Motion-Compensated 4D Cone-Beam Computed Tomography

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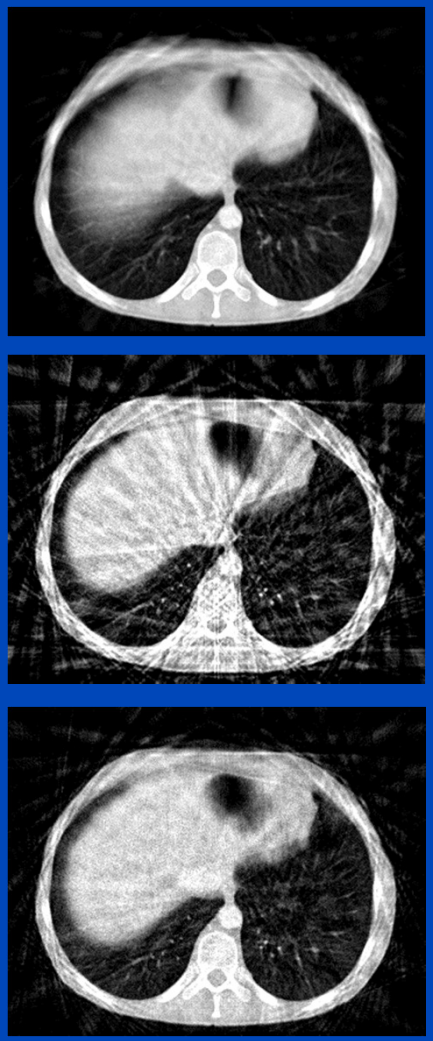
Image Guidance for Radiation Therapy

- **Linac with on-board imaging**
  - Limited data acquisition frame rate
  - Slow gantry rotation (≥ 60 s per 360 °)
  - Requires phase-correlated reconstruction to avoid motion artifacts

- **Aims for the new 4D algorithm:**
  - Decrease of motion artifacts
  - Increase temporal resolution
  - Decrease image noise
  - Increase dose usage

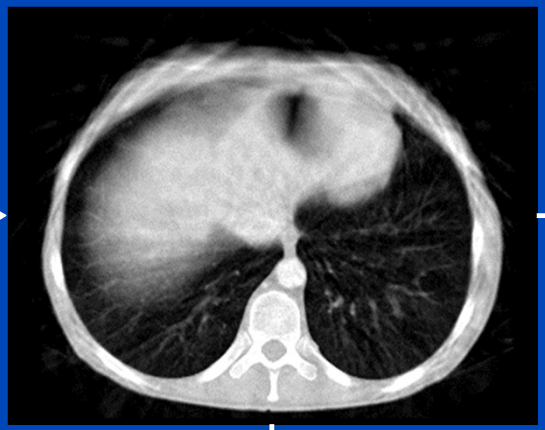
Reconstruction Techniques

- **Feldkamp[1] (FDK)**
  - All projections used
  - Non phase-correlated ⇒ motion artifacts
- **Phase-Correlated Feldkamp (PCF)**
  - Feldkamp applied on phase bins
  - Only phase-correlated projections used
    - » Streak artifacts
- **McKinnon-Bates[2] (MKB)**
  - Initial image with Feldkamp
  - Adding correction image based on phase-correlated projections



[1] Feldkamp et al., *Practical cone-beam algorithm*, J Opt Soc Am, A6(1), 1984, 612–619
[2] McKinnon et al., *Towards imaging the beating heart usefully with a conventional CT scanner*, IEEE Trans Biomed Eng, BME-28(2), 1981, 123–127

McKinnon-Bates Algorithm

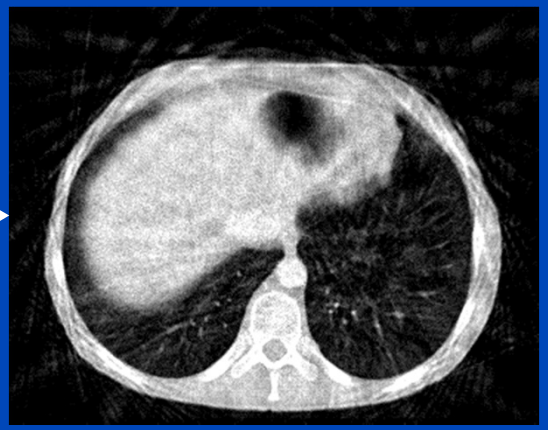


Initial image with motion blurring due to respiratory motion

C/W = -200/1400 HU

+

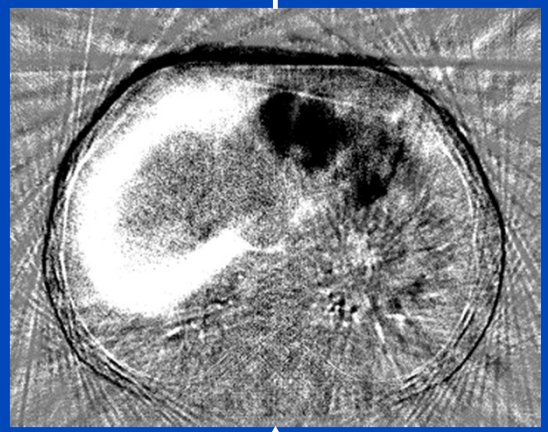
Corrected Image



C/W = -200/1400 HU

Data

Forward projection



Correction image with high temporal resolution

C/W = 0/500 HU

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Phase-information

Phase-correlated reconstruction

McKinnon et al., *Towards imaging the beating heart usefully with a conventional CT scanner*, IEEE Trans Biomed Eng, BME-28(2), 1981, 123–127

Motion Compensation

- **Backprojection of projections of phase j**

$$f_j(x, y, z)$$

- **Time-dependent transformation $\mathrm{T}_{j,i}$**

$$f_i(x, y, z) \approx \mathrm{T}_{j,i}[f_j](x, y, z)$$

- **Motion compensation**

$$f_i(x, y, z) \approx \frac{1}{N} \sum_{j=1}^{N} \mathrm{T}_{j,i}[f_j](x, y, z)$$

Motion-Compensated Reconstruction in Image-Guided Radiation Therapy

- Motion modeling by
  - registration of 4D clinical CT data set[1,2]
  - registration of PCF to clinical CT data set[3]
  - registration of PCF reconstructions with each other[3]
    - » A large number of projections is required
    - » In measurements the multiply-gantry rotation technique was used
  - Almost artifact-free PCF reconstructions were demonstrated[1,2,3]
- Our new approach should work
  - for a low number of projections (no special acquisition technique)
  - without need of clinical CT data

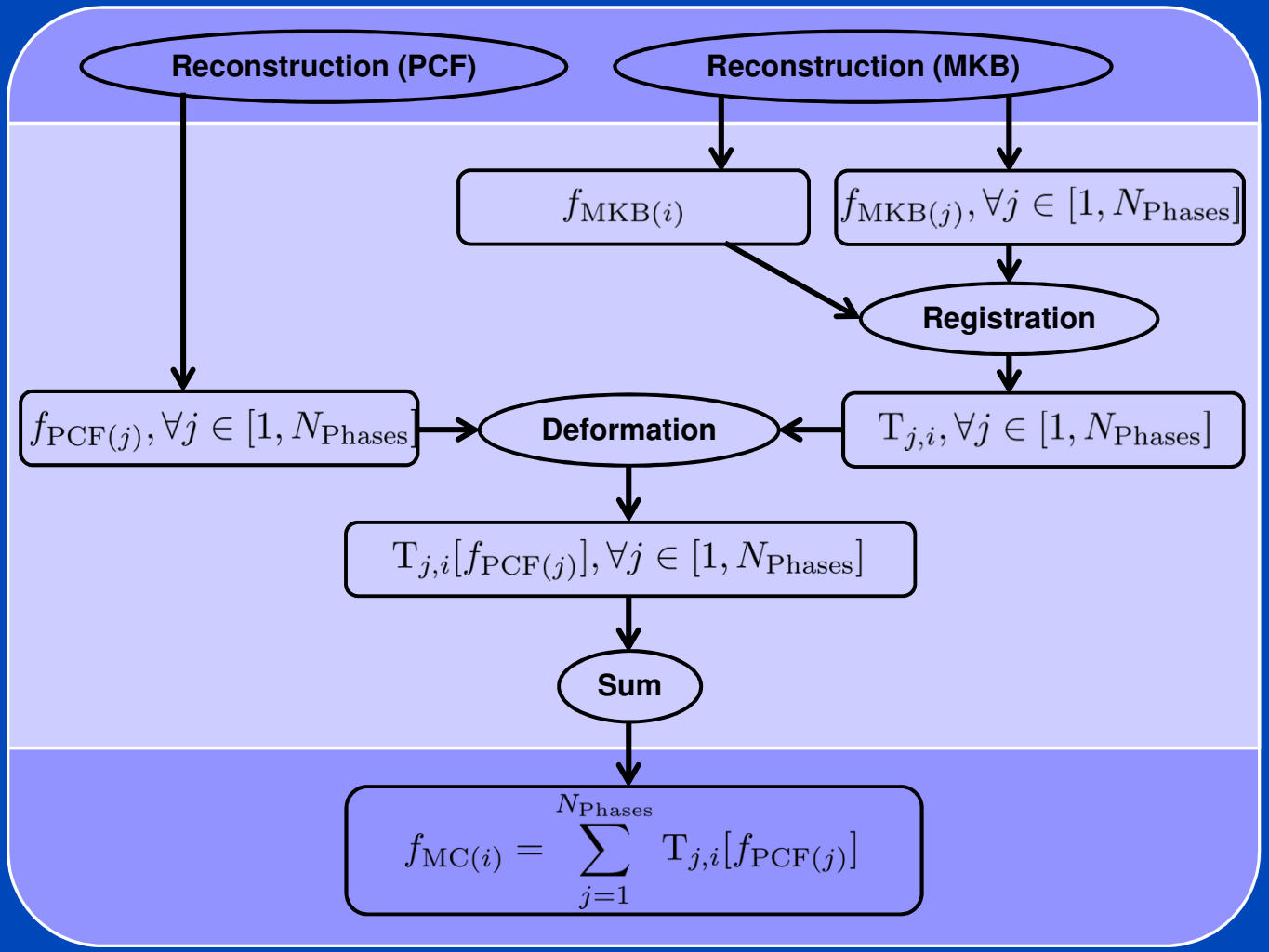
[1]Li et al., *Motion correction for improved target localization with on-board cone-beam computed tomography*, Phys Med Biol, 51(2), 2006, 253–267
[2]Rit et al., *On-the-fly motion-compensated cone-beam CT using an a priori model of the respiratory motion*, Med Phys, 36(6), 2009, 2283–2296
[3]Li et al., *Enhanced 4D cone-beam CT with inter-phase motion model*, Med Phys, 34(9), 2007, 3688–3695

Our Approach

- **Determination of motion vector fields (MVFs) via non-rigid registration of 4D CBCT reconstructions**
  - **CBCT data itself are used**
  - **No need of clinical CT data**
    - » **Eliminates influence of variation in tissue and motion between CBCT and clinical CT data acquisition**
  - **Demons algorithm[1] with symmetric forces[2] and step width control**
    - » **Intensity-based non-rigid registration algorithm (optical flow)**
- **Use of MKB instead of PCF reconstructions in registration process**
  - **Robustness due to decreased impact of sparsifying artifacts on the registration process**

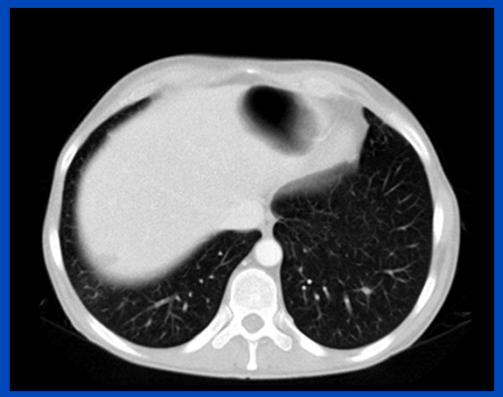
[1] Thirion, *Image matching as a diffusion process*, Med Image Anal, 1998, 2(3), 243–260
[2] Wang et al., *Validation of an accelerated 'demons' algorithm,* Phys. Med. Biol., 50, 2005, 2887–2905

Illustration of the Approach



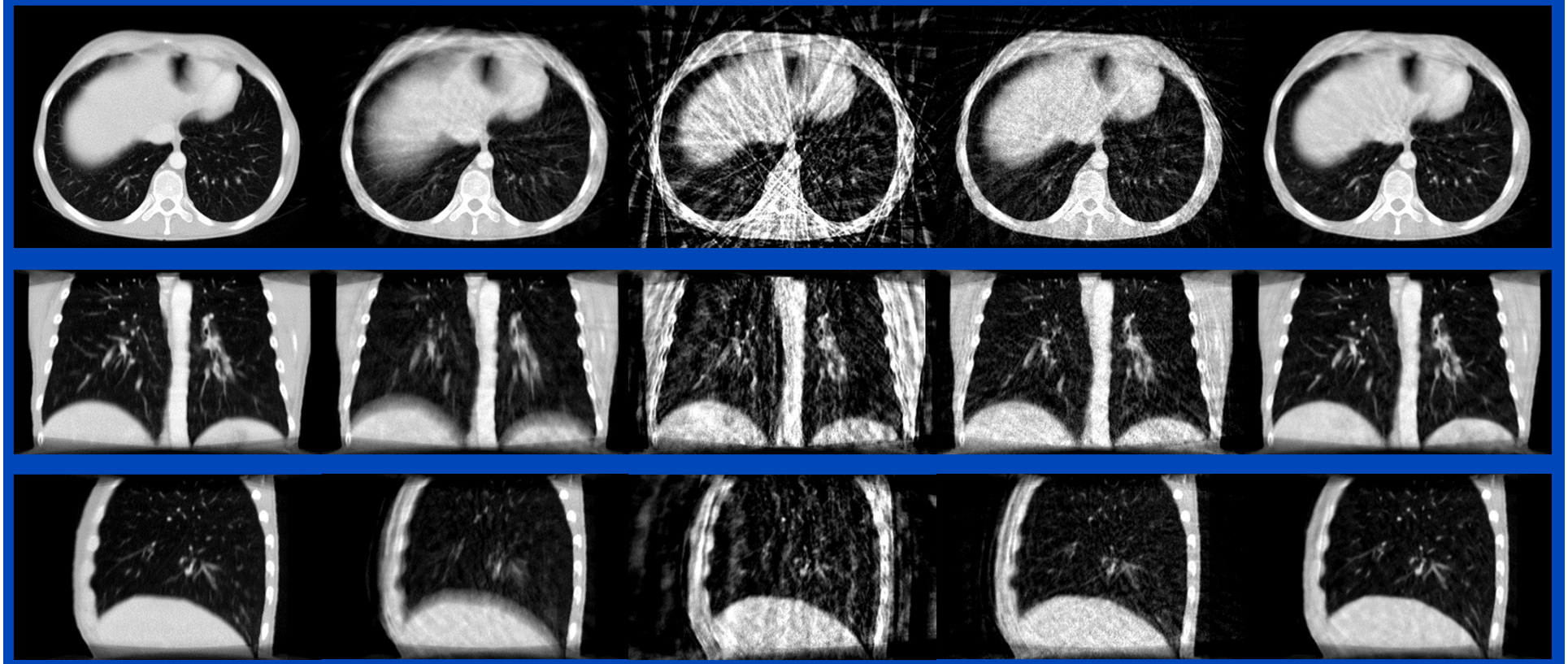
Simulations and Measurements

- On-board flat panel CBCT (Varian True Beam)
  - 60 s full-scan
  - 651 projections
- Simulation
  - Clinical CT data set as phantom
  - Realistic MVFs generated and added
  - Laterally extended detector
  - Quantum noise added
- Measurements
  - Shifted detector to avoid truncation
- Reconstruction
  - 20 phase bins (size = 10%)



Simulation (Mid-Inhale)

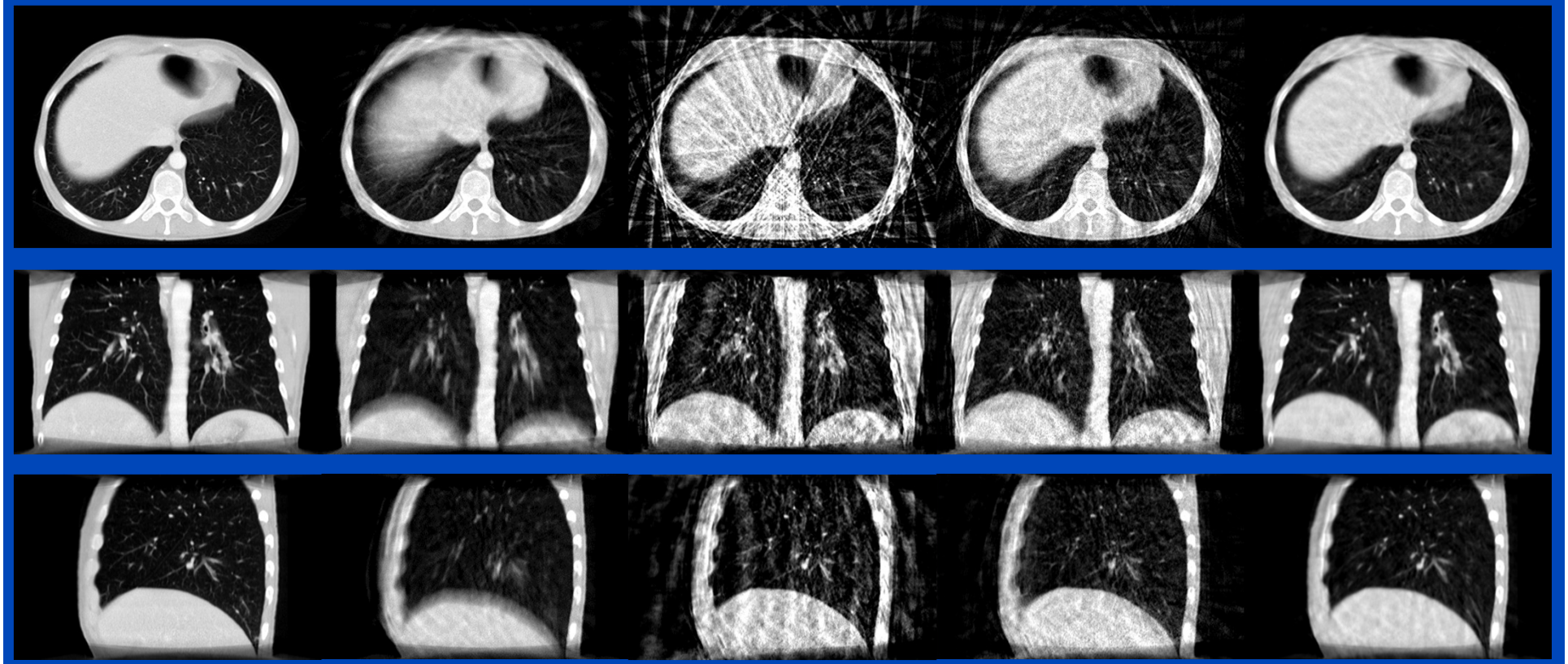
Ground Truth | Feldkamp | PC Feldkamp | McKinnon-Bates | Motion-Compensated



FAU dkfz.

Simulation (All Phases)

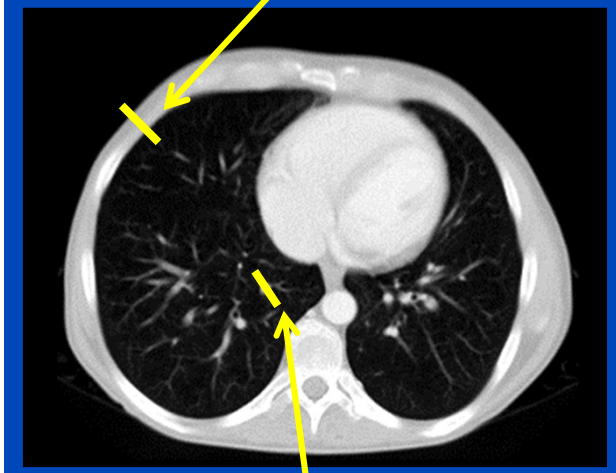
Ground Truth | Feldkamp | PC Feldkamp | McKinnon-Bates | Motion-Compensated



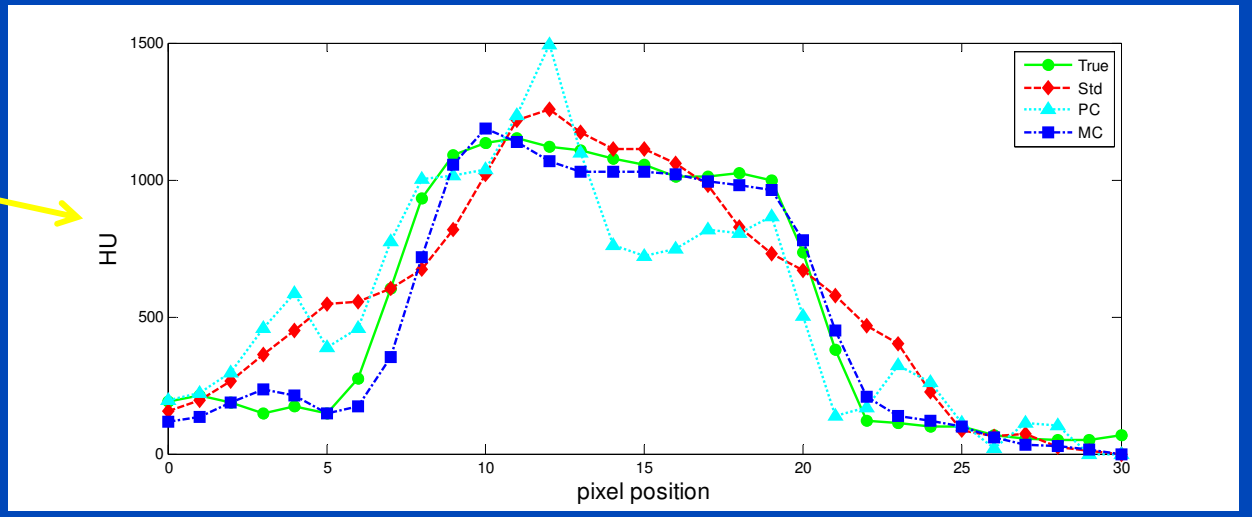
FAU dkfz.

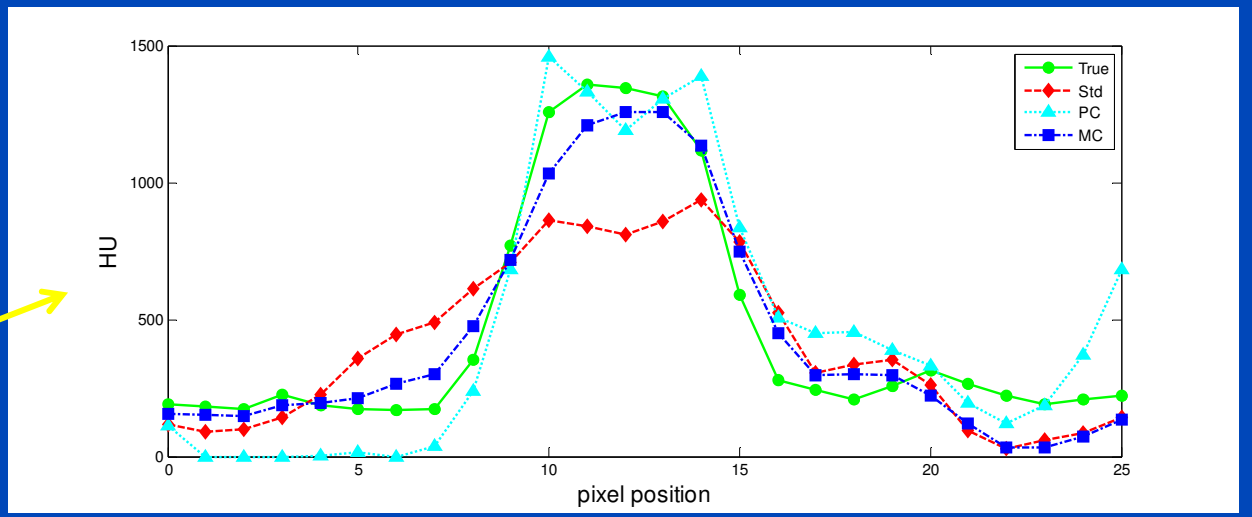
Profiles (Mid-Inhale)

Moving chest wall



Moving blood vessel
(with contrast agent)

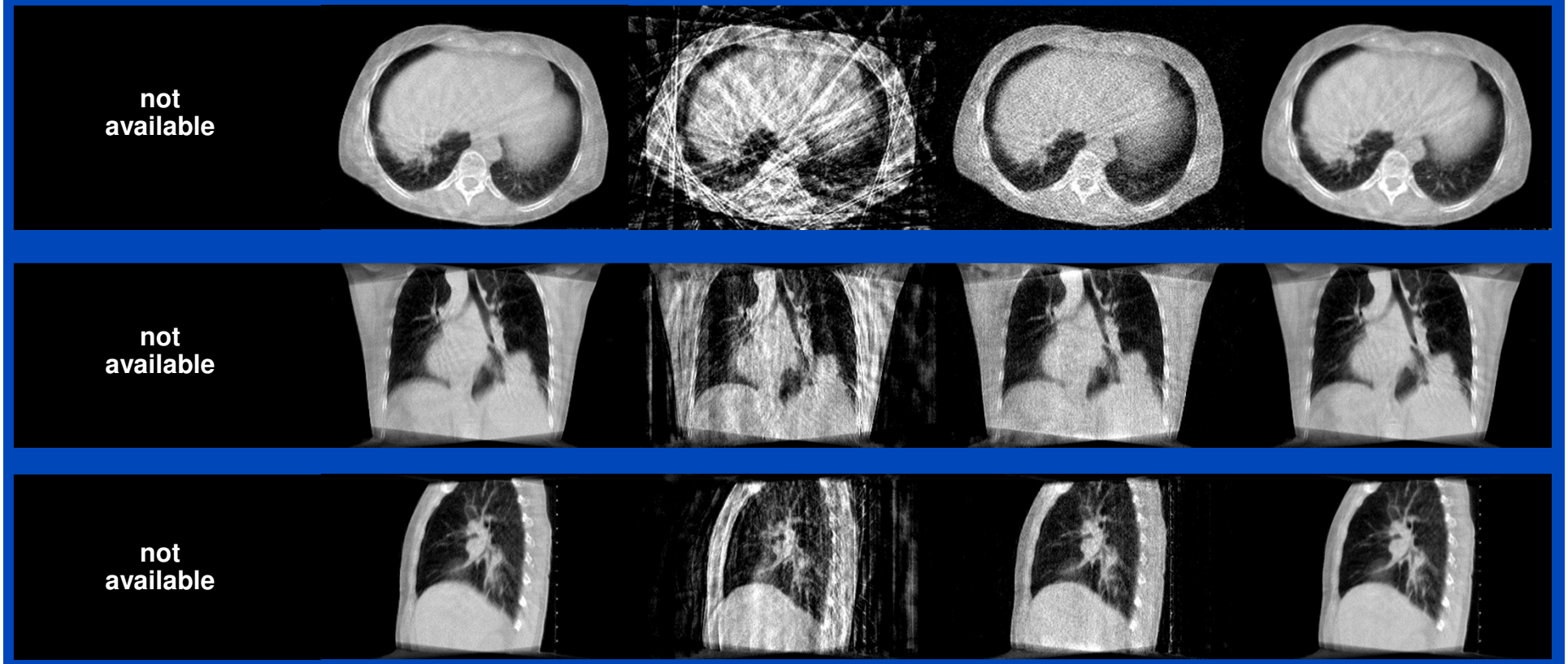




FAU

dkfz.

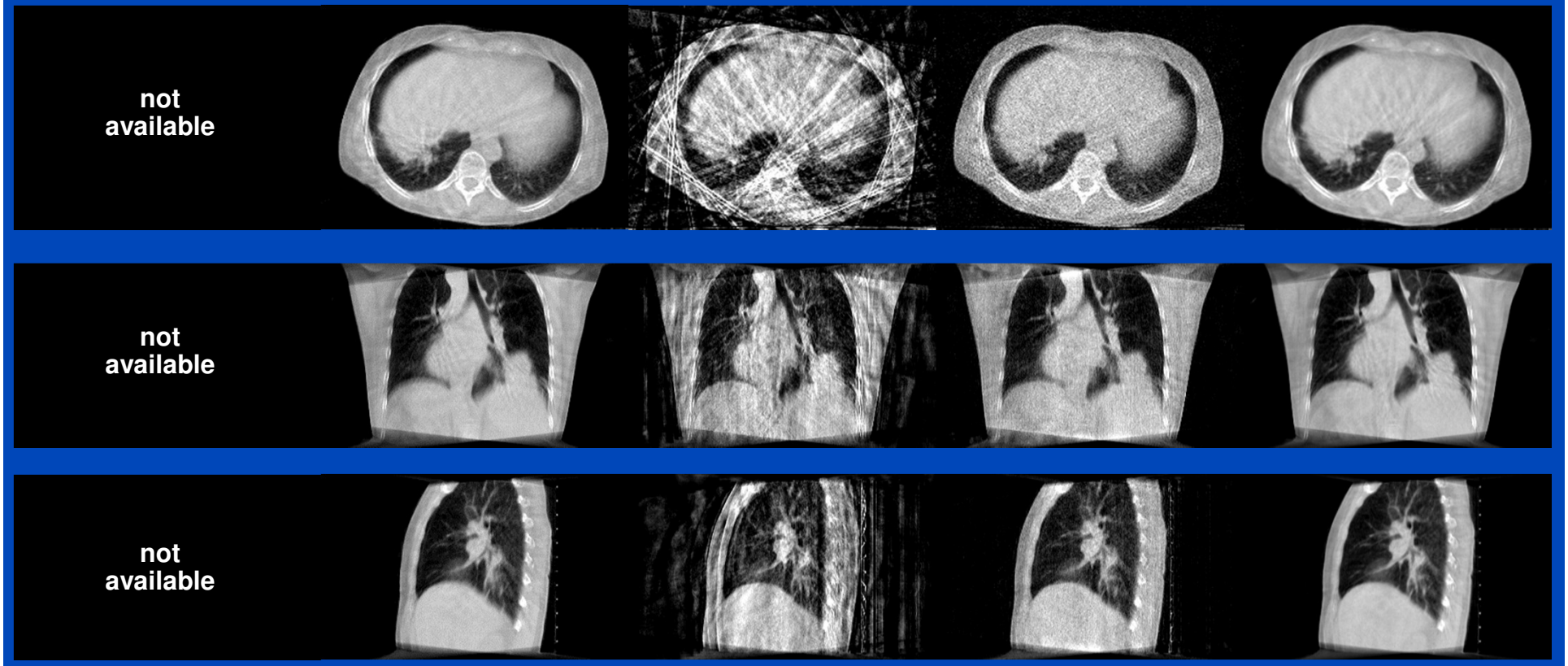
Patient Data (End-Inhale)



C/W = -200/1400 HU

FAU dkfz.

Patient Data (All Phases)



C/W = -200/1400 HU

FAU dkfz.

Conclusions and Outlook

- Low image noise due to full dose usage
- Significantly reduced motion artifacts
- Robustness to undersampling artifacts
- No necessity to rely on the planning data from clinical CT
- Changes in organ and tumor size and position can be correctly detected
- Outlook
  - Detect motion vector fields directly from the PCF images
  - Improve motion vector field consistency by imposing cyclic constraints
  - Iteratively improve on the motion vector fields and on image quality

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