Compensating for Irregular Respiratory Motion in Cone-Beam CT (CBCT): Motion Vector Field Resampling

Sebastian Sauppe[1], Marcus Brehm[2], Pascal Paysan[2], Dieter Seghers[2], and Marc Kachelrieß[1]

[1] German Cancer Research Center (DKFZ), Heidelberg, Germany

[2] Varian Medical Systems Imaging Laboratory, Baden-Dättwil, Switzerland

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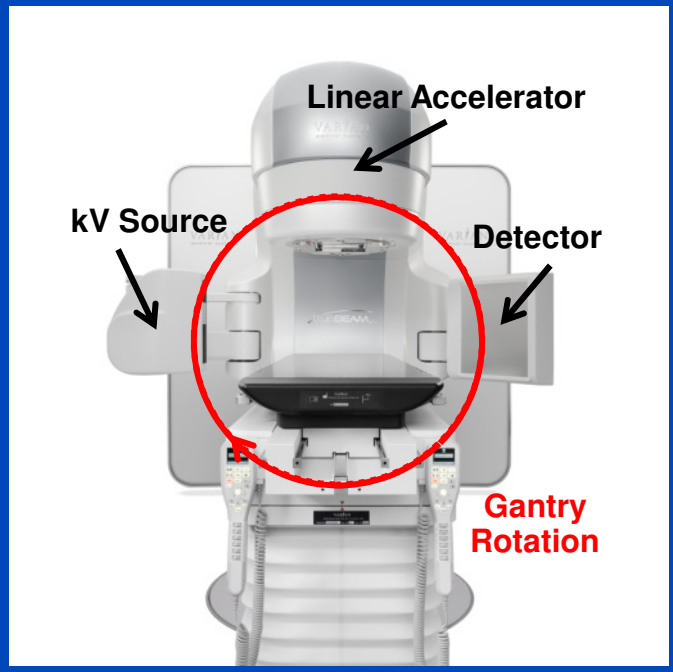
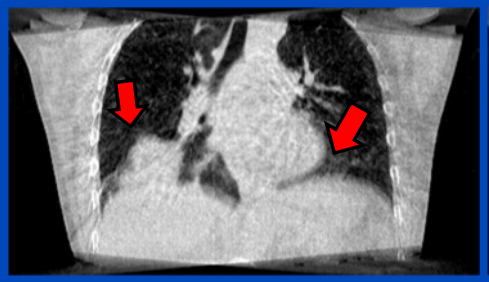
Slowly Rotating CBCT Devices

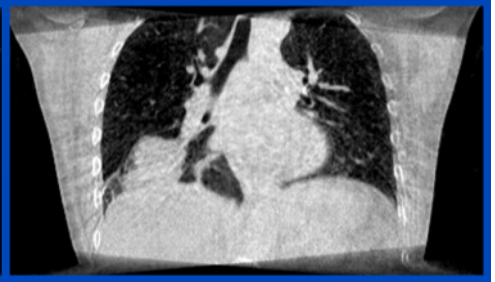
- Image-guided radiation therapy (IGRT)
  - Cone-beam CT (CBCT) imaging unit mounted on gantry of a LINAC treatment system
  - Accurate information about patient motion required for radiation therapy
- Slow gantry rotation speed of 6° per second (60 s/360°)
  - Much slower than clinical CT devices
- Breathing about 10 to 30 respiration cycles per minute (and thus per scan)
- Heartbeat about 50 to 80 beats per minute

Account for patient motion!





Motion blurring in standard 3D reconstruction



5D* motion compensation removes almost all motion blurring

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*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.

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Aims

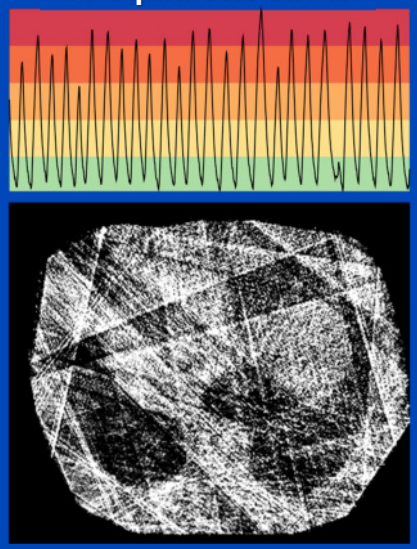
- To provide high fidelity motion-compensated (MoCo) respiratory- or cardiac-correlated volumes from CBCT.
- To further increase the temporal resolution by motion vector field (MVF) resampling.
- Use cases for MoCo (in the field of radiation therapy):
  - Accurate patient positioning
  - Reduce irradiation of the heart (organ at risk)
  - Treatment verification
  - Online treatment adaption
  - …

Why MVF Resampling?

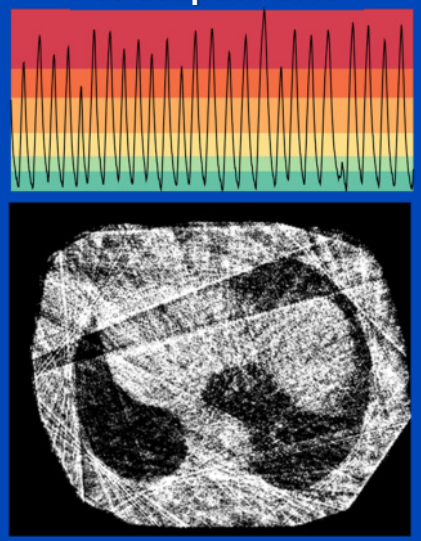
- Phase binning = nearly homogeneous projection angle distribution
- Amplitude binning = reflects chest motion amplitude
- Idea:
  - Start with phase binning to obtain good initial MVF estimates.
  - Switch to amplitude binning afterwards to consider variations in amplitude.

Amplitude Gating

10 equidistant bins

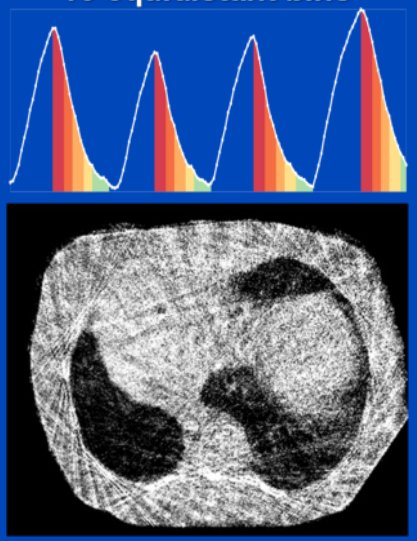


10 adaptive bins



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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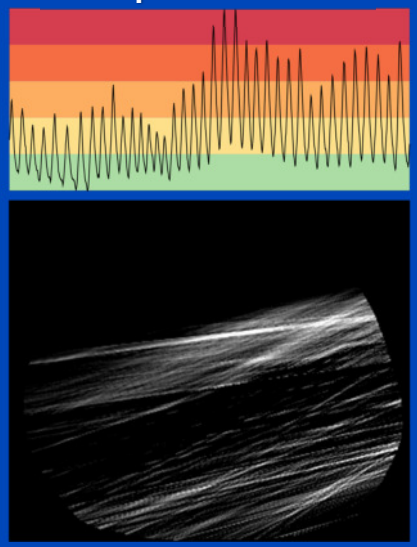
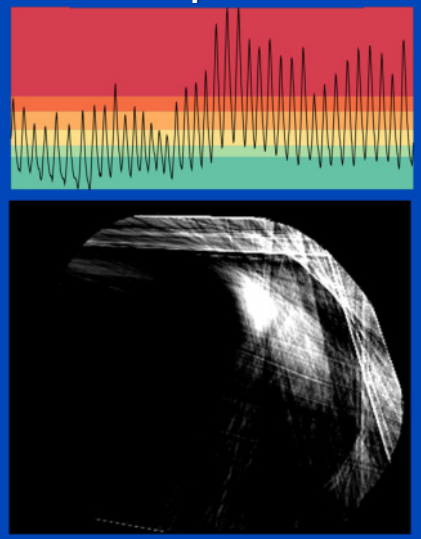


10 adaptive bins



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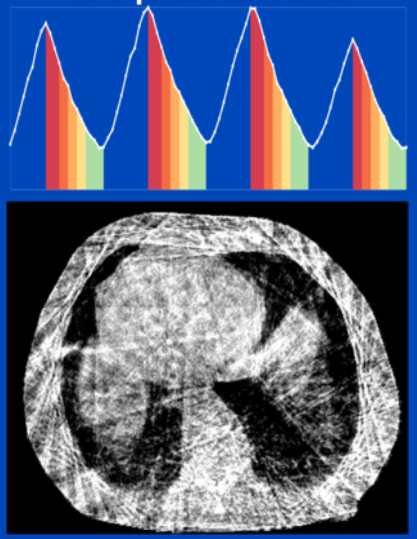

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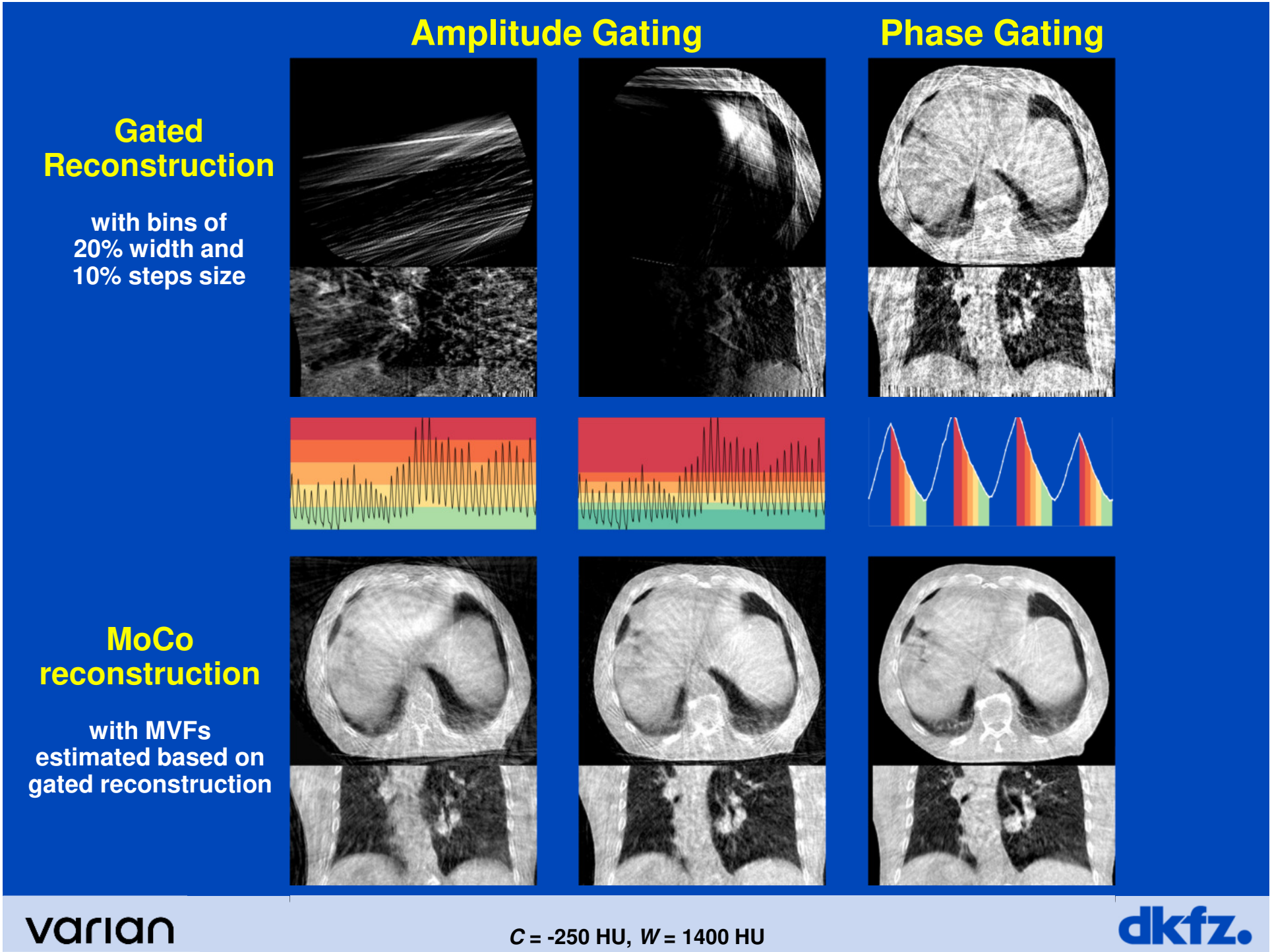
Amplitude Gating
Phase Gating
Gated Reconstruction
with bins of 20% width and 10% steps size
MoCo reconstruction
with MVFs estimated based on gated reconstruction
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C = -250 HU, W = 1400 HU
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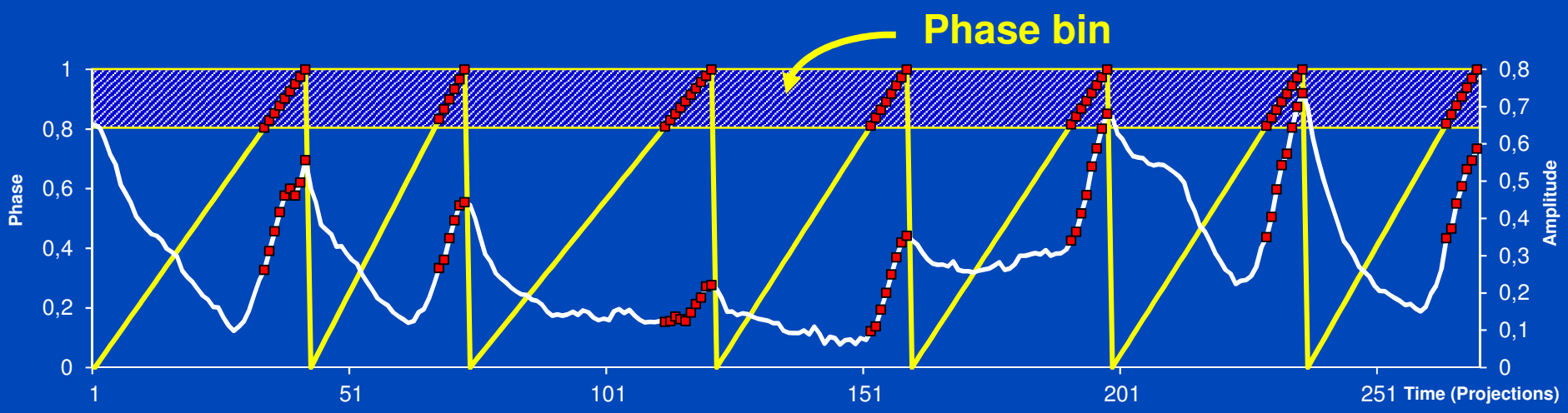
Step 1: Phase Gating

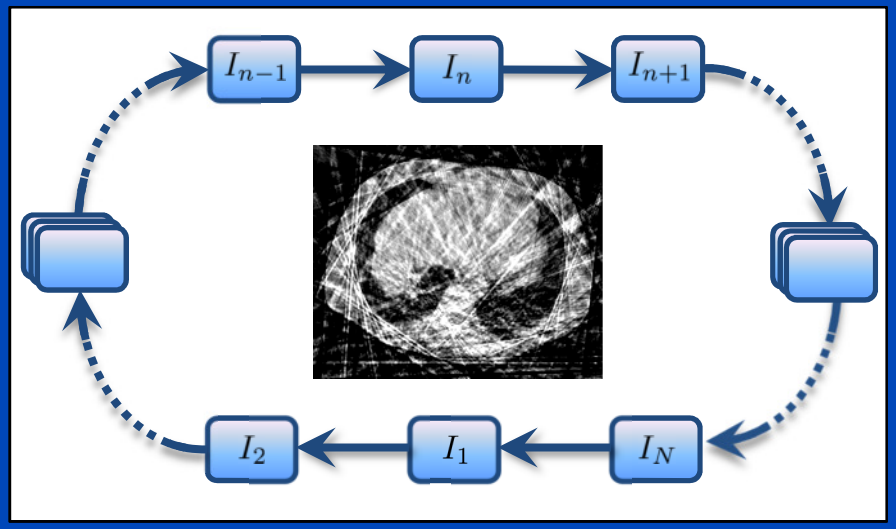


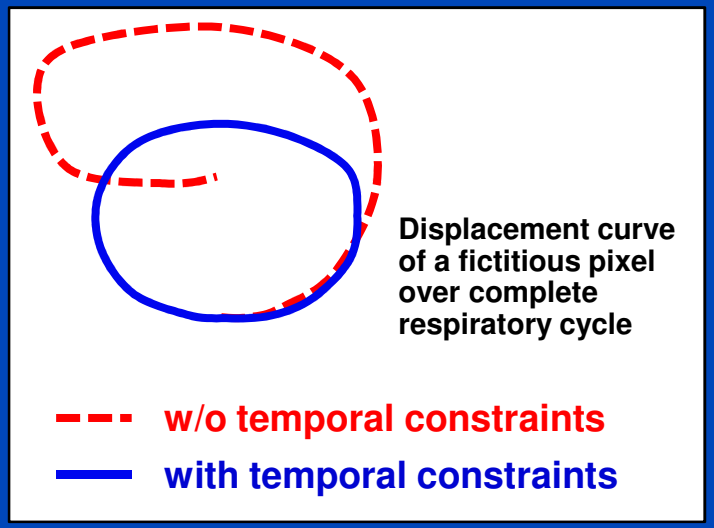
- The white curve shows a respiratory amplitude signal (external monitor)
- The yellow curve shows the dedicated phase signal (modulo 1)
- The red squares are phase-gated projections (phase and amplitude ordinates)

- 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.

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

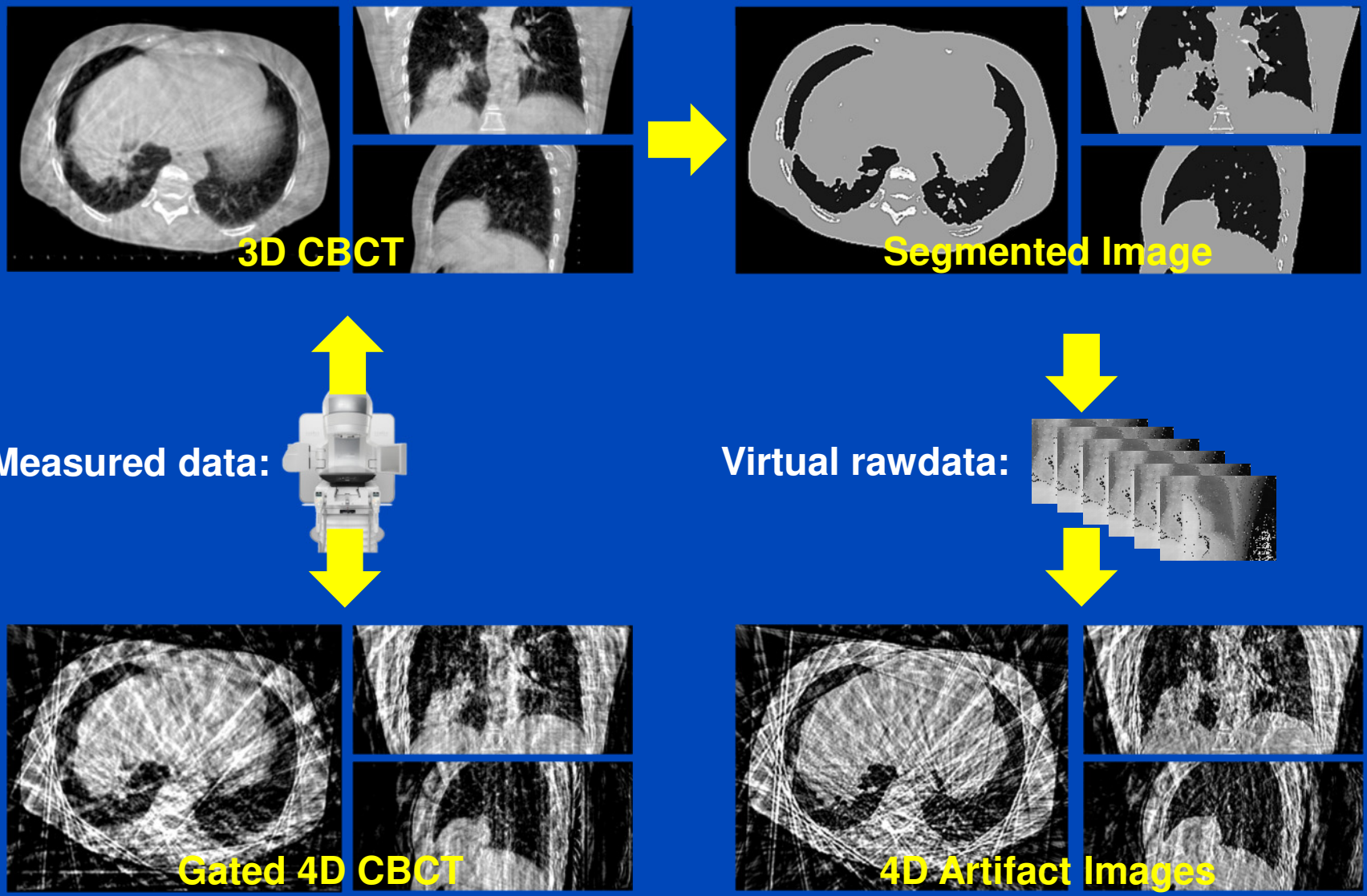
- Motion estimation only between adjacent phases
- Incorporate additional knowledge
  - A priori knowledge of quasi periodic breathing pattern
  - Non-cyclic motion is penalized
  - Error propagation due to concatenation is reduced





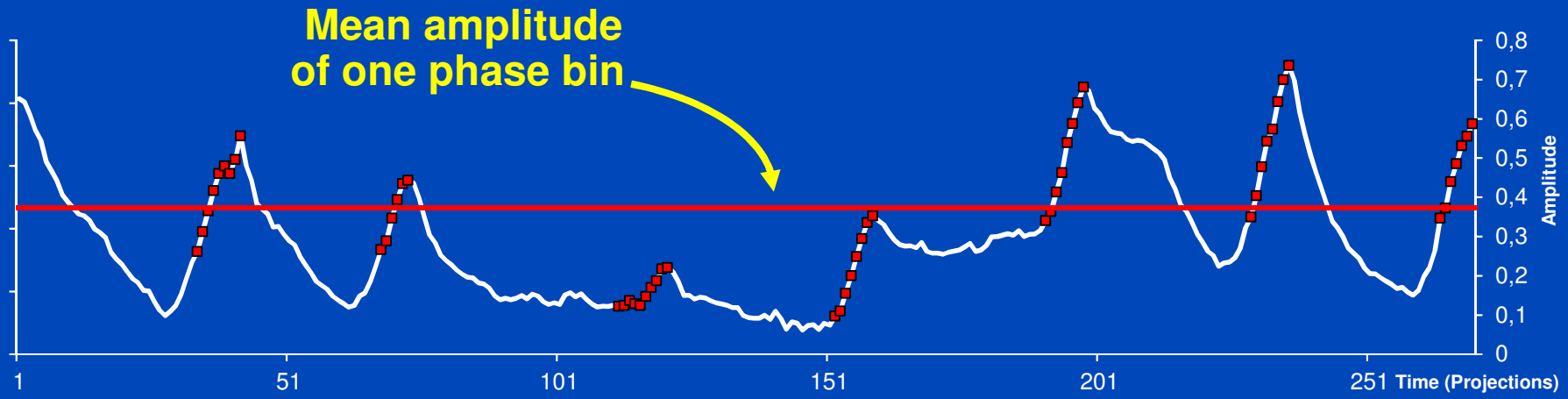
Brehm, Paysan, Oelhafen, Kunz, and Kachelrieß, "Self-adapting cyclic registration for motion-compensated cone-beam CT in image-guided radiation therapy," Med. Phys. 39(12):7603-7618, 2012.

Step 2: b) Motion Estimation
with Artifact-Model-Based Regularization (aMoCo)



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.

Mean Amplitude of Phase Bins

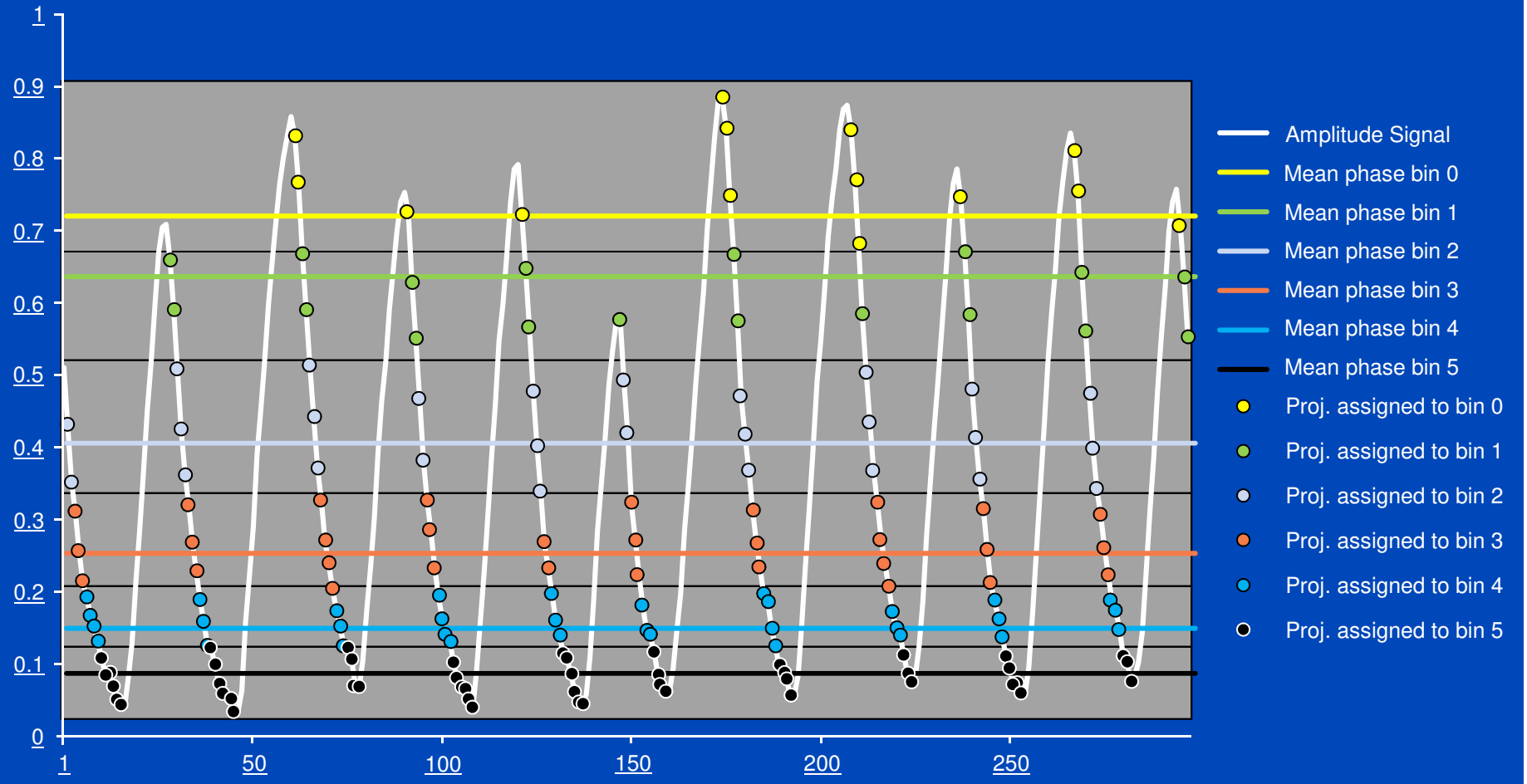


- The white curve shows a respiratory amplitude signal
- The red line represents the average amplitude of all projections in this phase

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

Step 3: Defining the Adaptive Amplitude Bins

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



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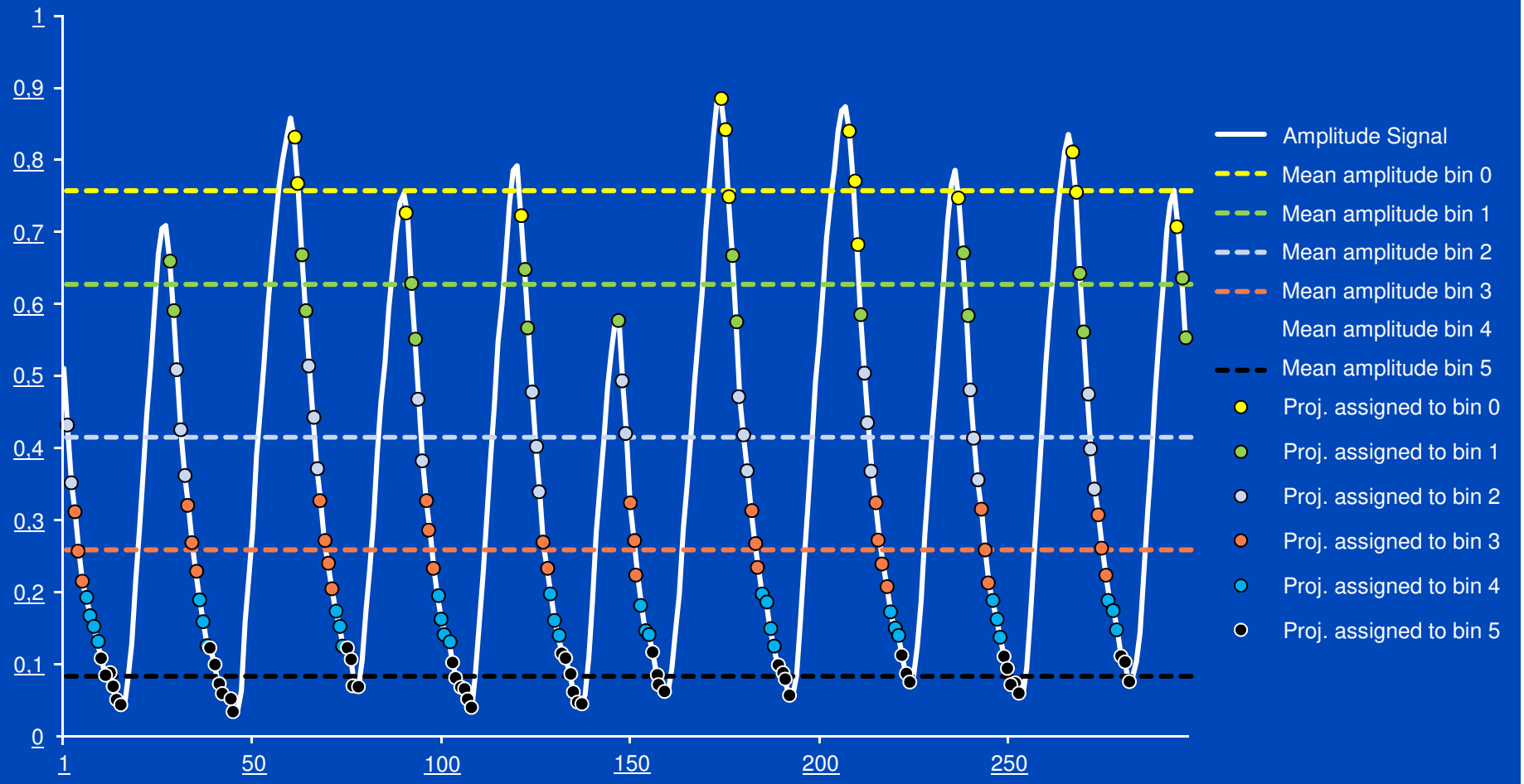
Step 4: Recalculation of the Mean Amplitudes



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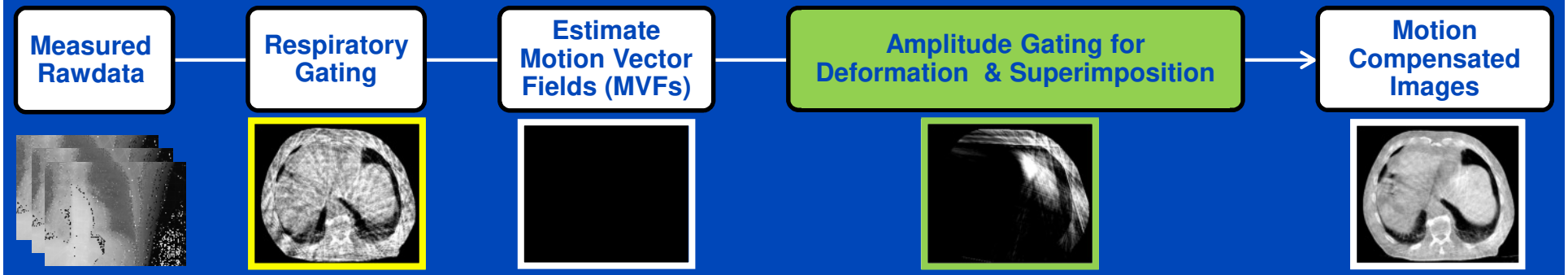
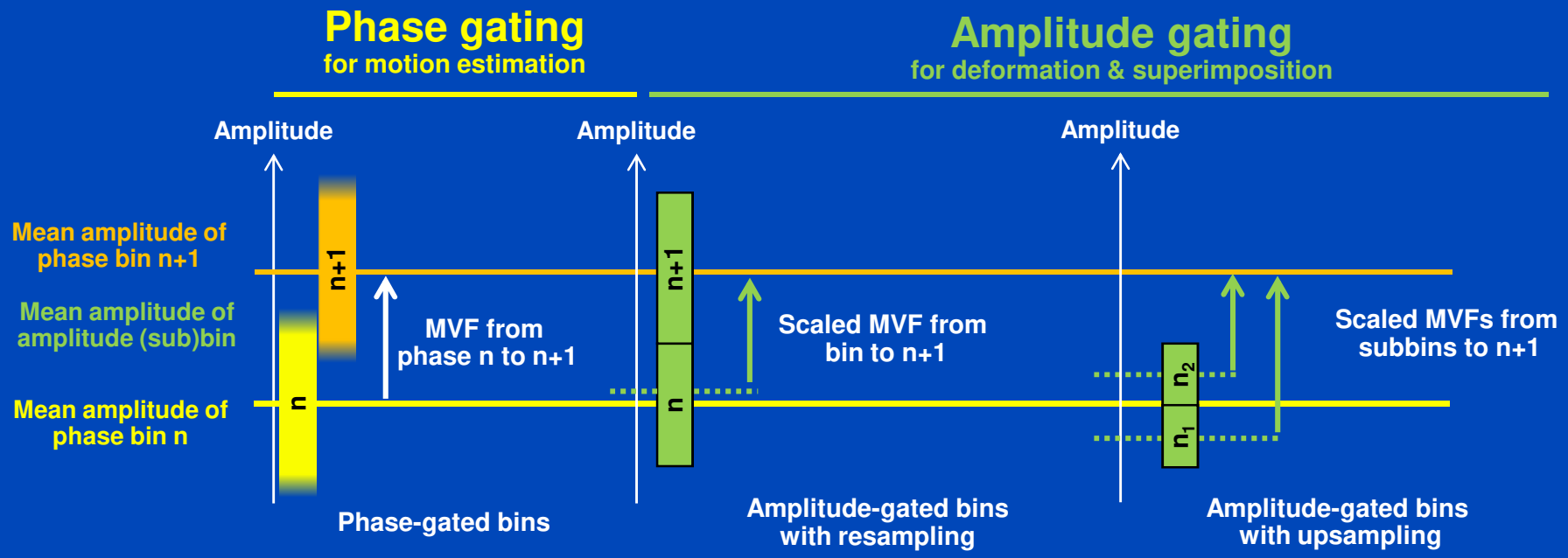
Switching
From Phase to Amplitude Binning





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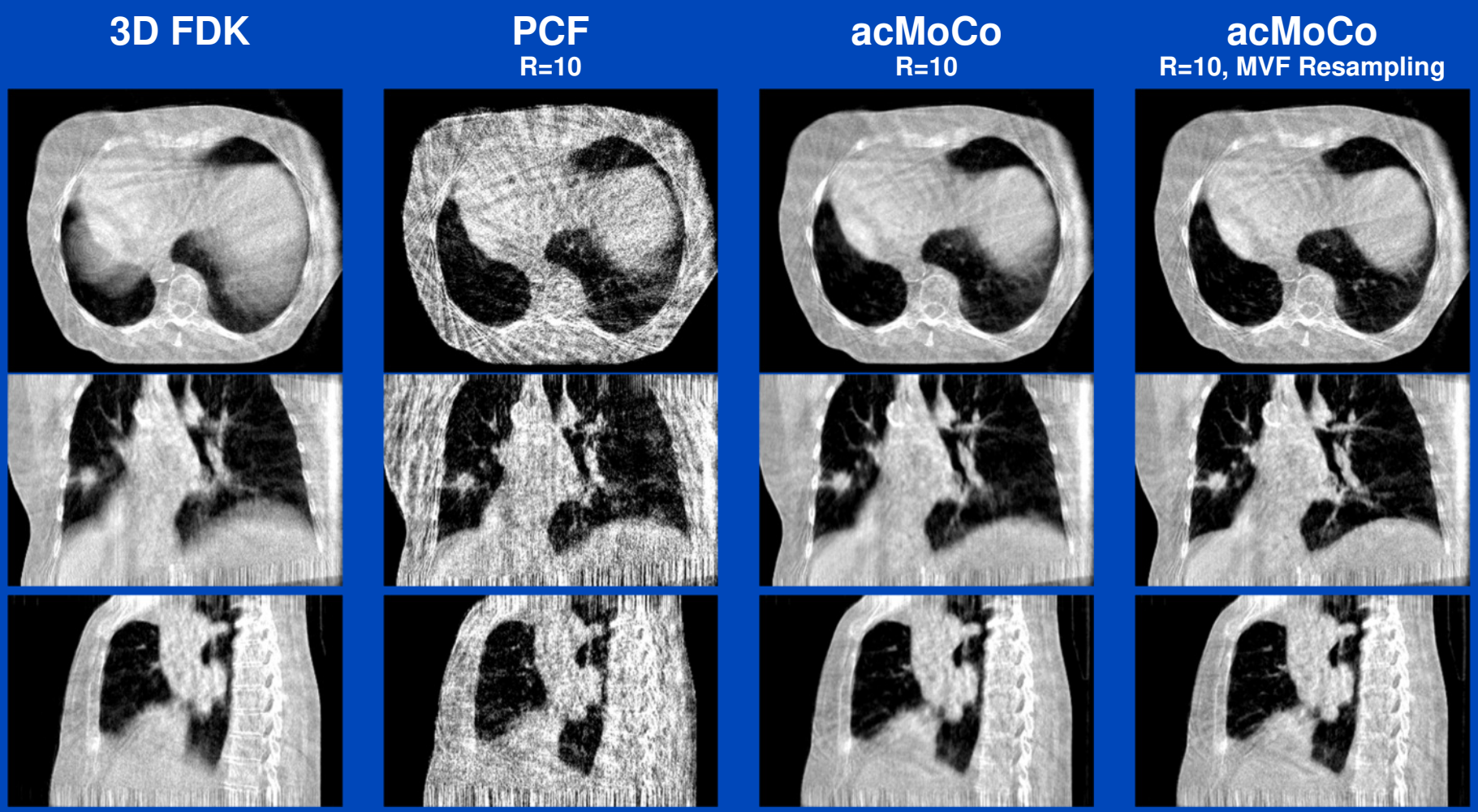
Patient Data

Motion Compensation R=10, 20% Bin Width
Scan Velocity 2 °/s with 7 fps, 13 rpm



C = -100, W = 1200 HU
playback speed 30 rpm

Summary

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

Thank You!

- This study was supported by Varian Medical Systems.

- 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).

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