines

Straight backprojection



Warped backprojection

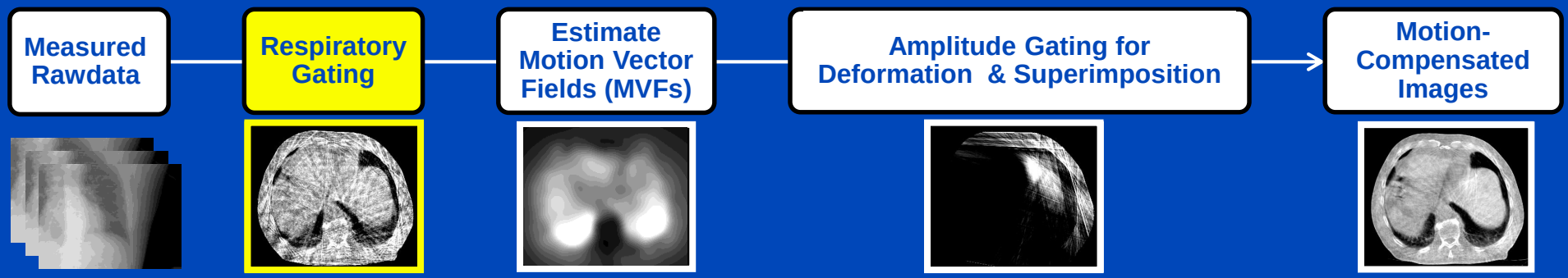


Aims

- To provide high fidelity motion-compensated (MoCo) respiratory- or cardiac-correlated volumes from CBCT.
- Reduce motion blurring by switch from phase to amplitude binning.
- To further increase the temporal resolution by motion vector field (MVF) upsampling in temporal dimension.
- Use cases for MoCo (in the field of radiation therapy):
  - Accurate patient positioning
  - Treatment verification
  - Online treatment adaptation
  - …

Motion Compensation (MoCo)

Motion Estimation Based on Phase Gating



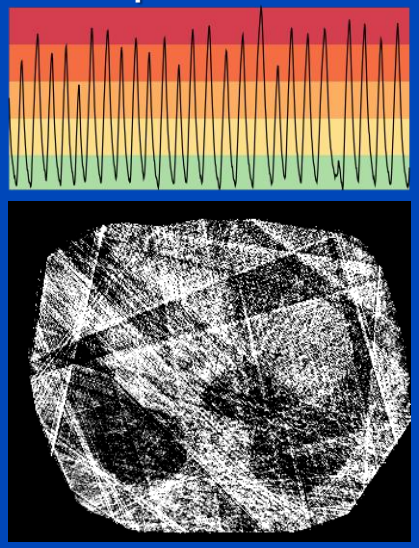
- **Respiratory gating is done based on motion phase signal.**
  - Each respiratory phase contains only a subset of the total number of projections and this leads to sparse view artifacts.
  - Each respiratory bin contains projections that cover the whole scan angular range.
  - This robust binning method ensures a homogeneous rawdata distribution for all respiratory bins. This is important for reliable motion estimation.
- **Disadvantage: Depending on the breathing pattern of the patient motion blurring occurs.**

Why MVF Resampling?

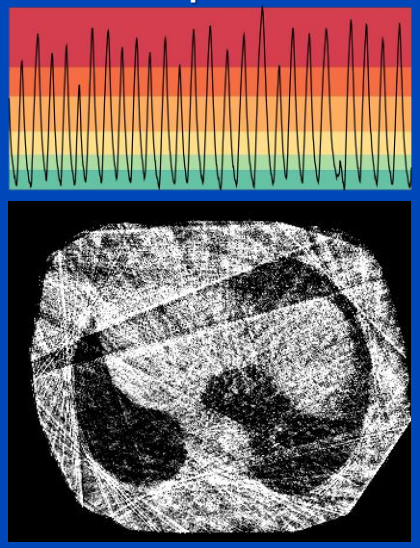
- Phase binning = nearly homogeneous projection angle distribution
- Amplitude binning = reflects chest motion amplitude
- Idea:
  - Start with phase binning to obtain good initial MVF estimates.
  - Switch to amplitude binning afterwards to consider variations in amplitude.

Amplitude Gating

10 equidistant bins

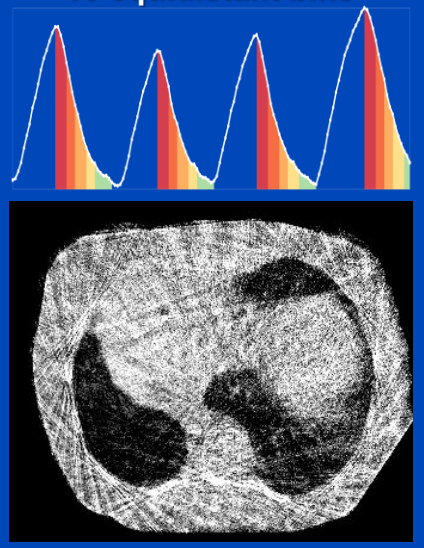


10 adaptive bins



Phase Gating

10 equidistant bins



Only the exhale bins are shown in the illustration. *C* = -100 HU, *W* = 1200 HU
Patient data provided by Wilko Verbakel, VU University Medical Center, Amsterdam.

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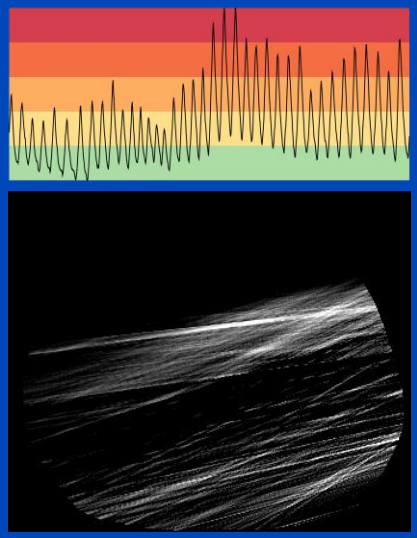
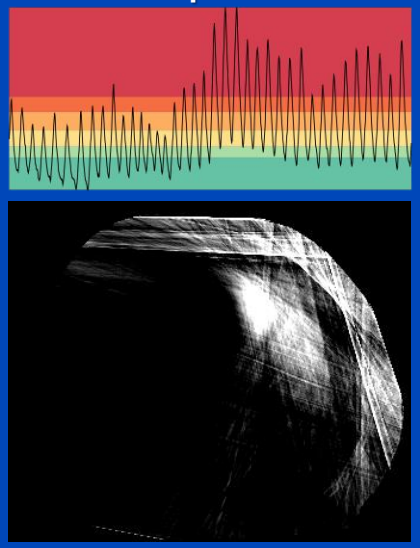
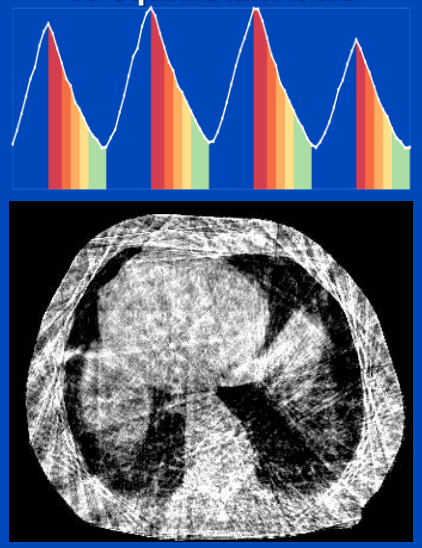


10 adaptive bins



Phase Gating

10 equidistant bins



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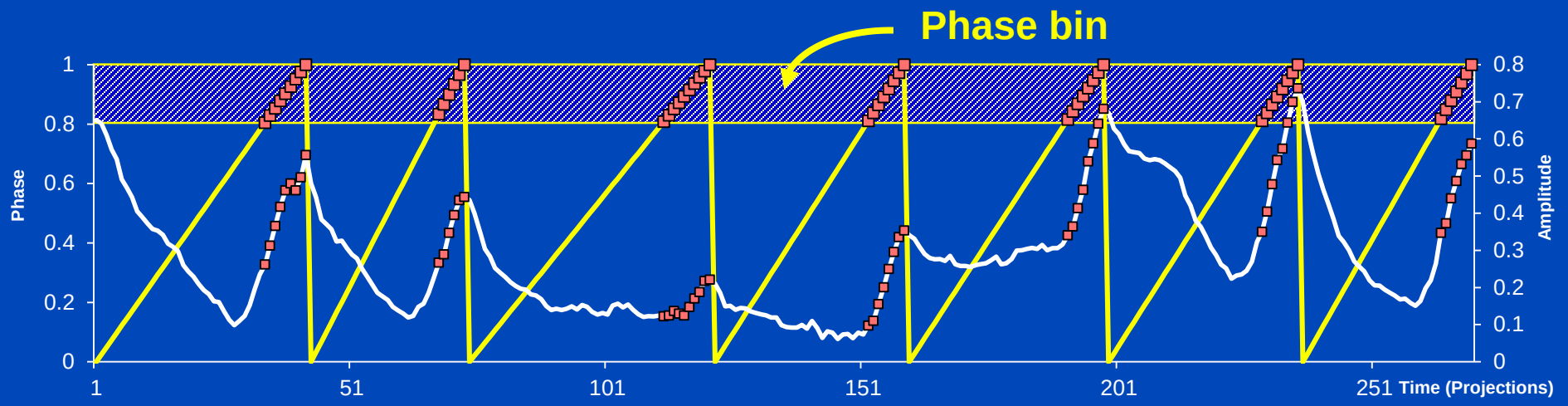
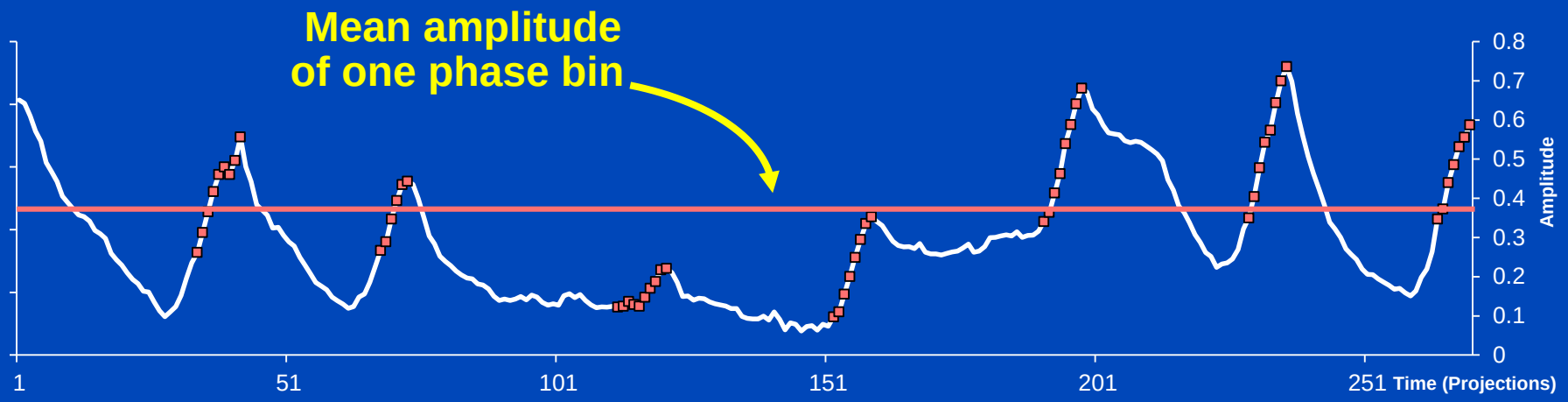
Step 1: Phase Gating



- The white curve shows a respiratory amplitude signal (external monitor)
- The yellow curve shows the dedicated phase signal (modulo 1)
- The red squares are phase-gated projections (phase and amplitude ordinates)

- Phase gating ensures a nearly uniform projection distribution for all phases
- Phase-gated projections may have a strong variation in their respiratory amplitude. This introduces motion blurring even with perfect MVFs.

Mean Amplitude of Phase Bins

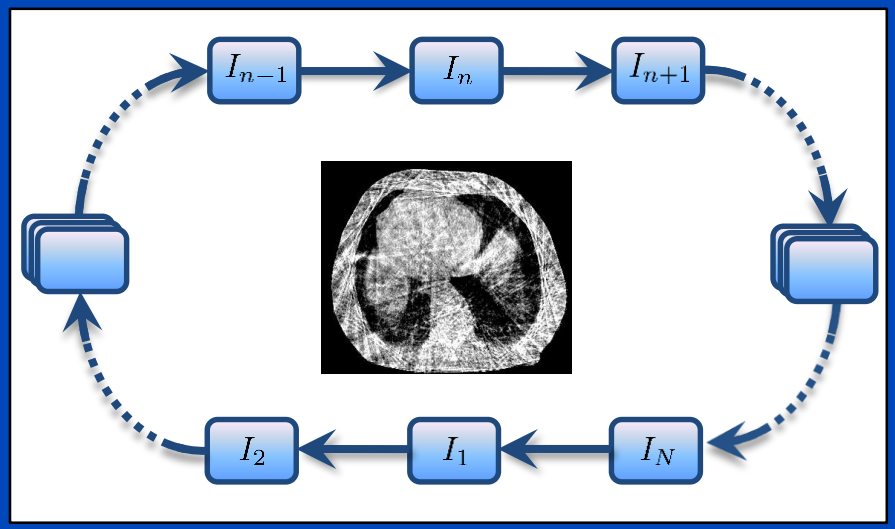


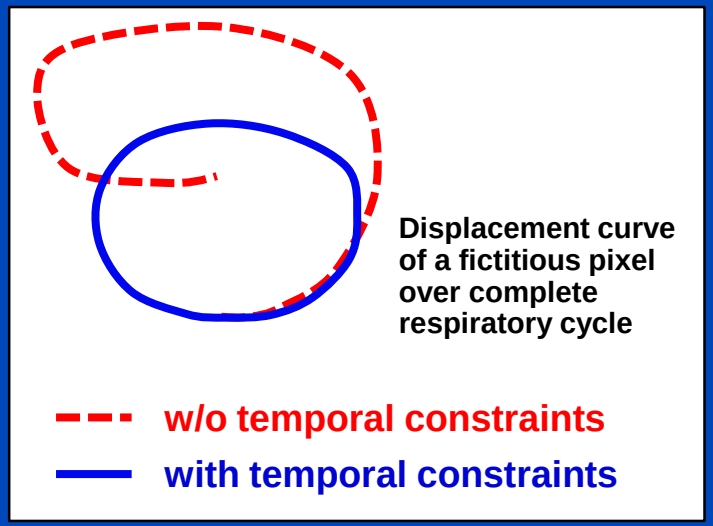
- The white curve shows a respiratory amplitude signal
- The red line represents the average amplitude of all projections in this phase

- Motion estimation is done between adjacent phase bins
- Pragmatic assumption: The MVFs describe the deformation between the mean amplitude of adjacent phase bins

Step 2: a) Motion Estimation
with Cyclic Regularization (cMoCo)

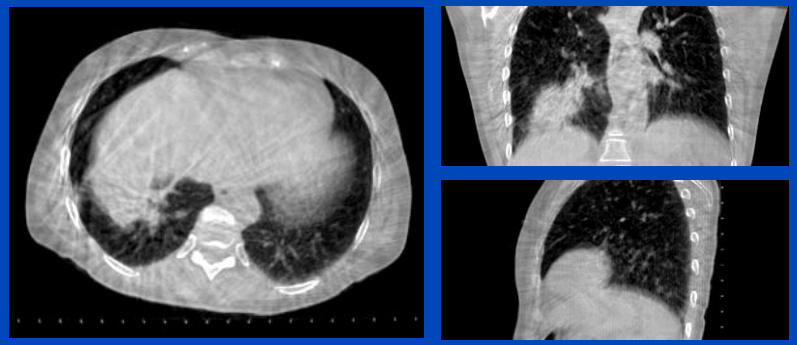
- Motion estimation only between adjacent phases
- Incorporate additional knowledge
  - A priori knowledge of quasi periodic breathing pattern
  - Non-cyclic motion is penalized
  - Error propagation due to concatenation is reduced



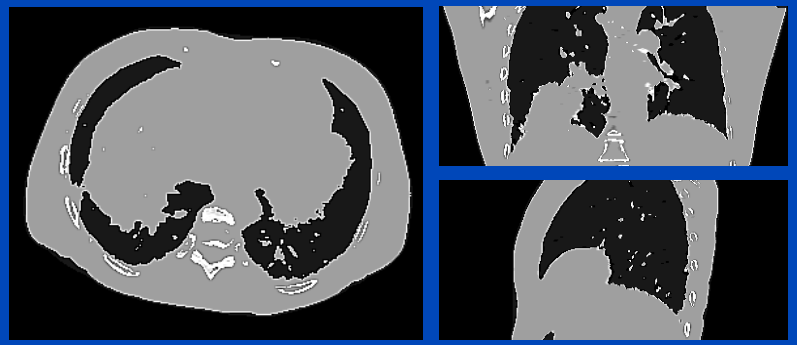


Brehm, Paysan, Oelhafen, Kunz, and Kachelrieß, "Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy," Med. Phys. 39(12), 7603-7618, 2012.

Artifact Model-Based MoCo (aMoCo)



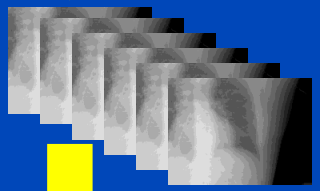
3D CBCT

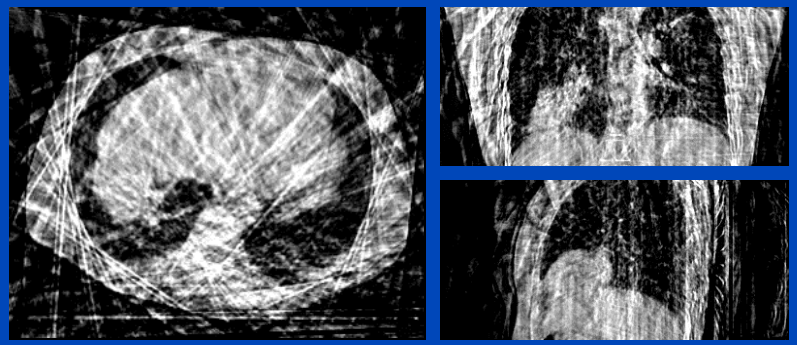


Segmented Image

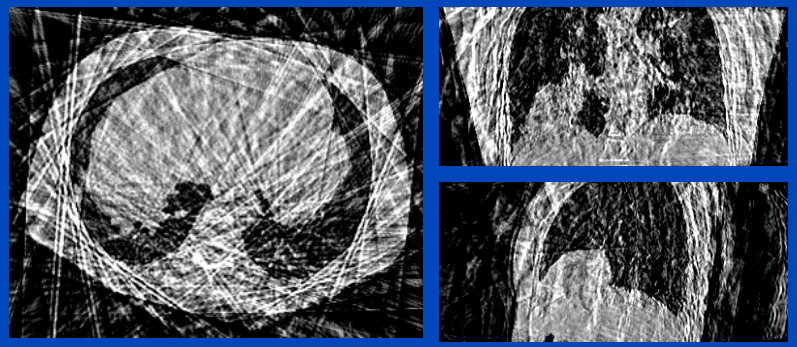
Measured data:

Virtual rawdata:





Gated 4D CBCT

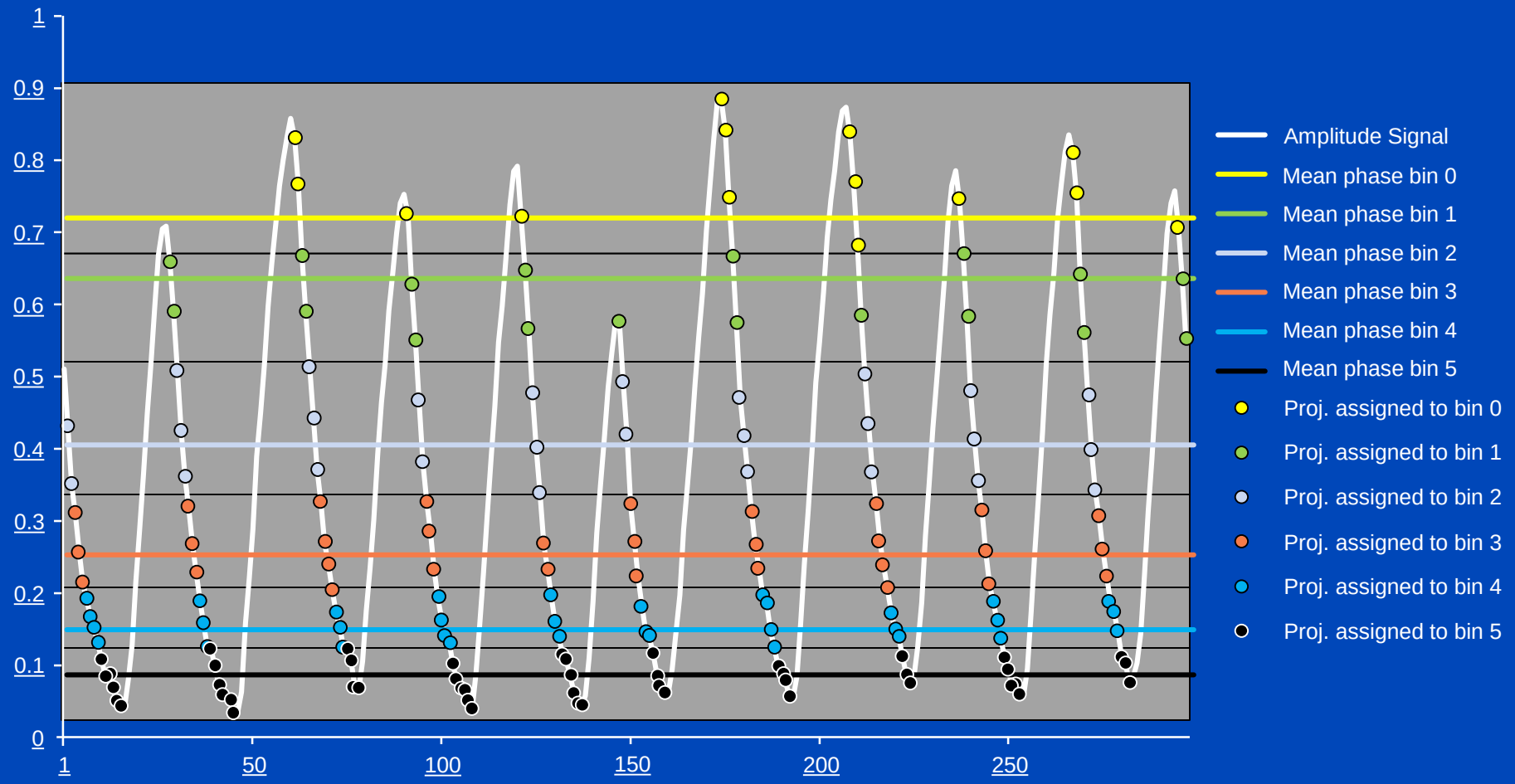


4D Artifact Images

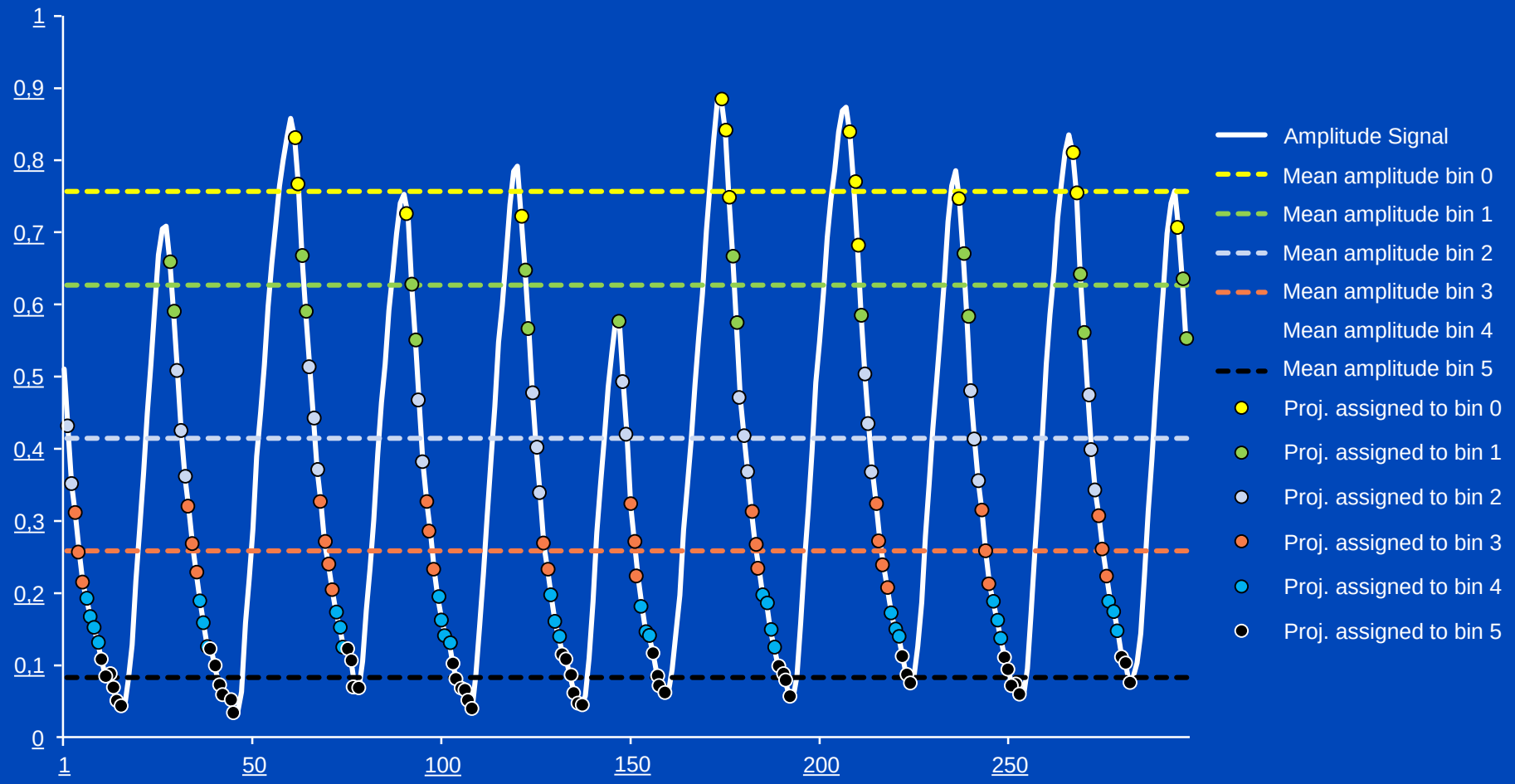
Brehm, Paysan, Oelhafen, and Kachelrieß, "Artifact-resistant motion estimation with a patient-specific artifact model for motion-compensated cone-beam CT" Med. Phys. 40(10):101913, 2013.

Step 3: Defining the Adaptive Amplitude Bins

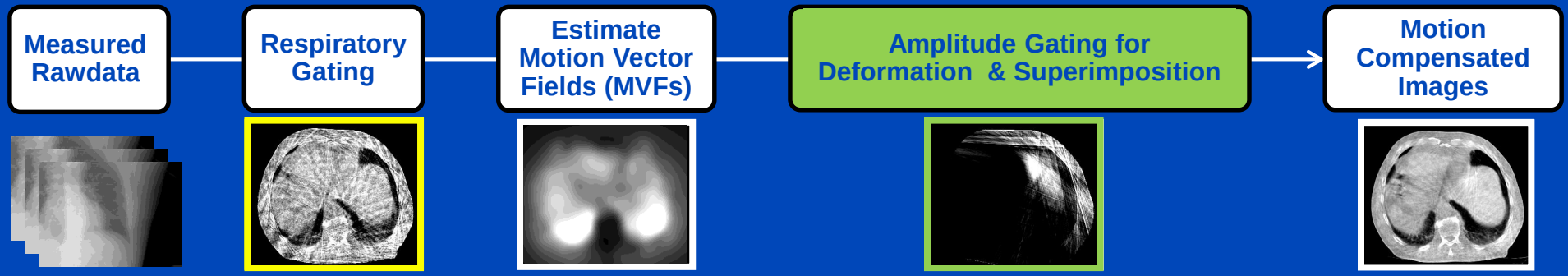
(exhale period shown, R=10, K=1)

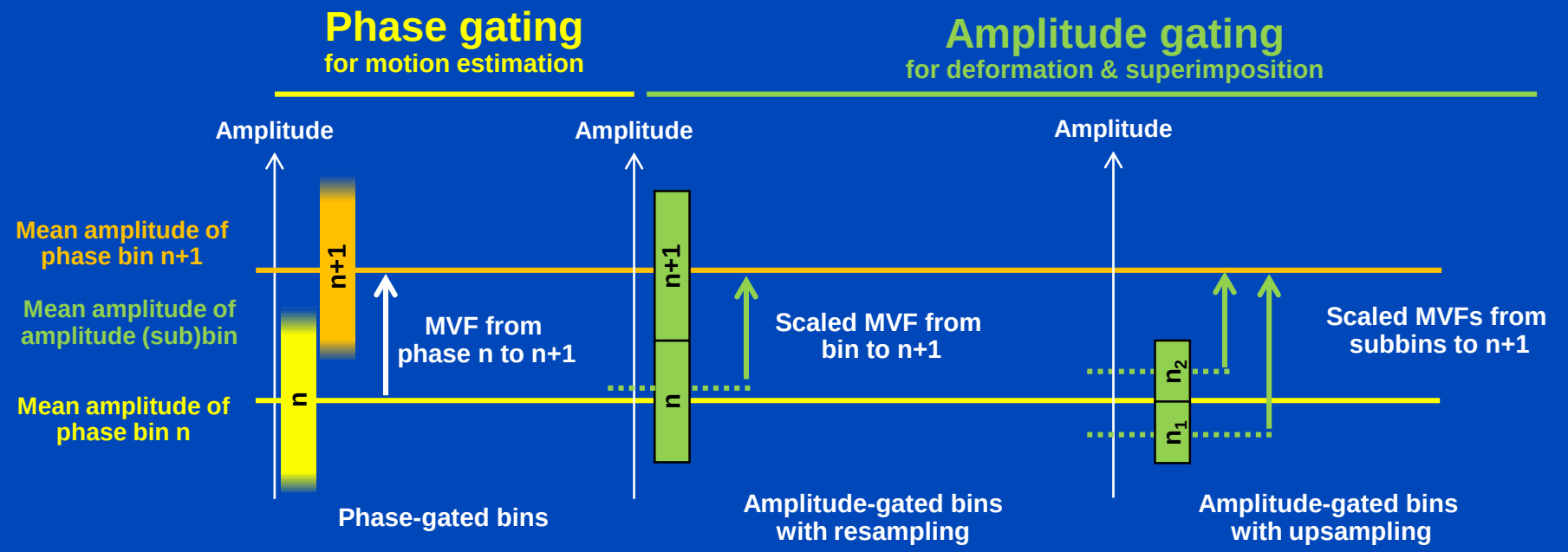


Step 4: Recalculation of the Mean Amplitudes



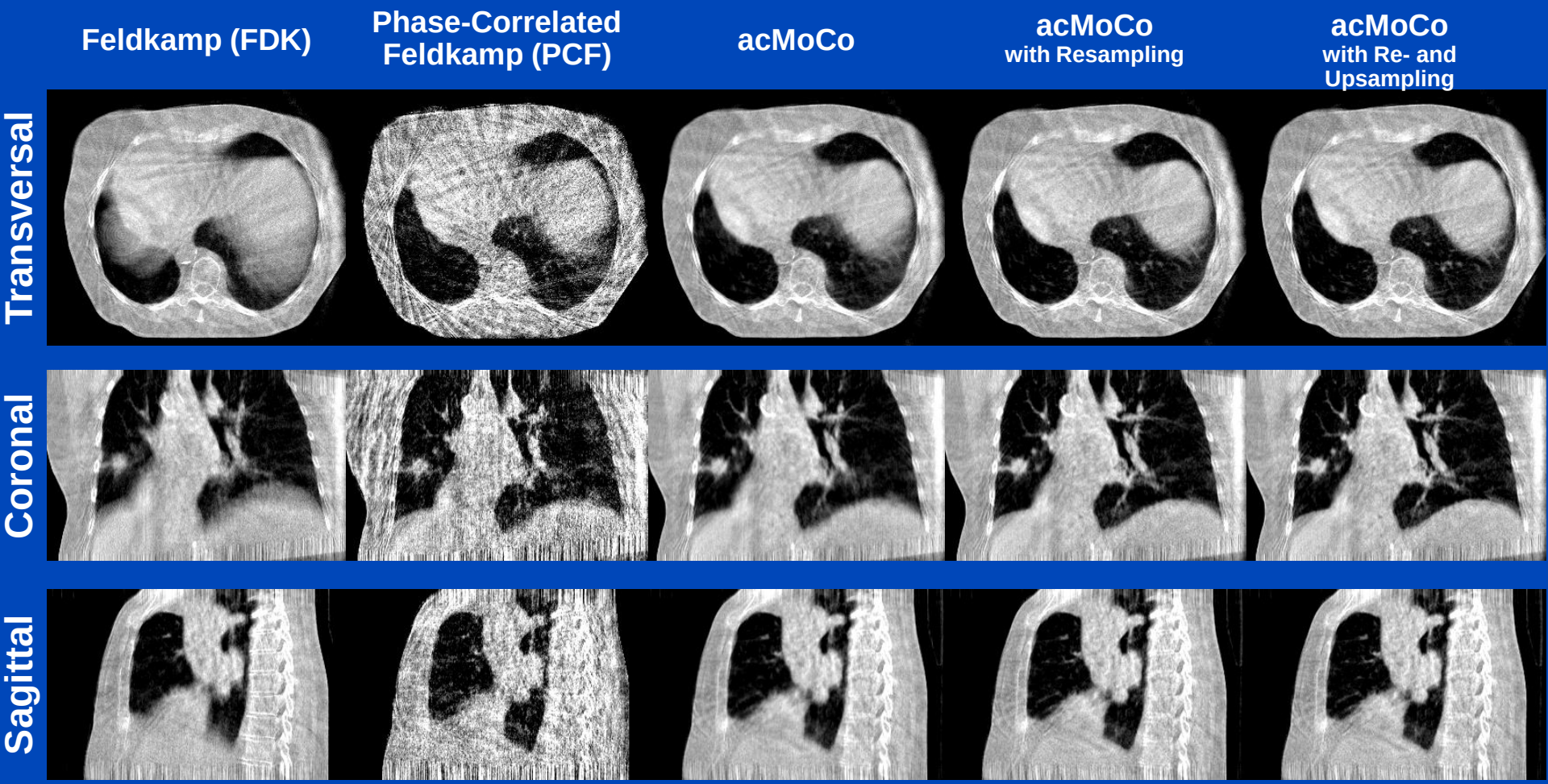
Switching From Phase to Amplitude Binning





Patient I

Motion Compensation R=10, 20% Bin Width
Scan Velocity 2 °/s with 7 fps, 21 rpm



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C = -100 HU, W = 1200 HU, playback speed 30 rpm
Patient data provided by Wilko Verbakel, VU University Medical Center, Amsterdam

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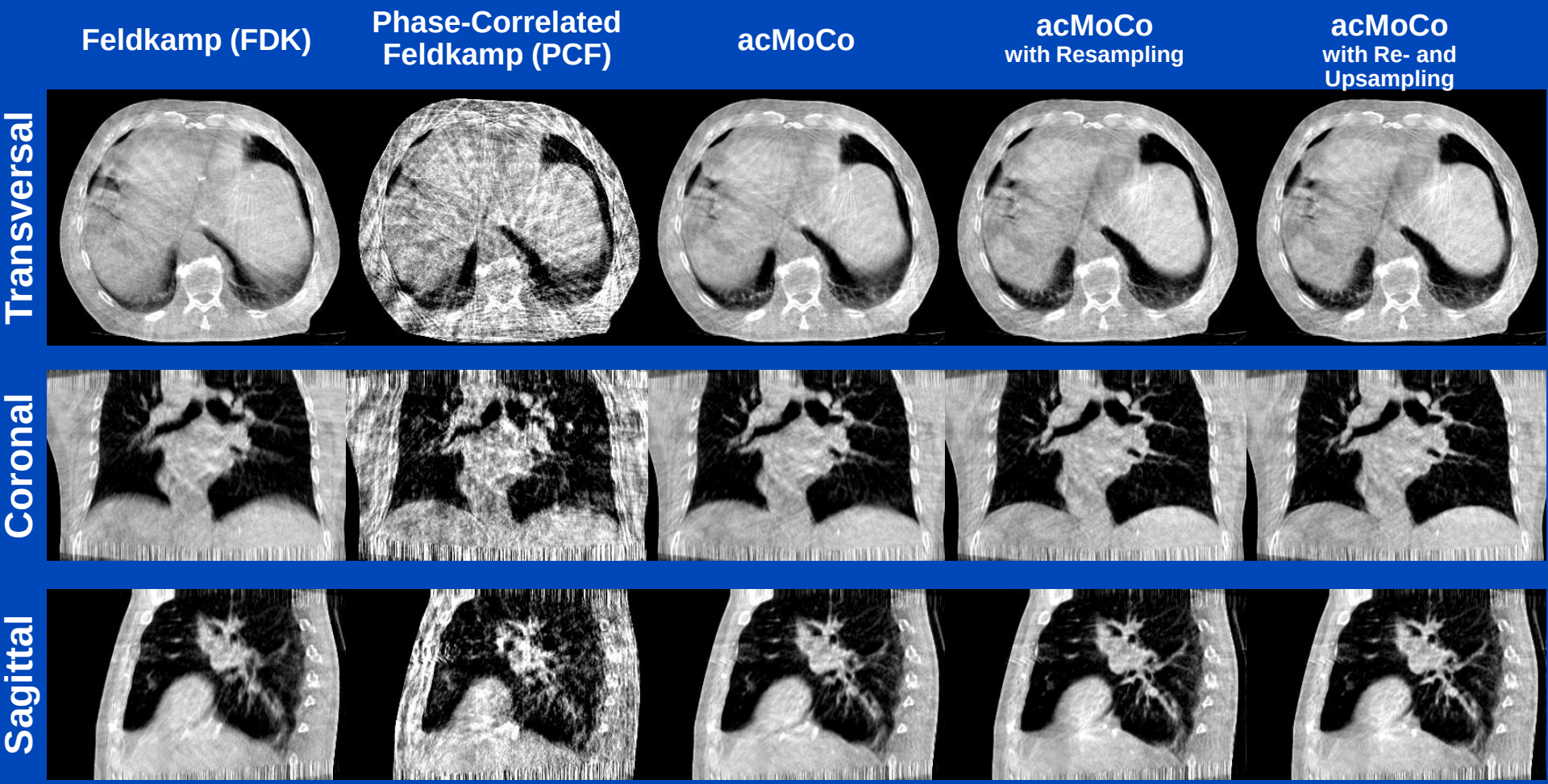
Patient II

Motion Compensation R=10, 20% Bin Width
Scan Velocity 3 °/s with 7 fps, 19 rpm



C = -100 HU, W = 1200 HU, playback speed 30 rpm
Patient data provided by Wilko Verbakel, VU University Medical Center, Amsterdam

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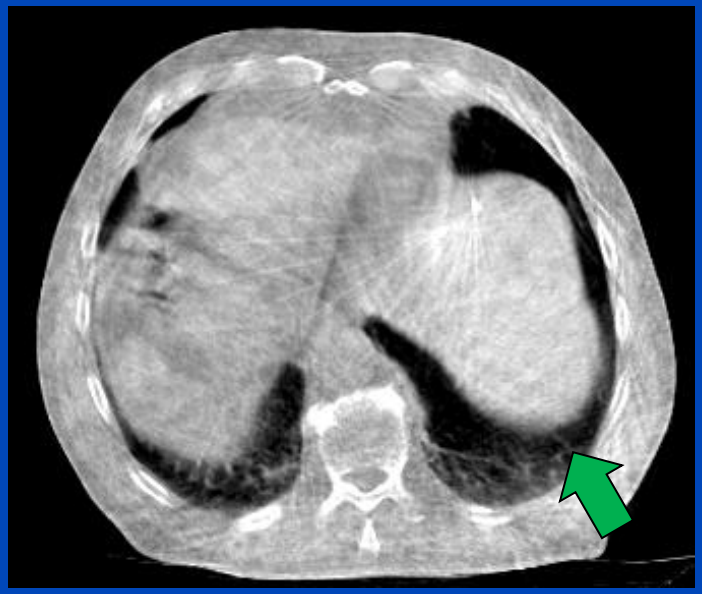
Patient II

Motion Compensation R=10, 20% Bin Width
Scan Velocity 3 °/s with 7 fps, 19 rpm

Transversal

acMoCo

acMoCo
with Resampling



C = -100 HU, W = 1200 HU, playback speed 30 rpm
Patient data provided by Wilko Verbakel, VU University Medical Center, Amsterdam

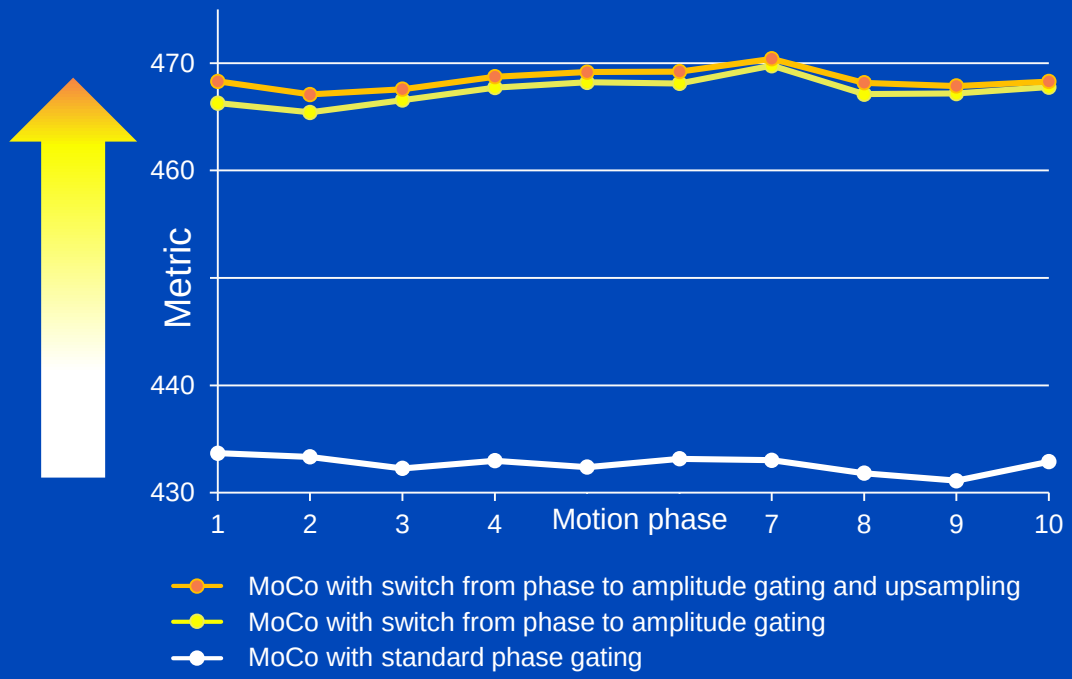
Sharpness Metric

Patient Data II

- **Sharpness metric $G(\mu)$ (image 3D gradient) was improved by switching from phase to amplitude gating by 8% and with additional upsampling up to 10%.**

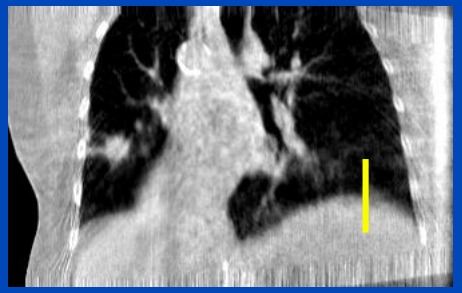
$$G(\mu) = \sum_j \nabla_x(\mu_j)^2 + \nabla_y(\mu_j)^2 + \nabla_z(\mu_j)^2$$

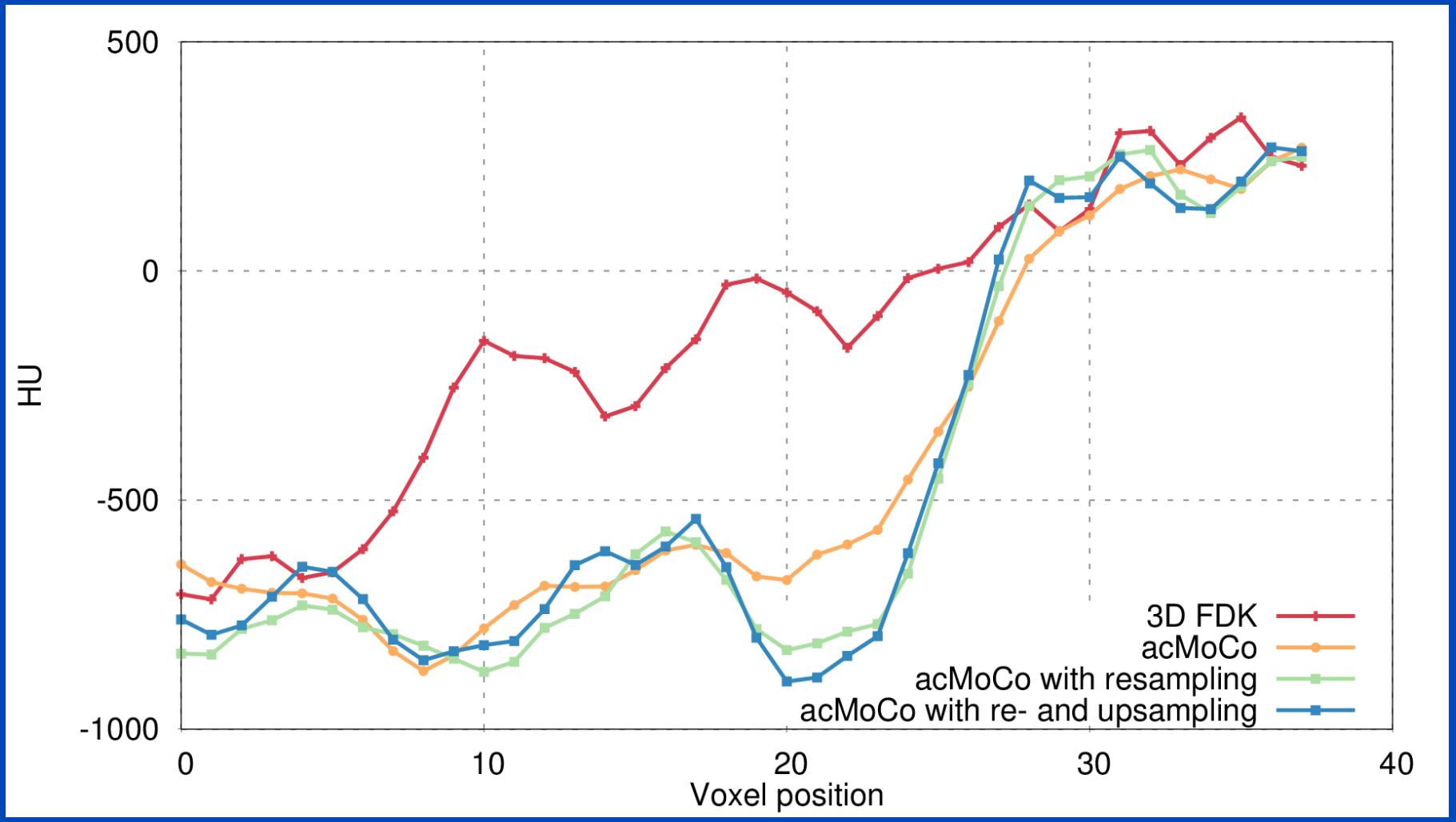
10% sharpness improvement



Edge Profile

Patient Data II, End Inhale Phase





Summary

- MVF resampling allows to robustly switch from phase to amplitude binning.
- Especially for irregular breathing pattern motion blurring was reduced.
- Motion blurring was reduced in all motion bins.
- MVF resampling does not increase computation time.
- The additional upsampling may not be necessary.

Thank You!

This study was supported by Varian Medical Systems.

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

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

Job opportunities through DKFZ's international PhD or Postdoctoral Fellowship programs (www.dkfz.de), or directly through Marc Kachelriess (marc.kachelriess@dkfz.de).