Medical Image Synthesis for Digital Simulation and Image Augmentation

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Disclosure

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Outline

- Digital phantom simulation:
  - Background
  - Developments
  - Clinical applications
- Image quality augmentation:
  - 3D/4D CBCT image enhancement
  - DTS image enhancement
  - Virtual imaging

Digital Phantom Simulation: Background

- Challenges in studies using patient data:
  - Lack of ground truth images
  - Impractical to optimize techniques using real patients if excessive dose will be induced.
  - Time consuming and resource demanding to build large patient database (deep learning).
  - Patient recruitment through clinical trials is slow and expensive, subject to IRB approval.

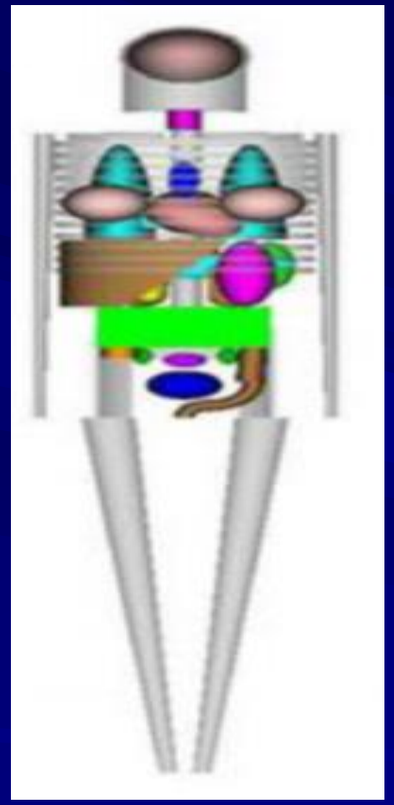
Digital Phantom Simulation: Background

- Advantages of digital phantoms:
  - Provide ground truth images for technique evaluation
  - Simulate different patient and imaging scenarios for technique optimization: investigate effects of different parameters and robustness of the algorithms
  - Build large patient database for data-demanding studies, such as AI
  - Virtual clinical trial: no radiation dose, no IRB required, low cost, high efficiency

Realism and Versatility are the key aspects of a digital phantom.

Digital Phantom Developments

1980s

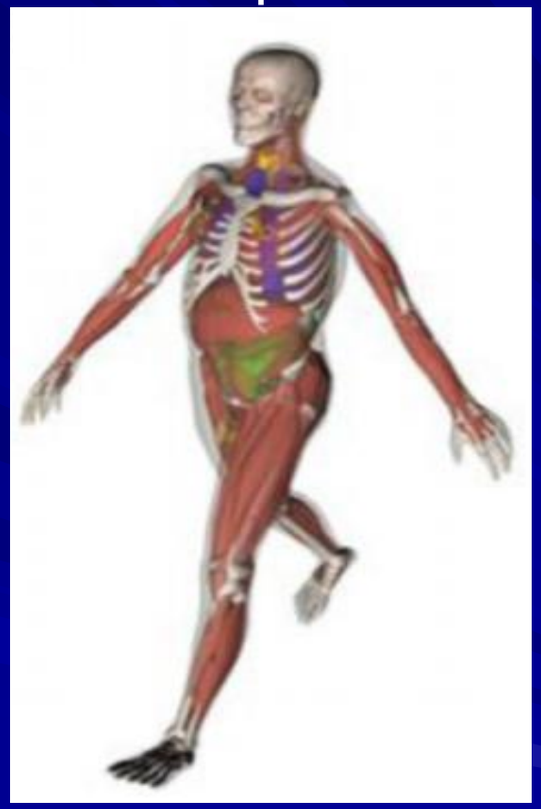


Mathematical or Stylized phantoms

1990-2000

Patient-based voxelized rigid phantoms

2001- present

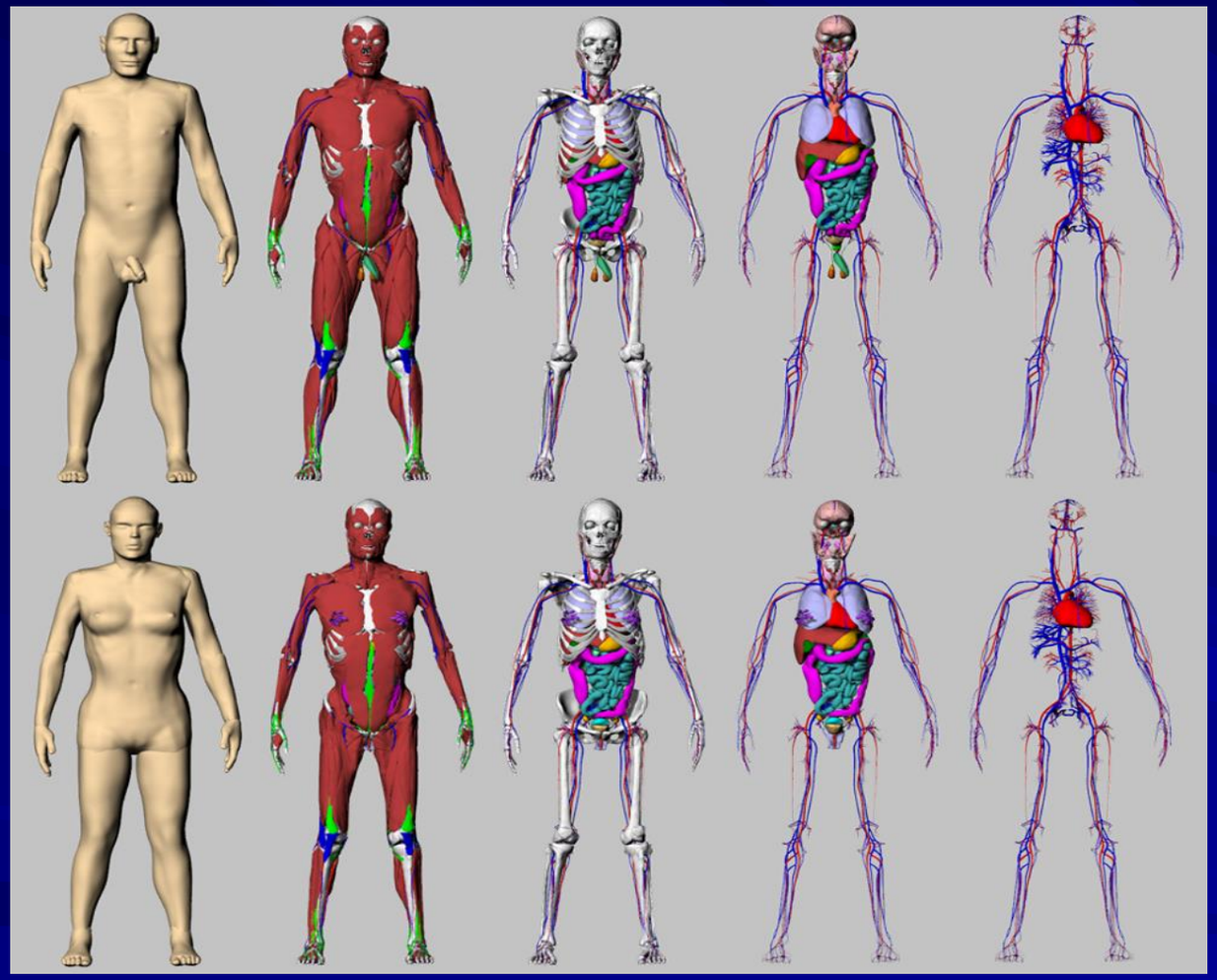


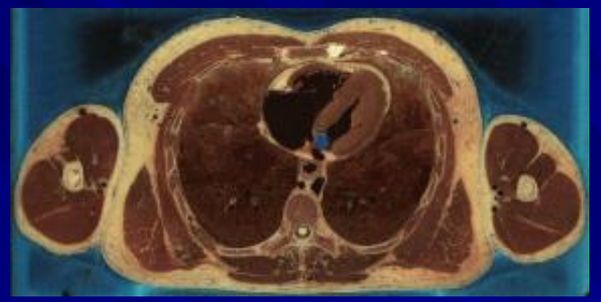
Deformable and moving 4D BREP/Hybrid phantoms

Xu et al, Phys Med Biol, 59, R233-R302, (2014)

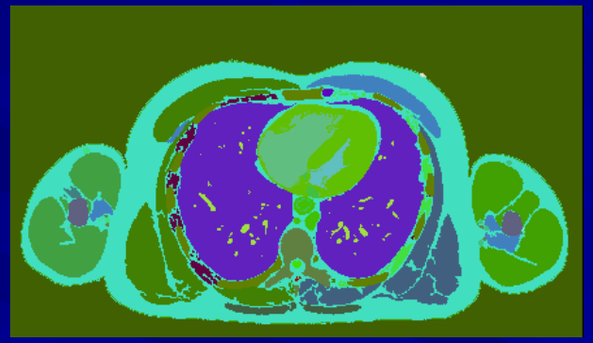
4D eXtended CArdiac-Torso (XCAT) Phantoms

Original Adult Models

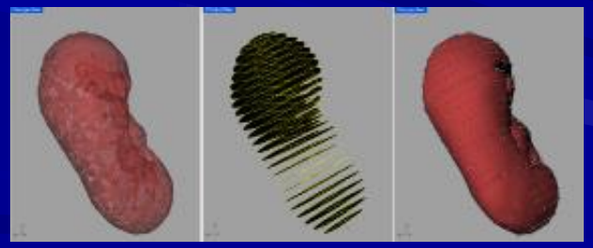




Visible Human Data



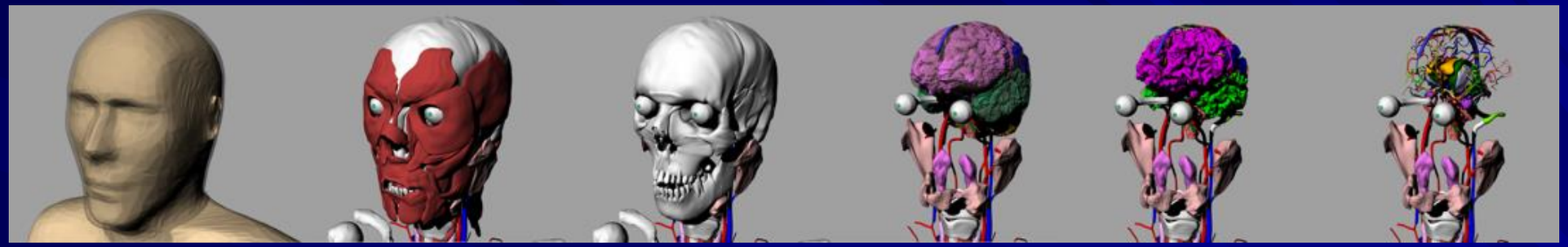
Segmented



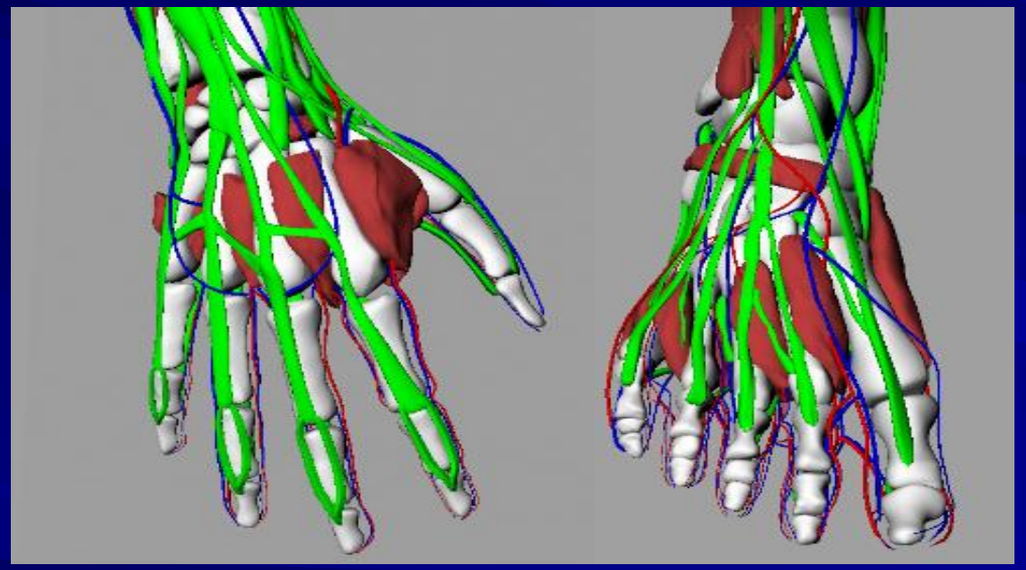
Converted to NURBS Surfaces

Segars el al, 4D XCAT phantom for multimodality imaging research, Med Phys, 37(9), (2010).

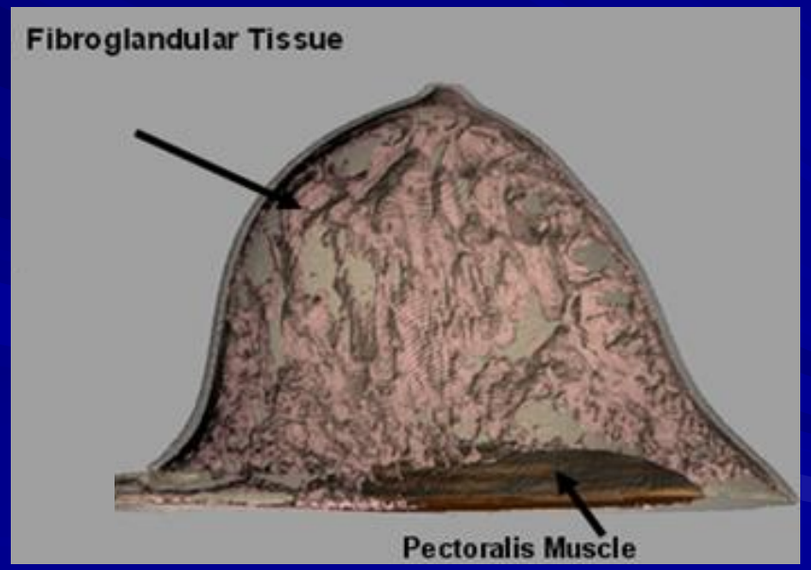
4D XCAT Phantom Anatomy



Detailed Brain Model based on MRI



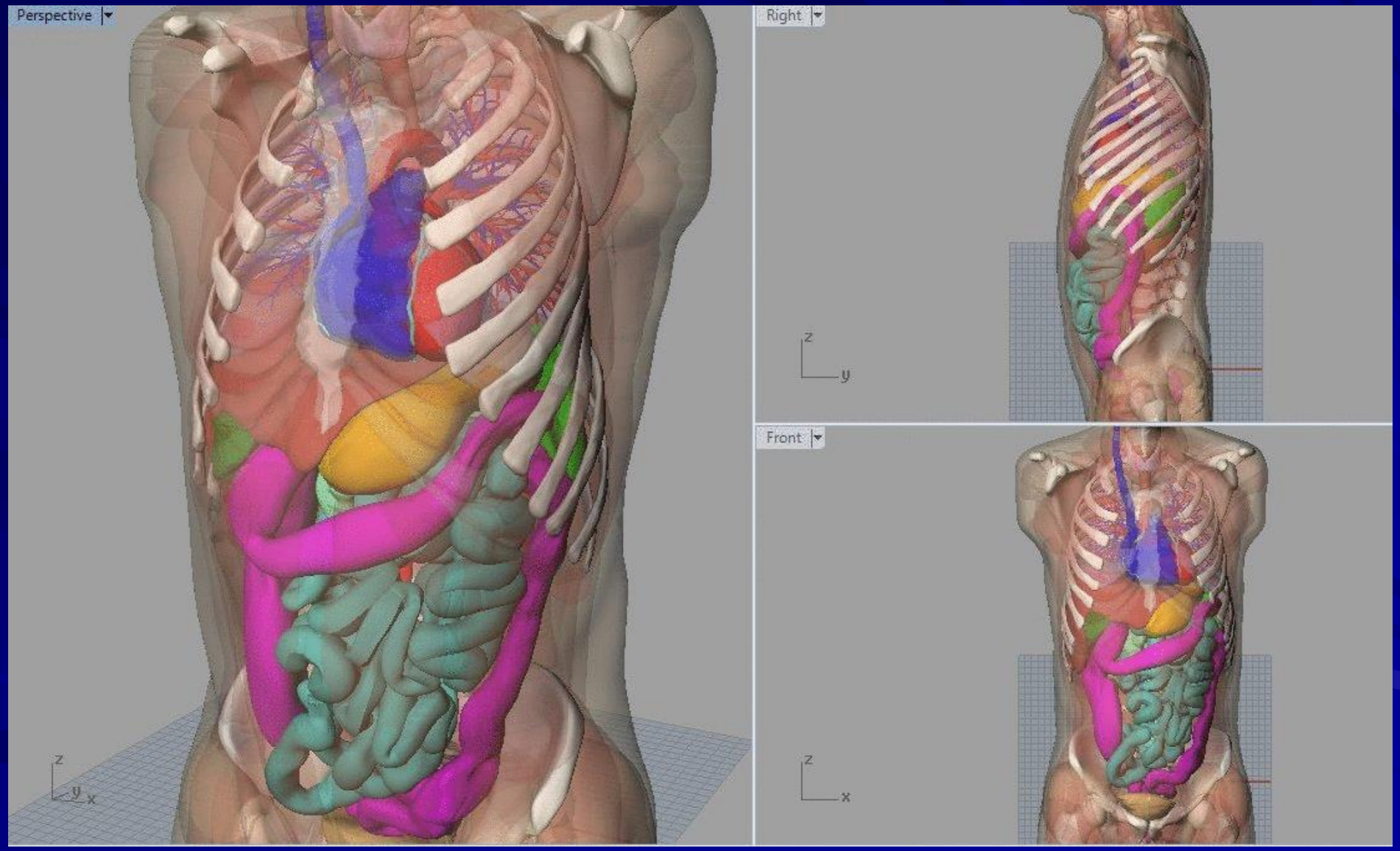
Detail in the hands and feet



High-resolution model of the female breast

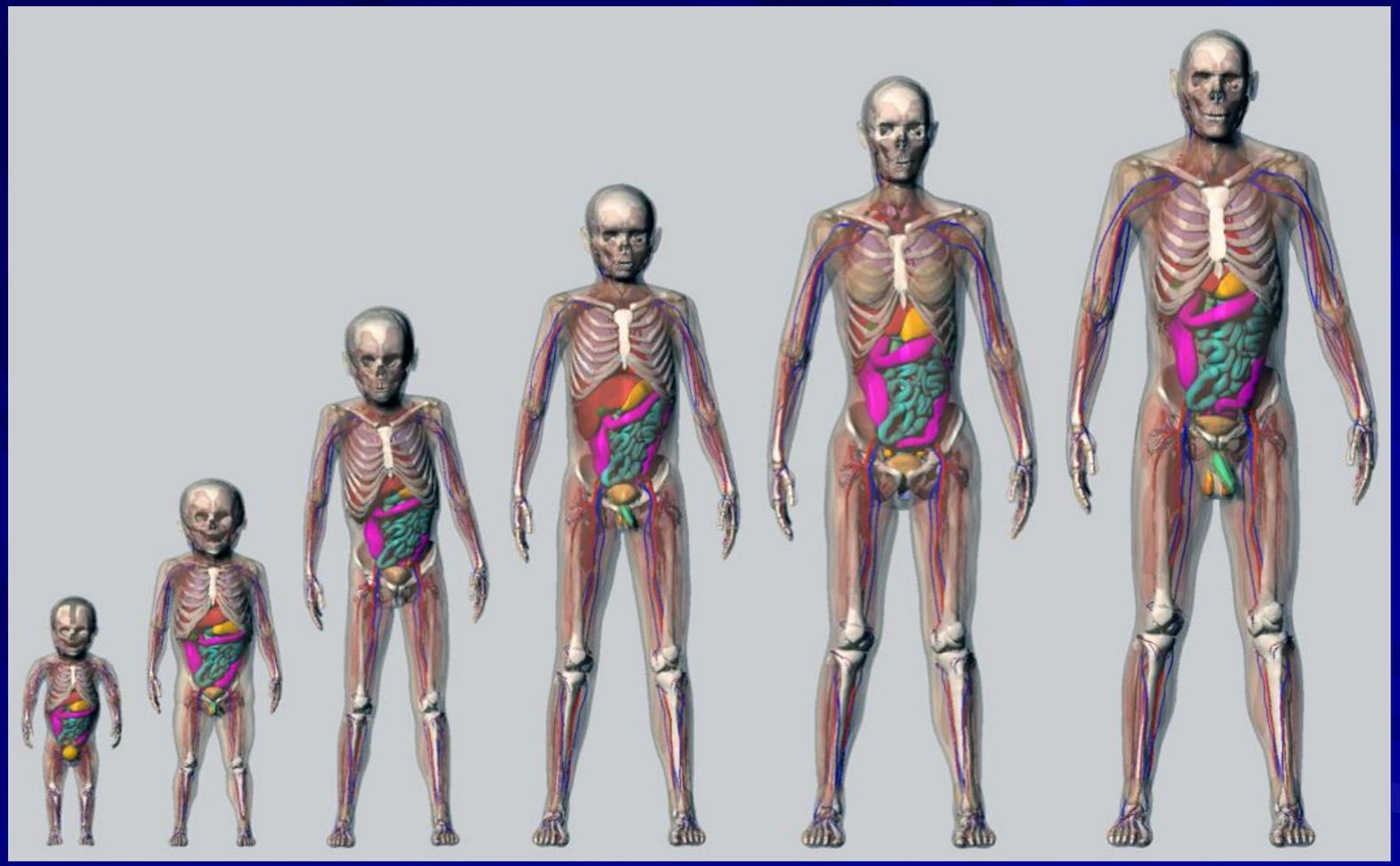
Courtesy of Paul Segars

Cardiac and Respiratory Models



Courtesy of Paul Segars

Population of XCAT Phantoms



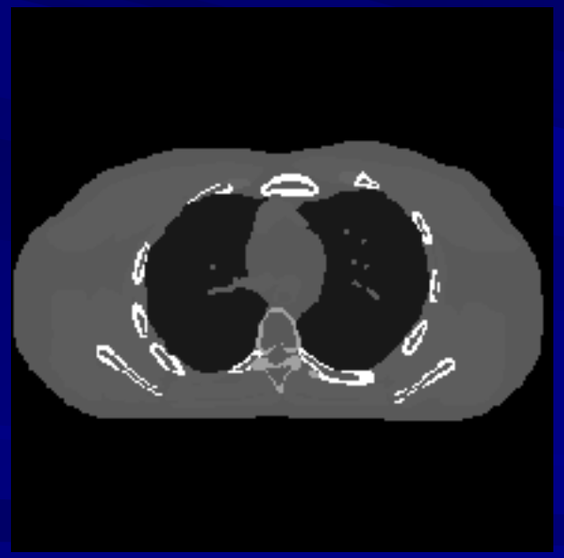
Segars el al, Population of anatomically variable 4D XCAT adult phantoms for imaging research and optimization, Med Phys, 40, (2013).

Norris el al, A set of 4D Pediatric XCAT Reference Phantoms for Multimodality Research, Med Phys, 41, (2014).

Segars el al, The development of a population of 4D pediatric XCAT phantoms for imaging research and optimization, Med Phys, (2015).

Generate Realistic Image Textures in the XCAT

XCAT

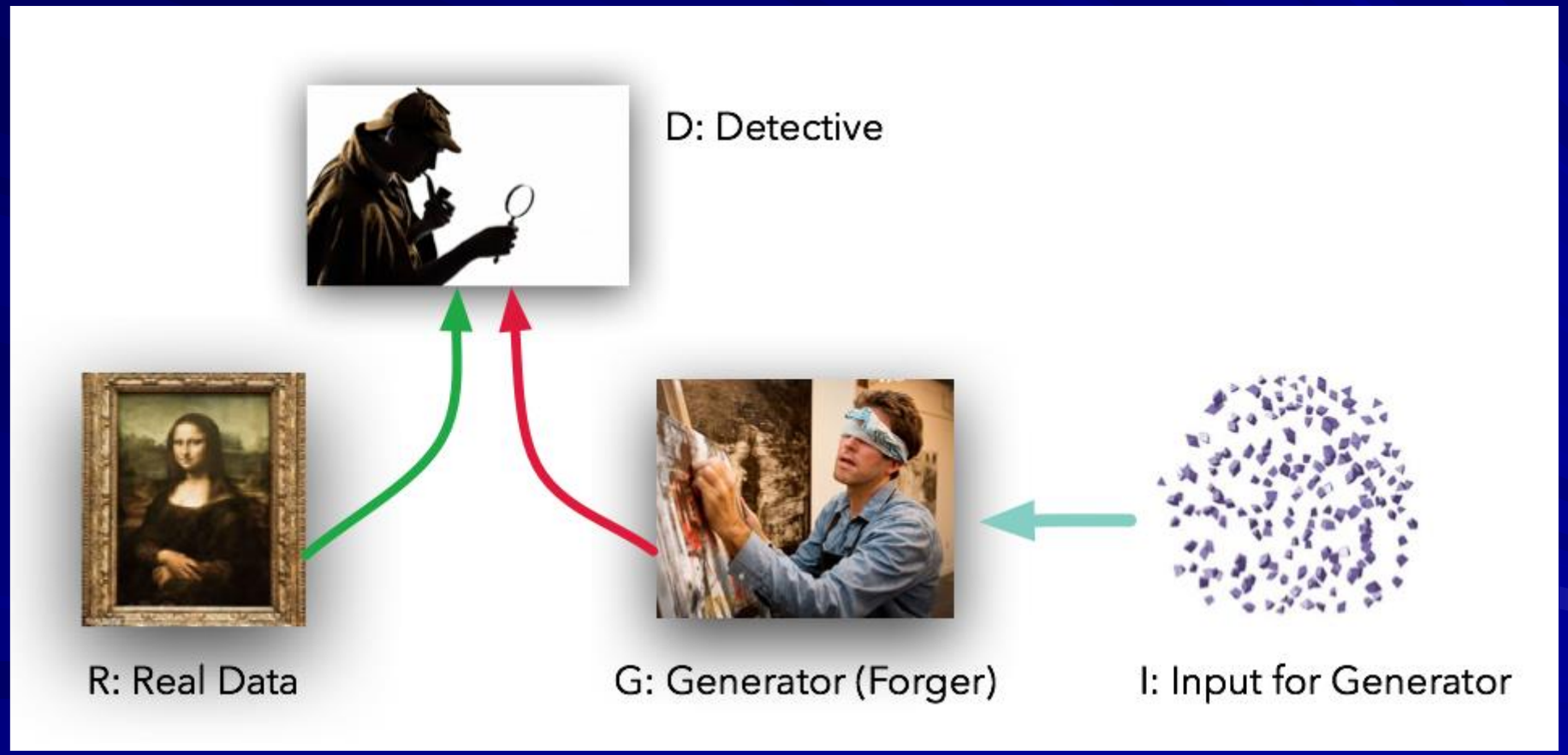


GAN

Multi-textured XCAT
(MT-XCAT)

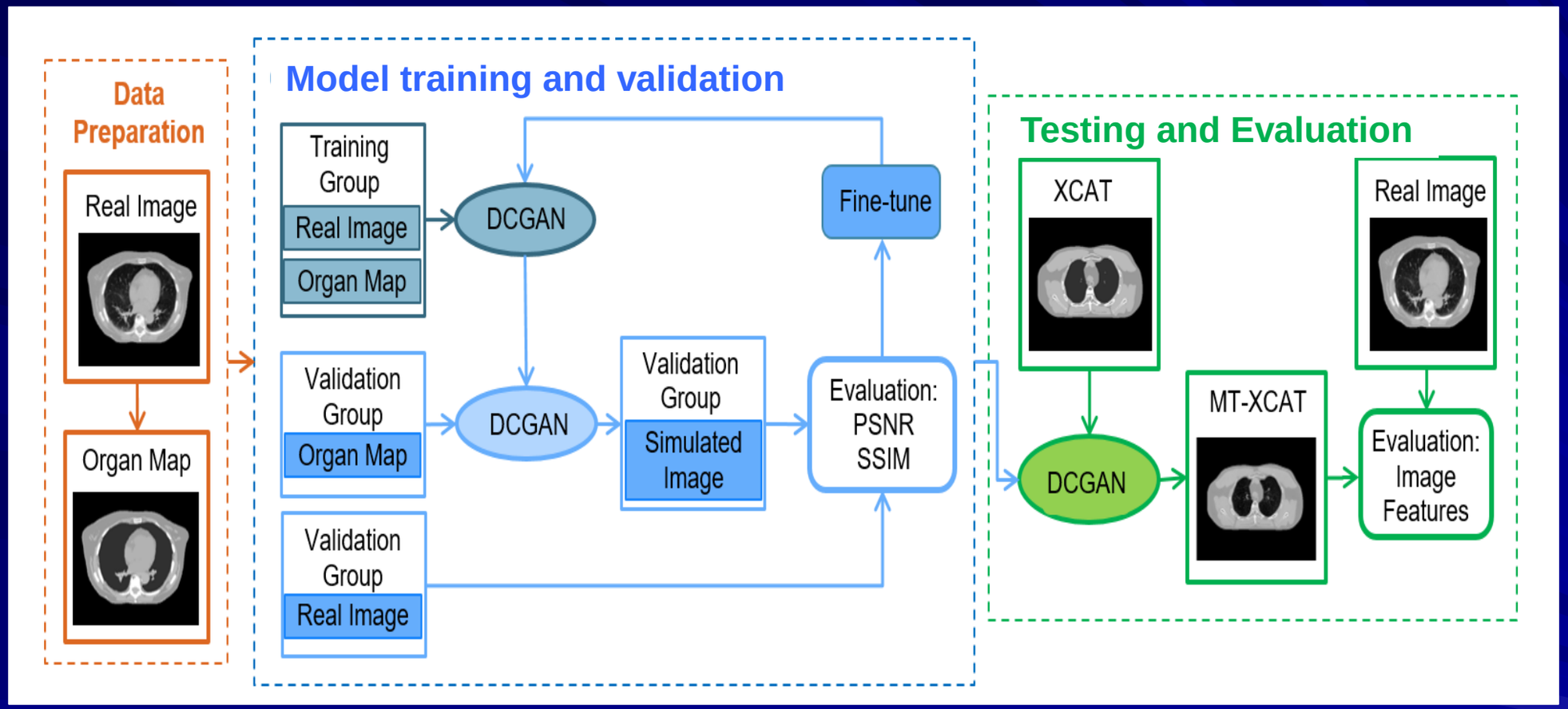
Generative Adversarial Network (GAN)

- Estimate generative models via an adversarial process



Goodfellow, I., et al. Generative adversarial nets. in Advances in neural information processing systems. 2014.

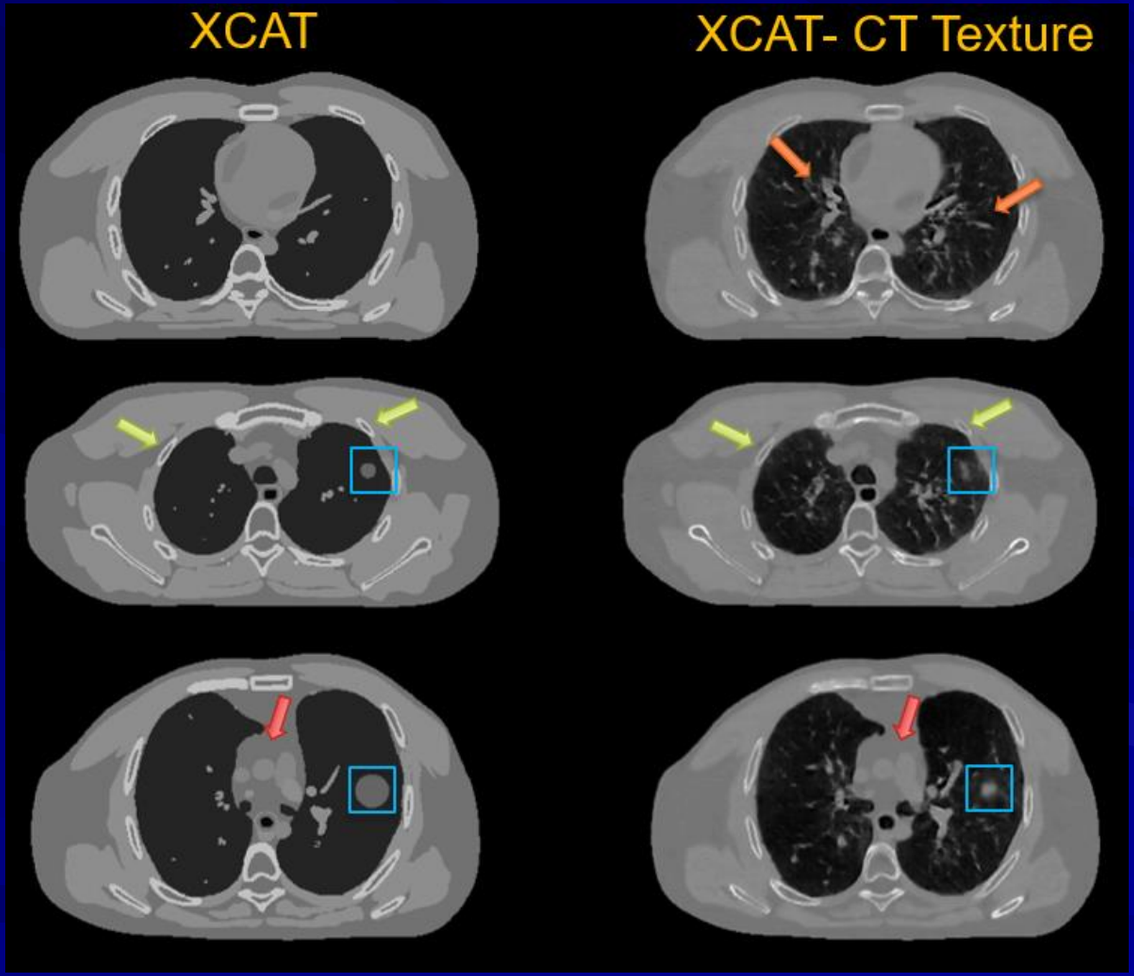
Generate MT-XCAT using D-CGAN



Training: train the neural network to update its model weights
Validation: tune model hyperparameters, such as size of network, learning rate, etc.
Testing: Final testing of the performance of the tuned model

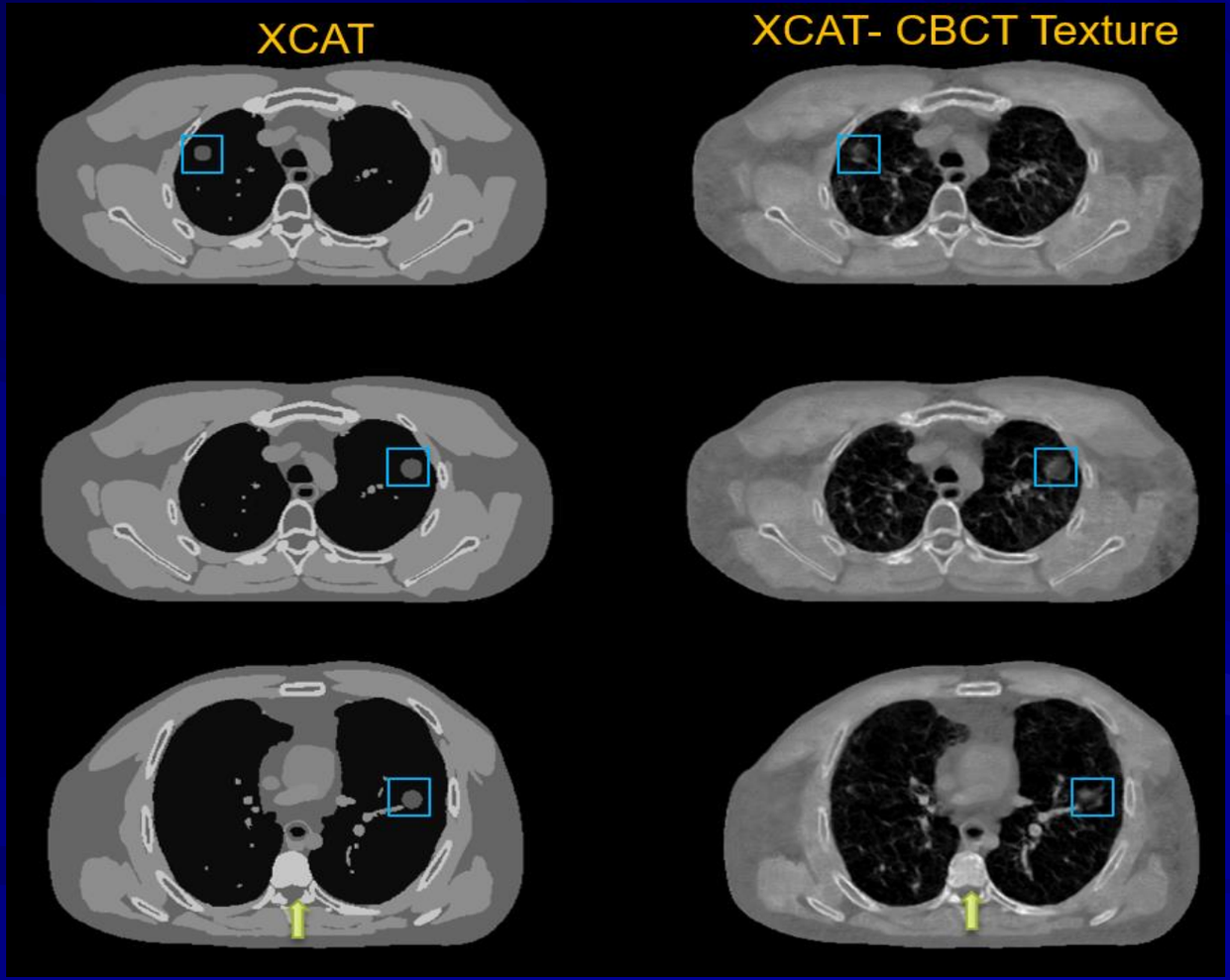
Chang, Y., Lafata, K., Segars, P., Yin, F., Ren, L. *Phys Med Biol*, *65(6)*, 065009, (2020)

Generate XCAT Phantom with CT Texture



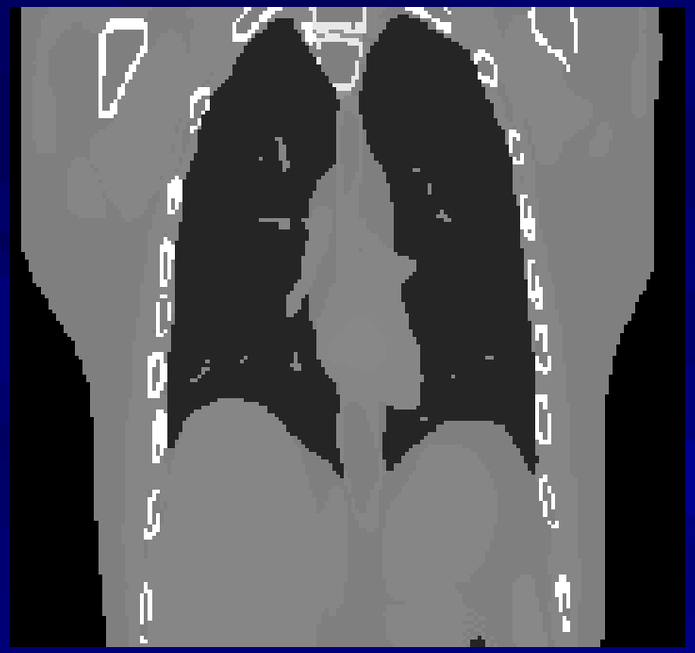
Chang, Y., Lafata, K., Segars, P., Yin, F., Ren, L. *Phys Med Biol*, *65(6)*, 065009, (2020)

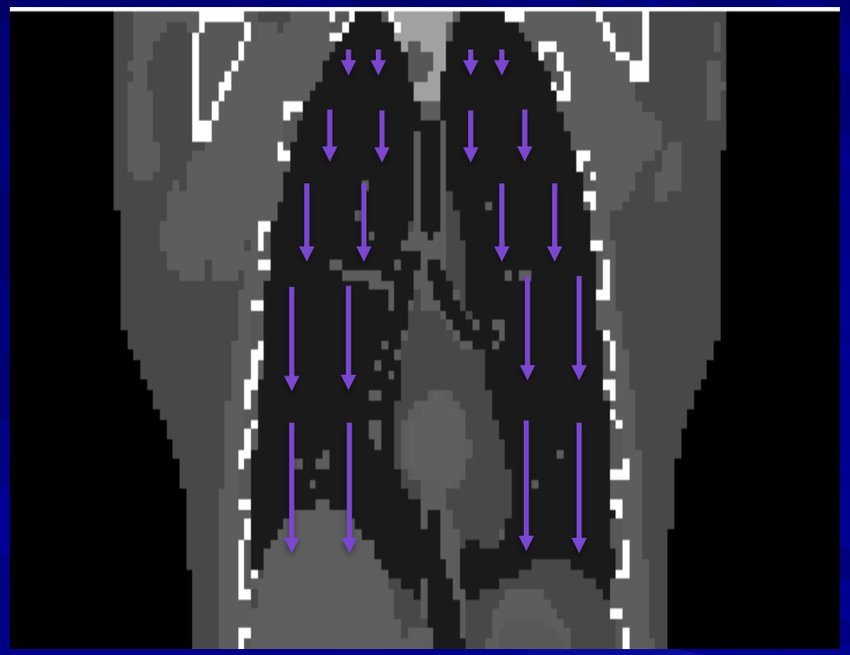
Generate XCAT Phantom with CBCT Texture



Chang, Y., Lafata, K., Segars, P., Yin, F., Ren, L. *Phys Med Biol*, *65(6)*, 065009, (2020)

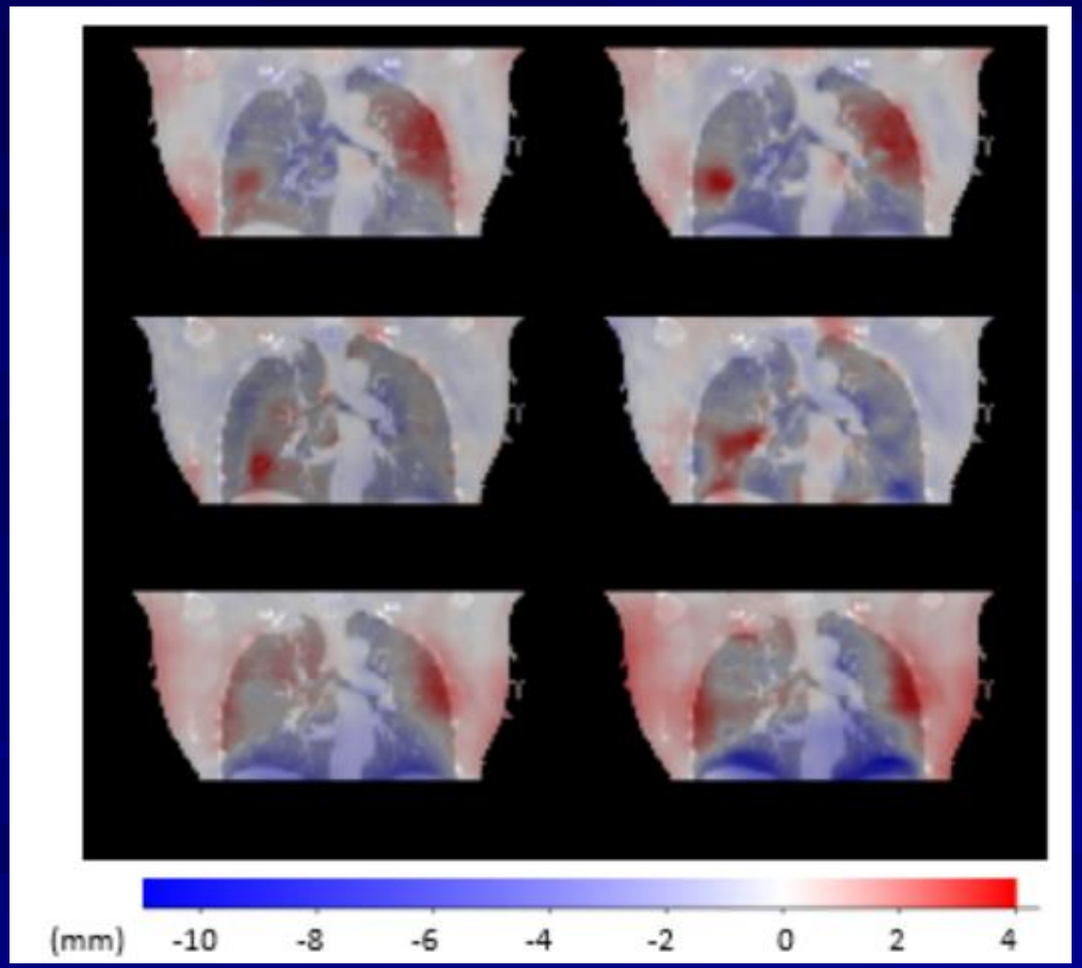
Generate XCAT Phantom with Realistic Respiratory Motions

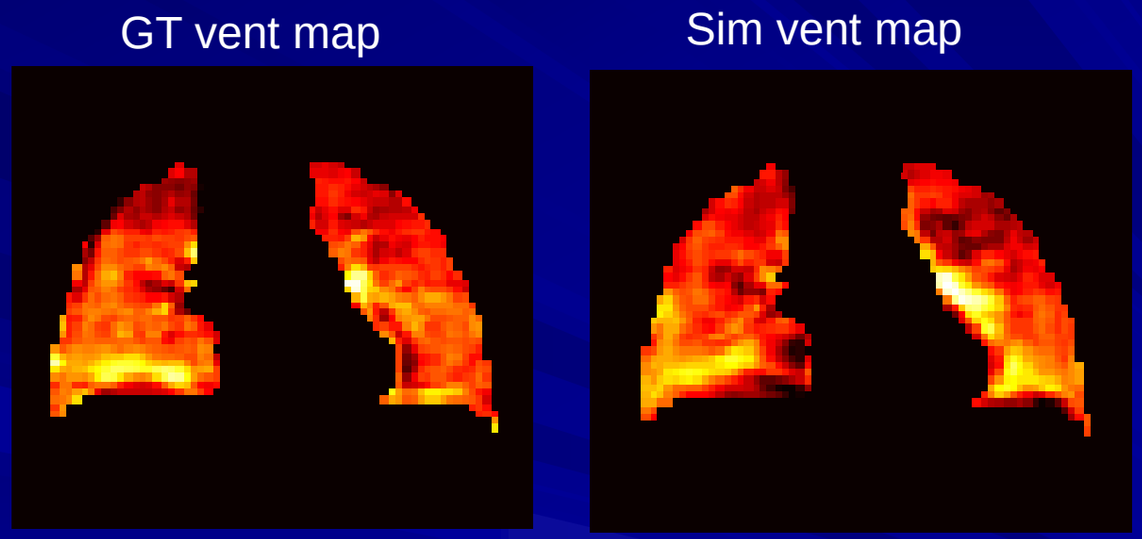




linearly increased respiratory motion

Generate XCAT Phantom with Realistic Respiratory Motions



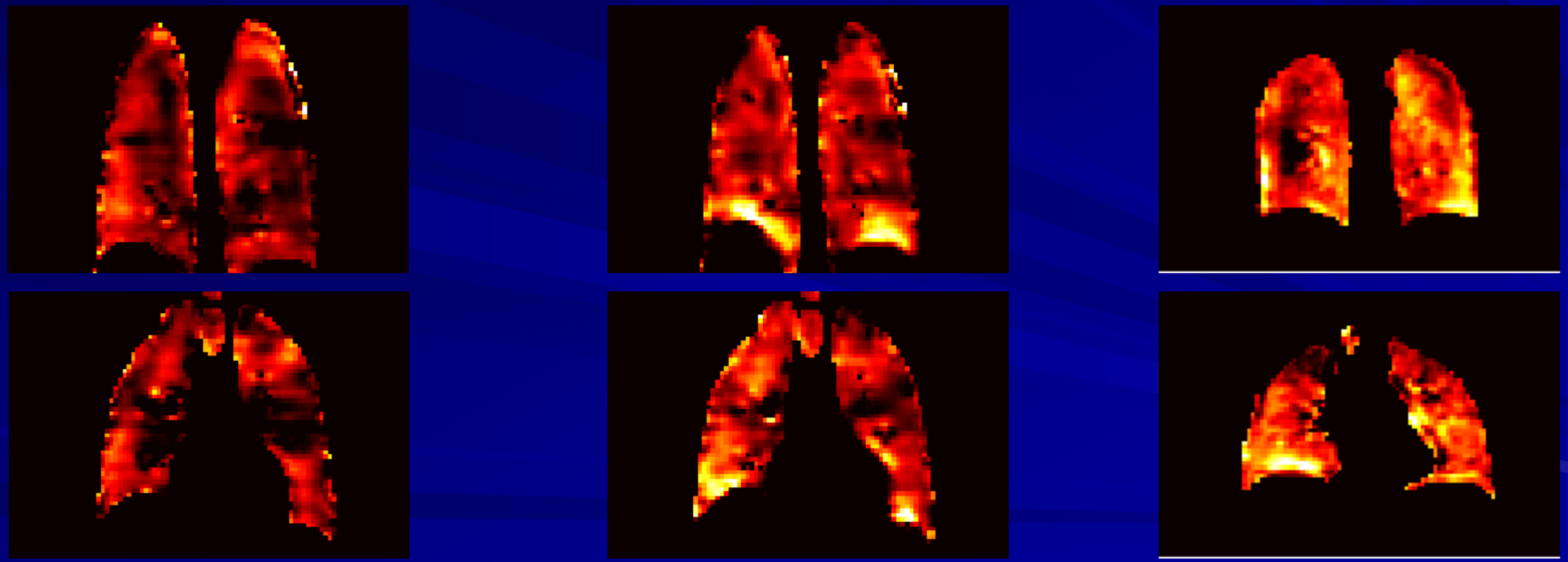


Chang et al, AAPM Young Investigator Symposium, 2020

Generate XCAT Phantom with Realistic Respiratory Motions

- Ventilation map comparison

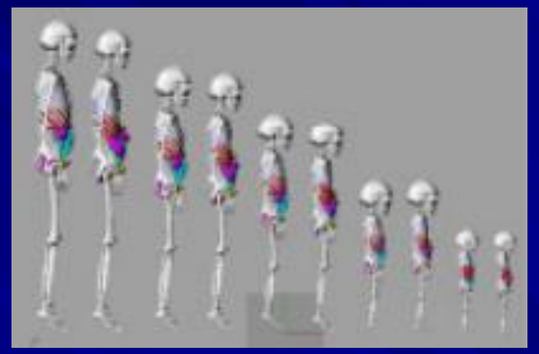
Original XCAT | Generated XCAT | Real CT



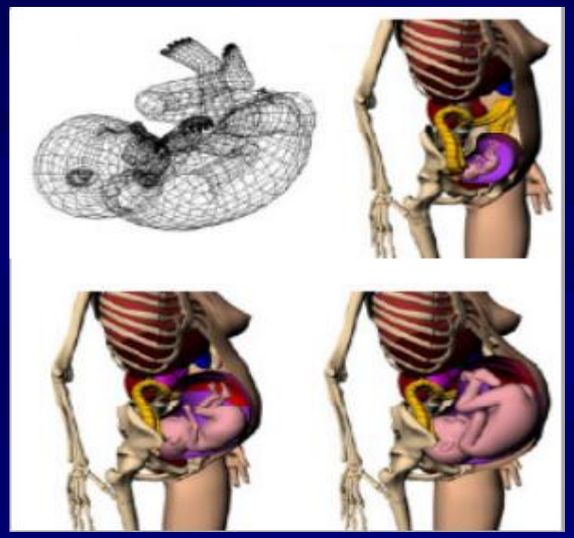
Chang et al, AAPM Young Investigator Symposium, 2020

Other Hybrid Phantoms

RPI phantoms for overweight and obese individuals, Ding et al. Phy Med Biol, 57, 2012

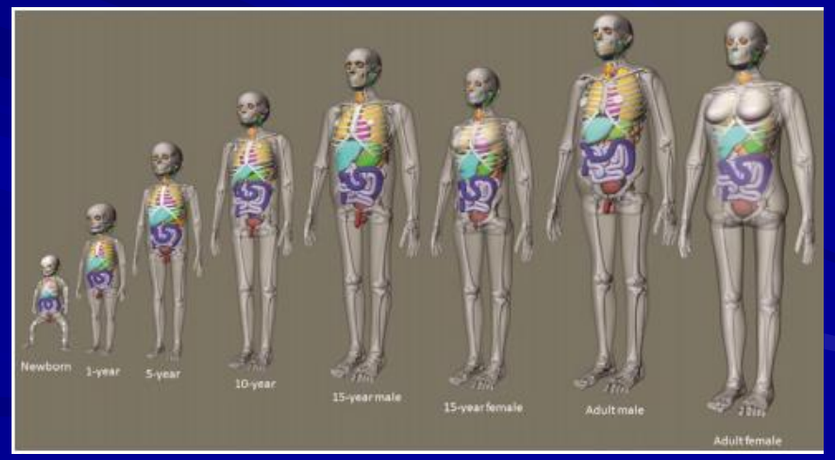


RADAR family of phantoms, Stabin et al.



RPI pregnancy phantoms, Xu et al, Phy Med Biol, 52 (23), 2007

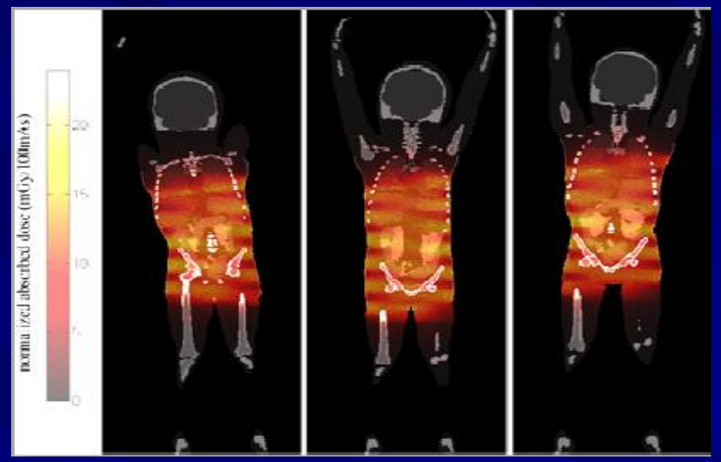
Virtual population by IT'IS



UF phantoms for different age groups

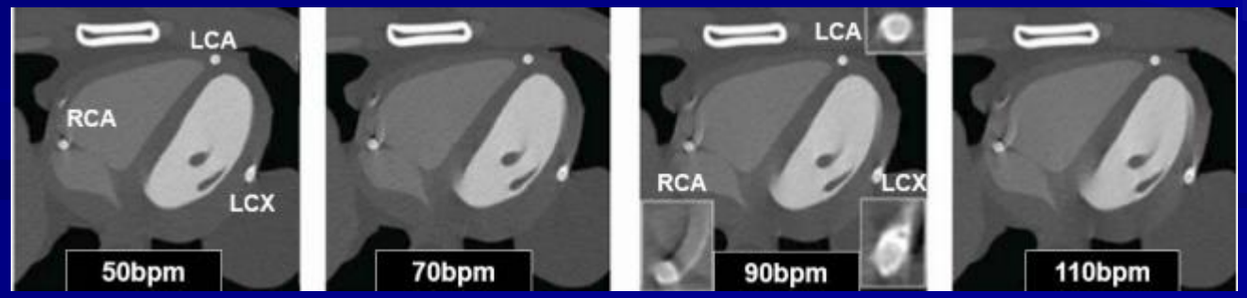
Applications

- Dosimetric study



Li et. al., Med Phys, 38(1), 408-419 (2011)

- Optimization and evaluation of imaging techniques: image reconstruction, processing, motion correction

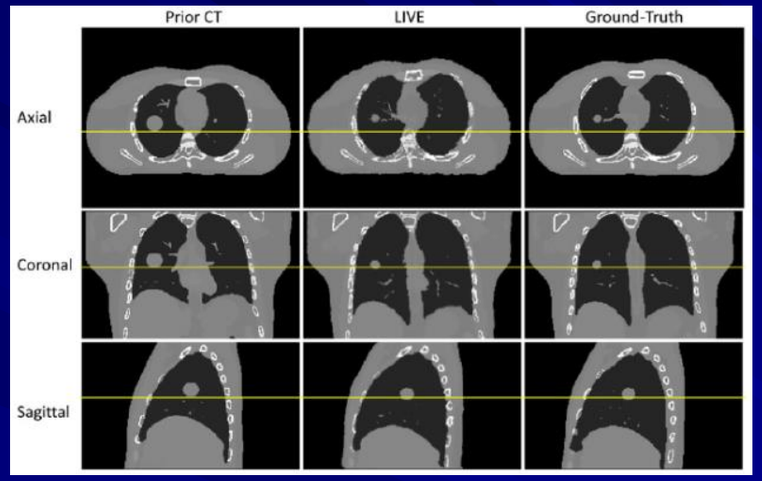


Coronary CT angiography simulation using XCAT with different heart rates to investigate motion artifacts

Fung et. al., Proc. 3rd Int. Conf. Image Formation X-Ray CT, 2014, pp. 376–379

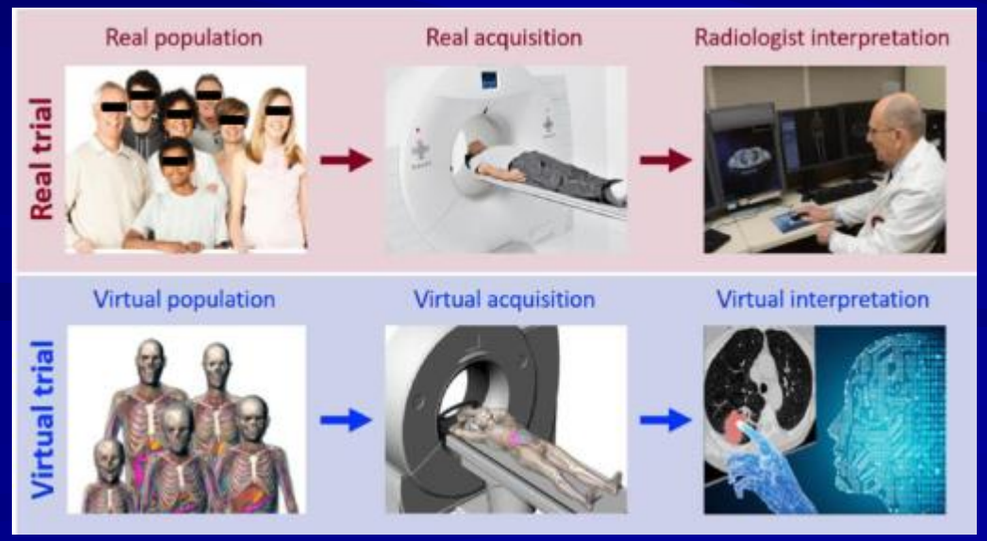
Applications

- Radiation therapy:
  4D imaging and treatment



Zhang et al, Medical Physics, 45(1), 340-351, 2018

- Patient database for model training (deep learning)
- Virtual clinical trial before the actual clinical trial



Abadi et al. *Journal of Medical Imaging* 7(4), 042805, 2020

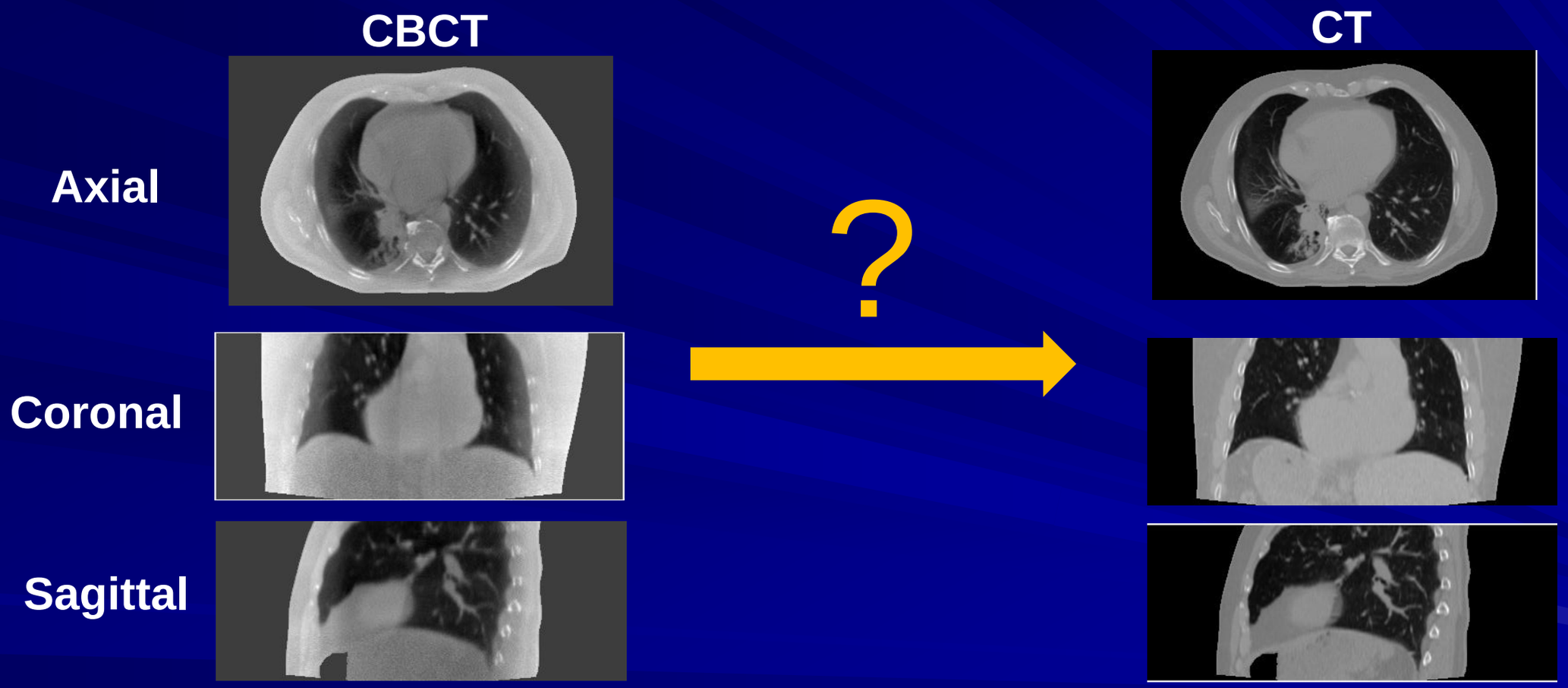
Summary

- Digital phantoms are valuable tools for addressing the challenges in patient studies.
- Significant progresses have been made to make the phantoms more realistic to mimic real patient population and the clinical workflow.
- Digital phantoms have a wide variety of applications with the potential to reduce the cost and improve the efficiency and precision of the clinical practice.

Outline

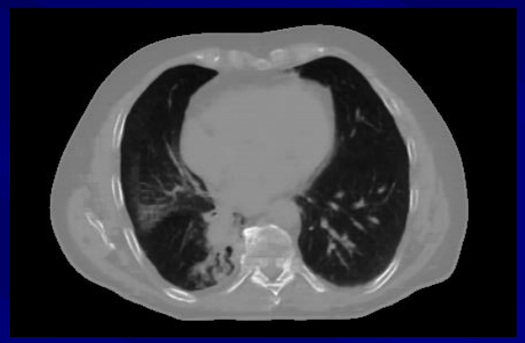
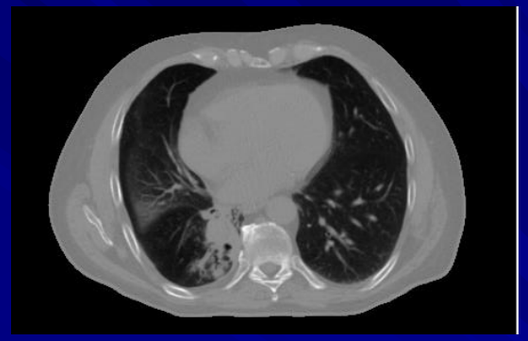
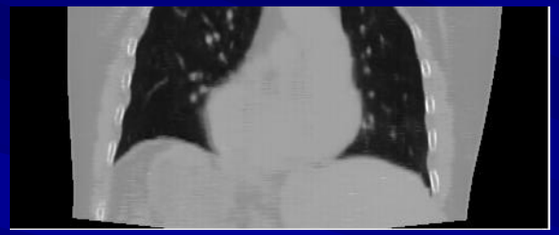
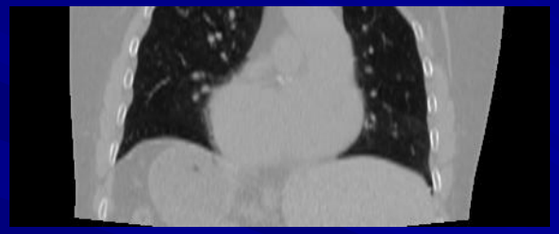
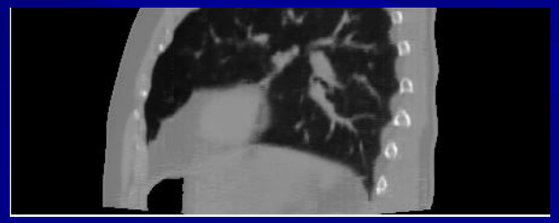
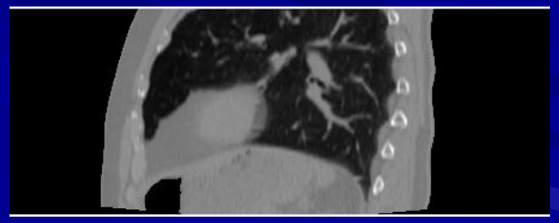
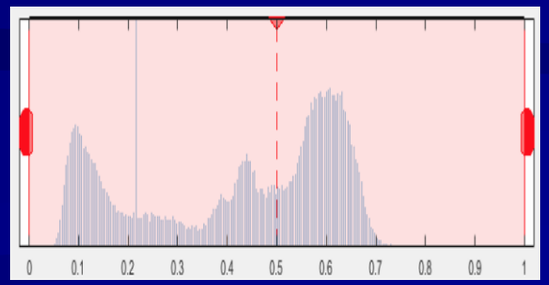
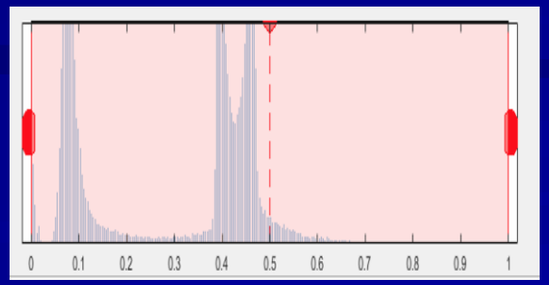
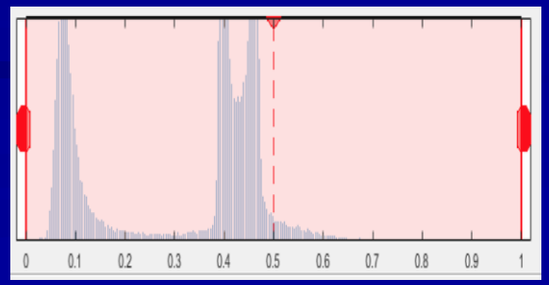
- Digital phantom simulation:
  - Background
  - Developments
  - Clinical applications
- Image quality augmentation:
  - 3D/4D CBCT image enhancement
  - DTS image enhancement
  - Virtual imaging

3D CBCT Image Enhancement



Pair of CT-CBCT data to train a DL model to enhance CBCT to match with CT

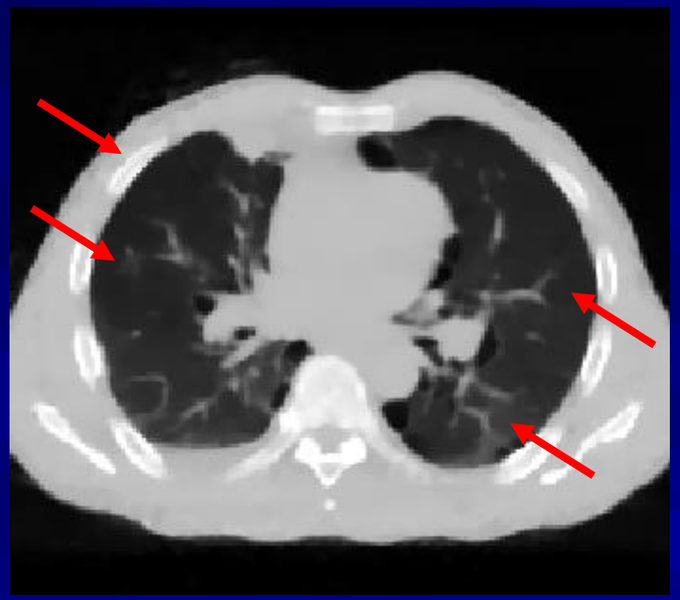
3D CBCT Image Enhancement

	CBCT	Enhanced CBCT	CT
Axial			
Coronal			
Sagittal			
Histogram			

4D-CBCT Image Enhancement

FDK-CBCT

TV-CBCT



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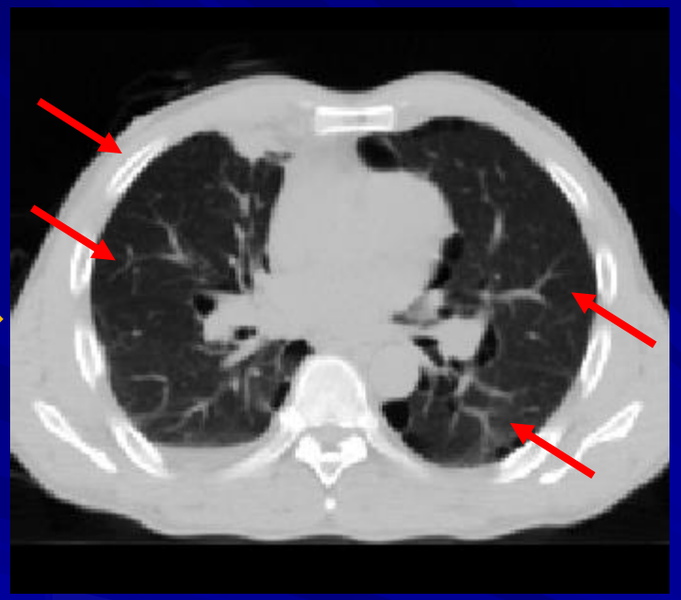
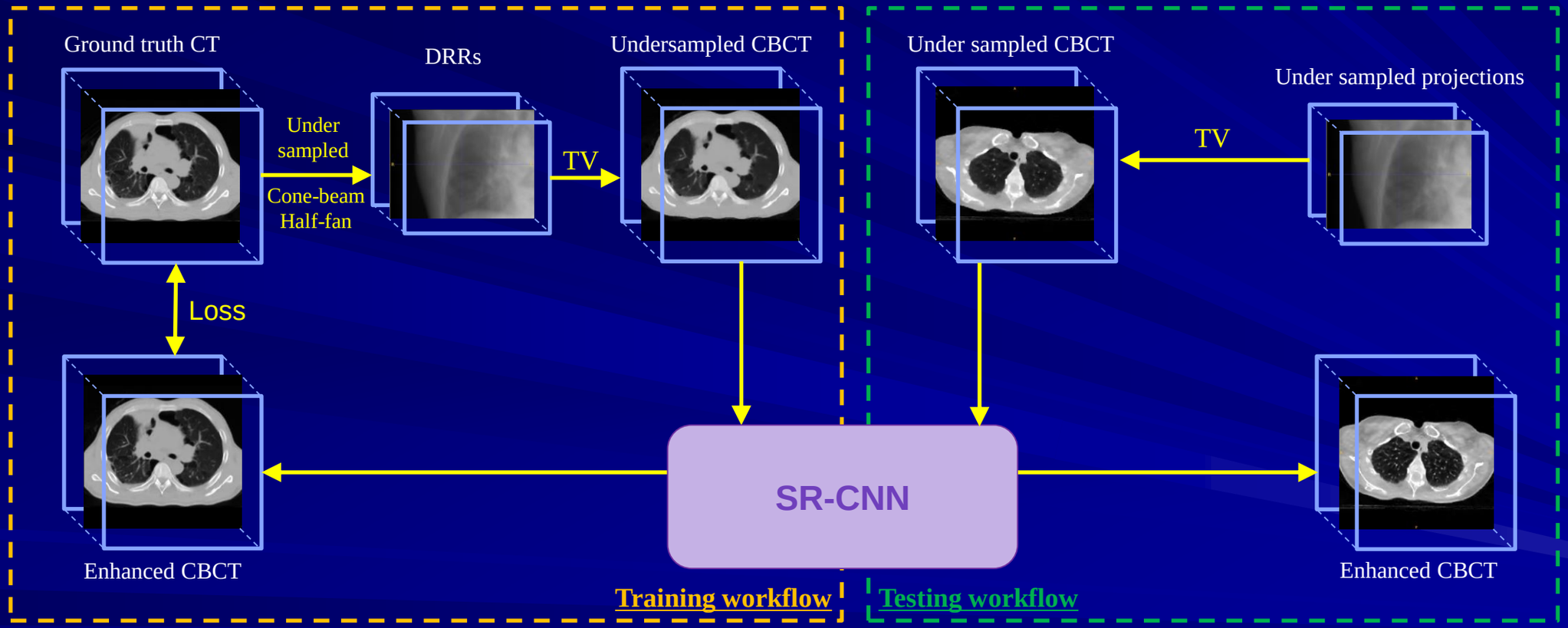
CT



72 half fan cone beam projections
FDK-CBCT: reconstructed by FDK backprojection
TV-CBCT: Reconstructed by iterative algorithm with total variation (TV) constraint

4D-CBCT Image Enhancement

Training and testing workflow



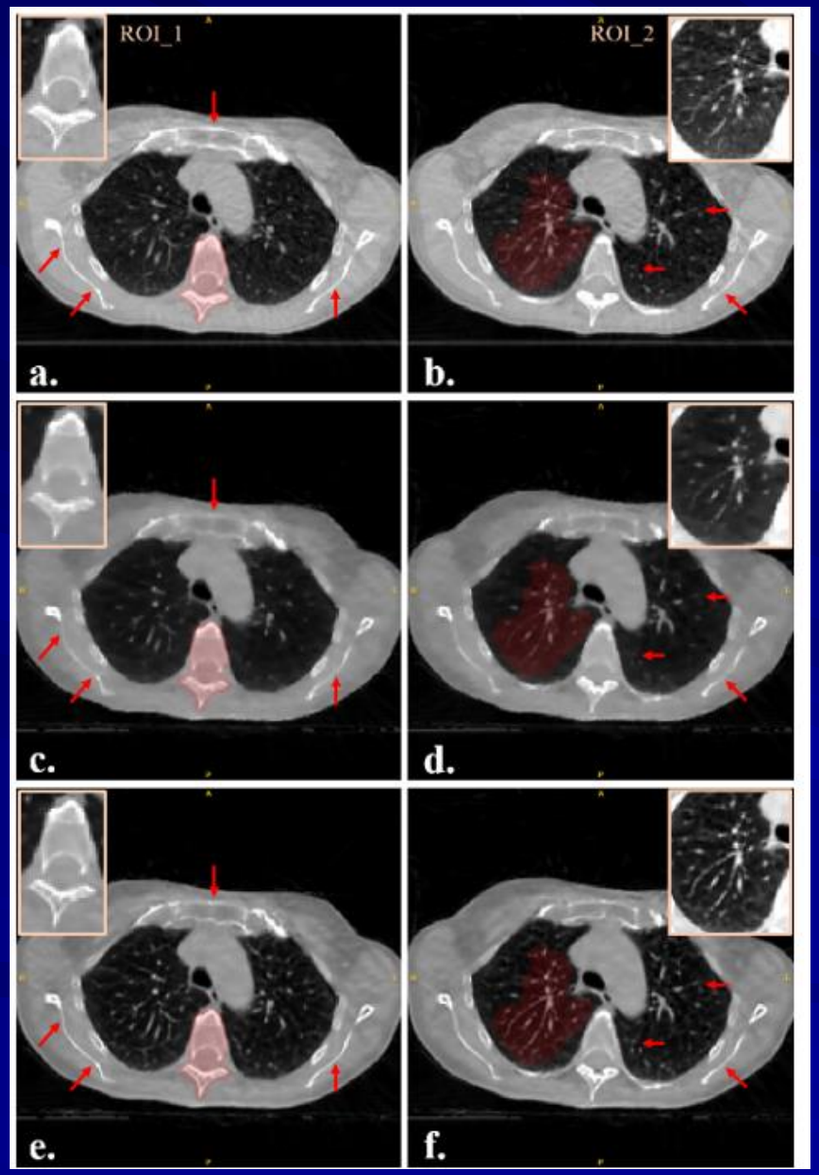
Jiang, Z., Chen, Y., Zhang, Y., Ge, Y., Yin, F. F., & Ren, L. *IEEE Trans Med Imaging*, *38*(11), 2705-2715, 2019

4D-CBCT Image Enhancement

Ground truth CBCT using 900 projections

Iteratively reconstructed CBCT using 120 projections

Enhanced CBCT using 120 projections

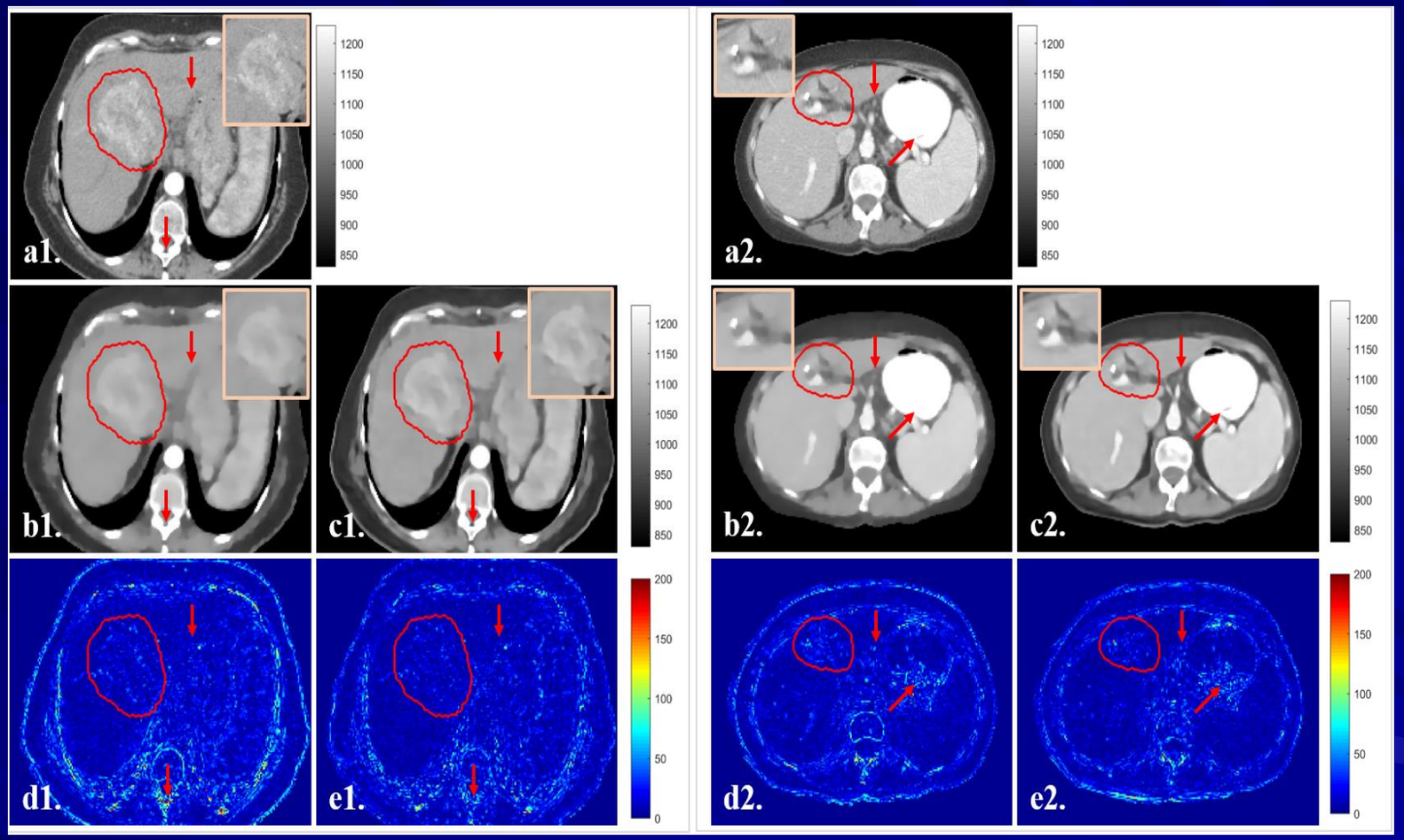


Jiang, Z., Chen, Y., Zhang, Y., Ge, Y., Yin, F. F., & Ren, L. *IEEE Trans Med Imaging*, *38*(11), 2705-2715, 2019

4D-CBCT Image Enhancement

CT

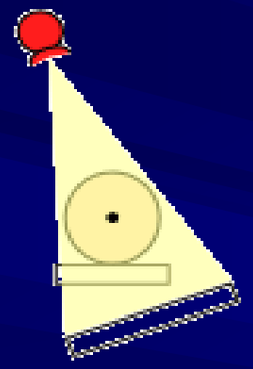
CBCT using 72 simulated projections



b1 and b2: TV_CBCT. c1 and c2: Enhanced CBCT

Jiang, Z., Chen, Y., Zhang, Y., Ge, Y., Yin, F. F., & Ren, L.
IEEE Trans Med Imaging, *38*(11), 2705-2715, 2019

Digital Tomosynthesis (DTS) Image Enhancement



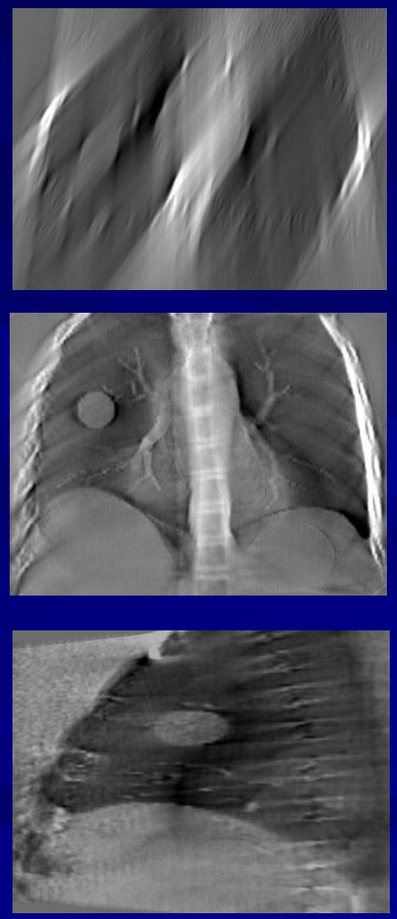
DTS

DTS (30˚)

Axial

Coronal

Sagittal



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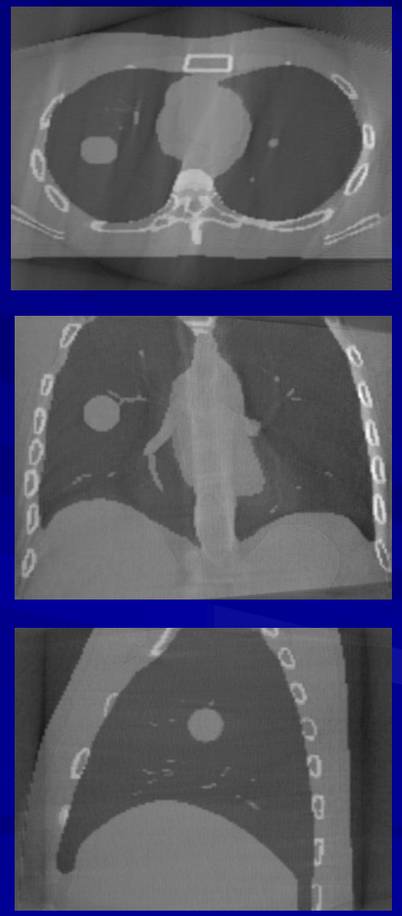
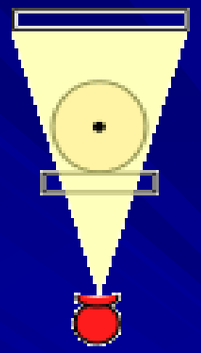
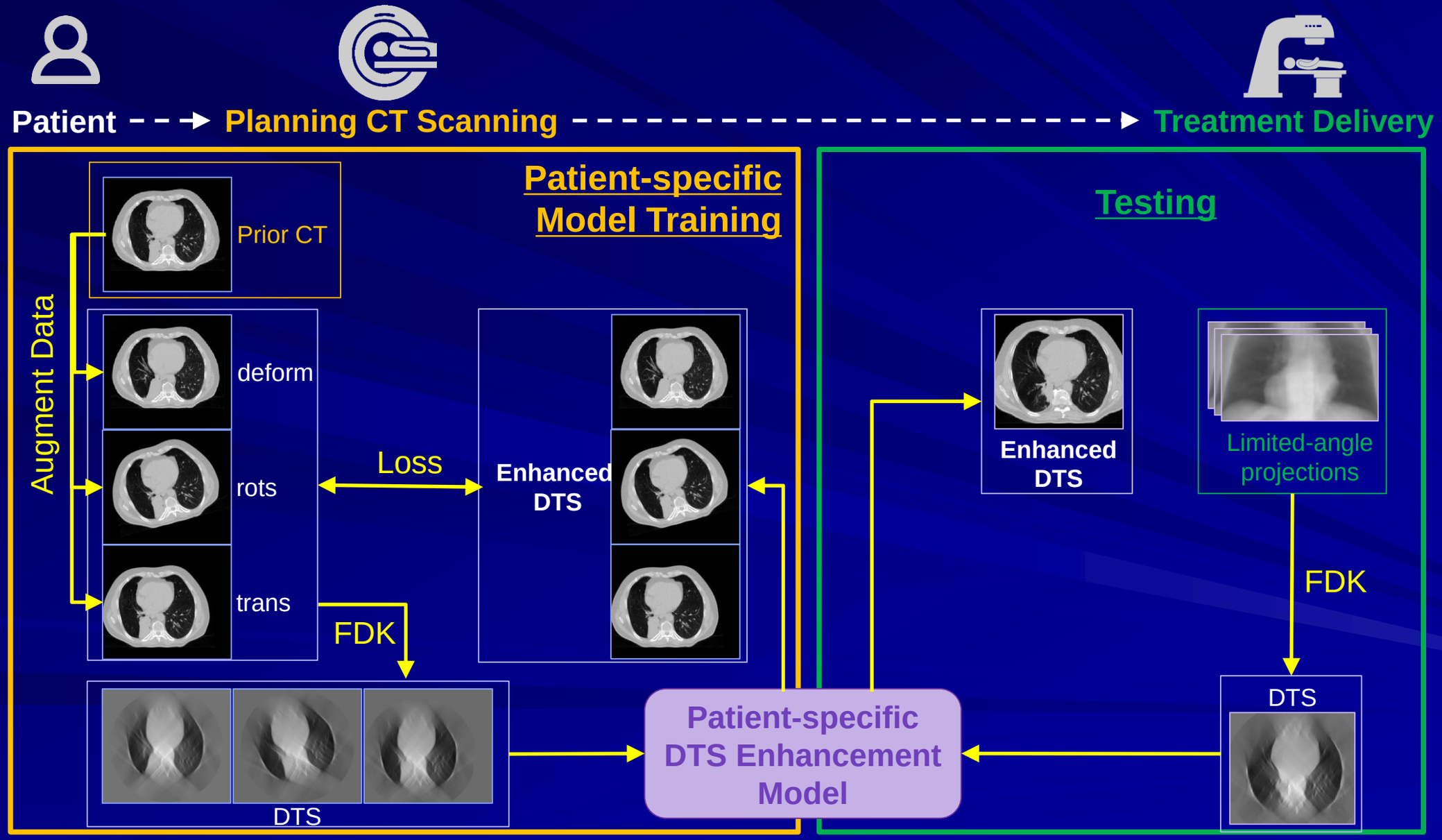
CBCT (200˚)





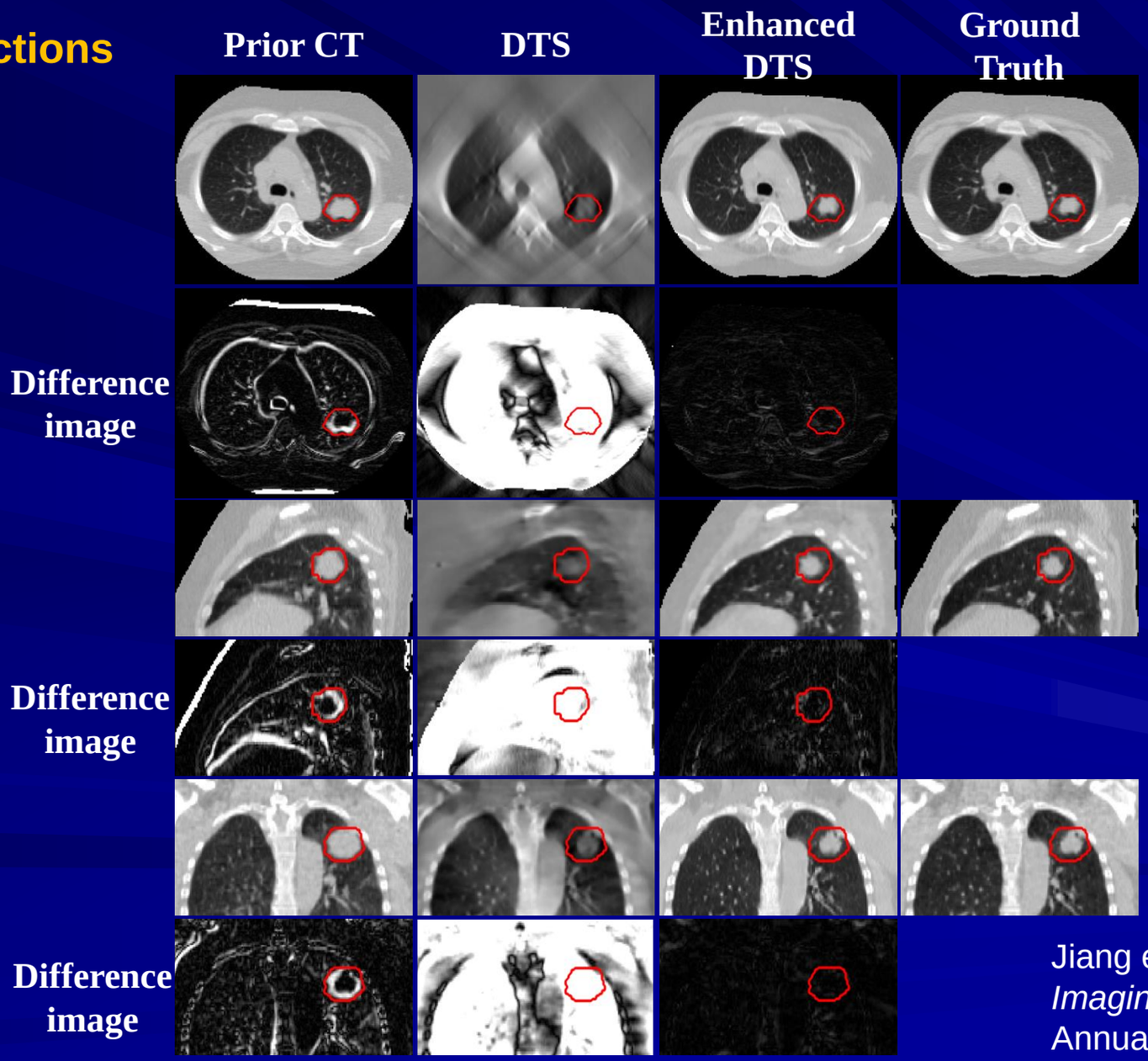
CBCT

DTS Enhancement using Patient-specific Model



DTS Enhancement

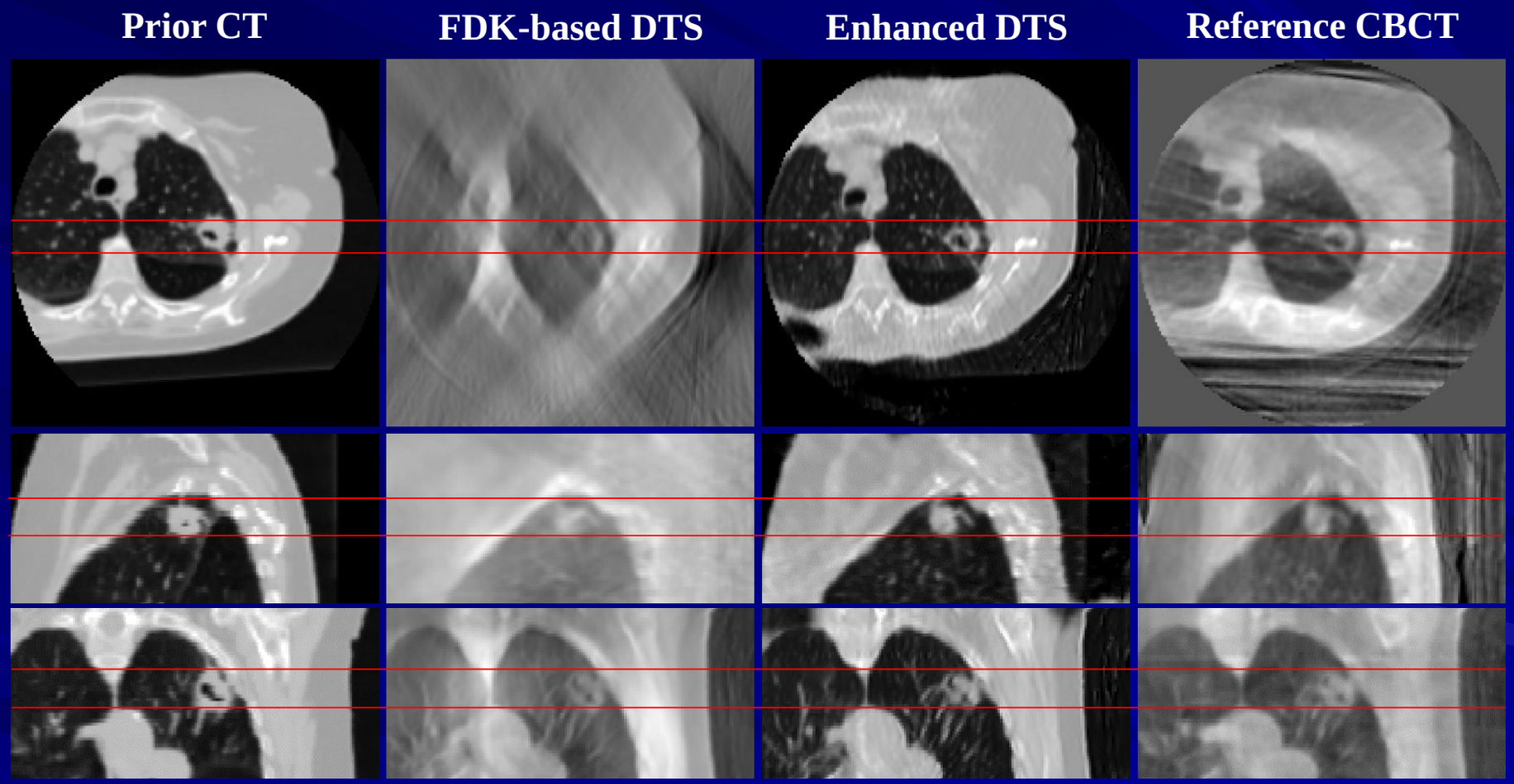
Simulated projections



Jiang et al, Wed, 11:30-12:30pm, *Novel Imaging Technologies for IGRT*, AAPM Annual Meeting, 2020

DTS Enhancement

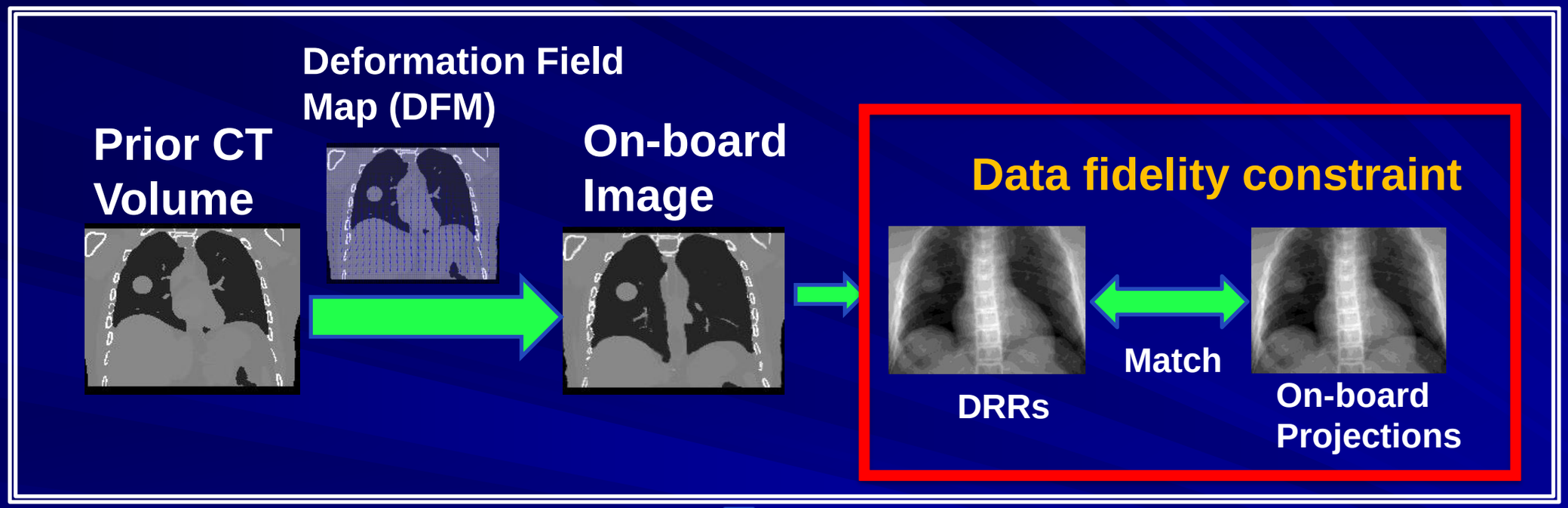
Real projections

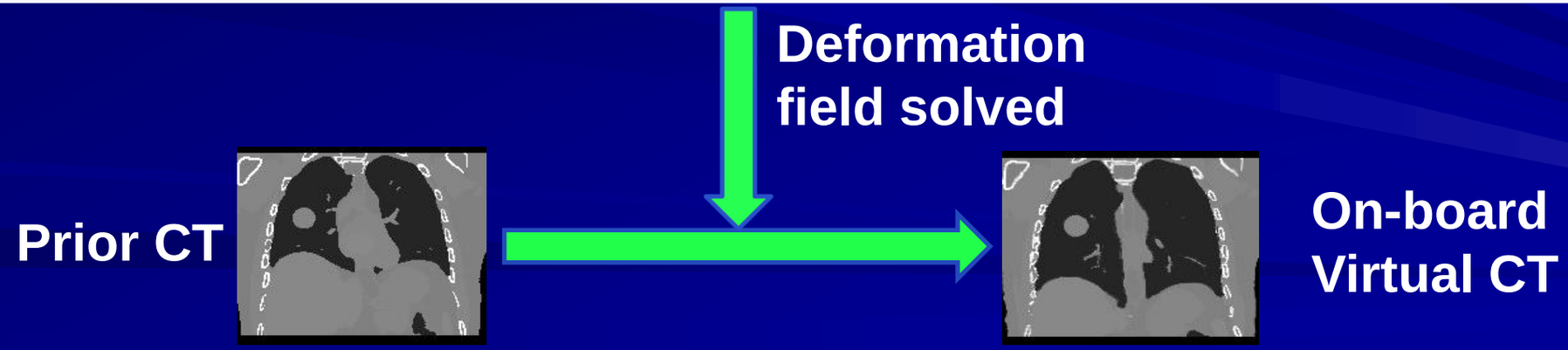


Prediction time ~1s

Jiang et al, Wed, 11:30-12:30pm, *Novel Imaging Technologies for IGRT*, AAPM Annual Meeting, 2020

Prior Knowledge based Virtual CT Generation

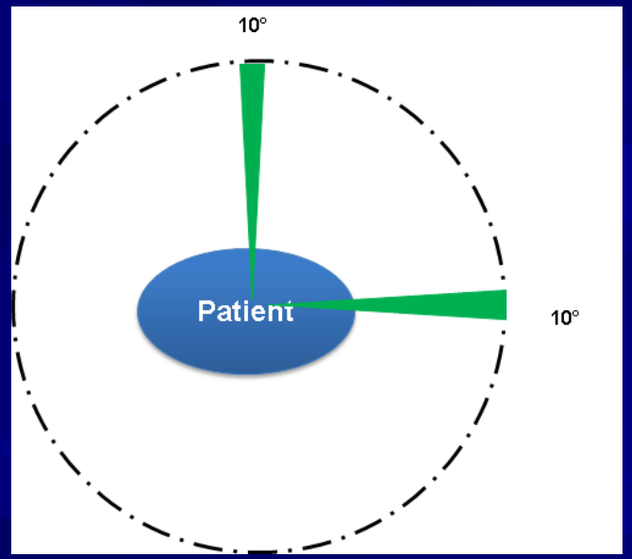


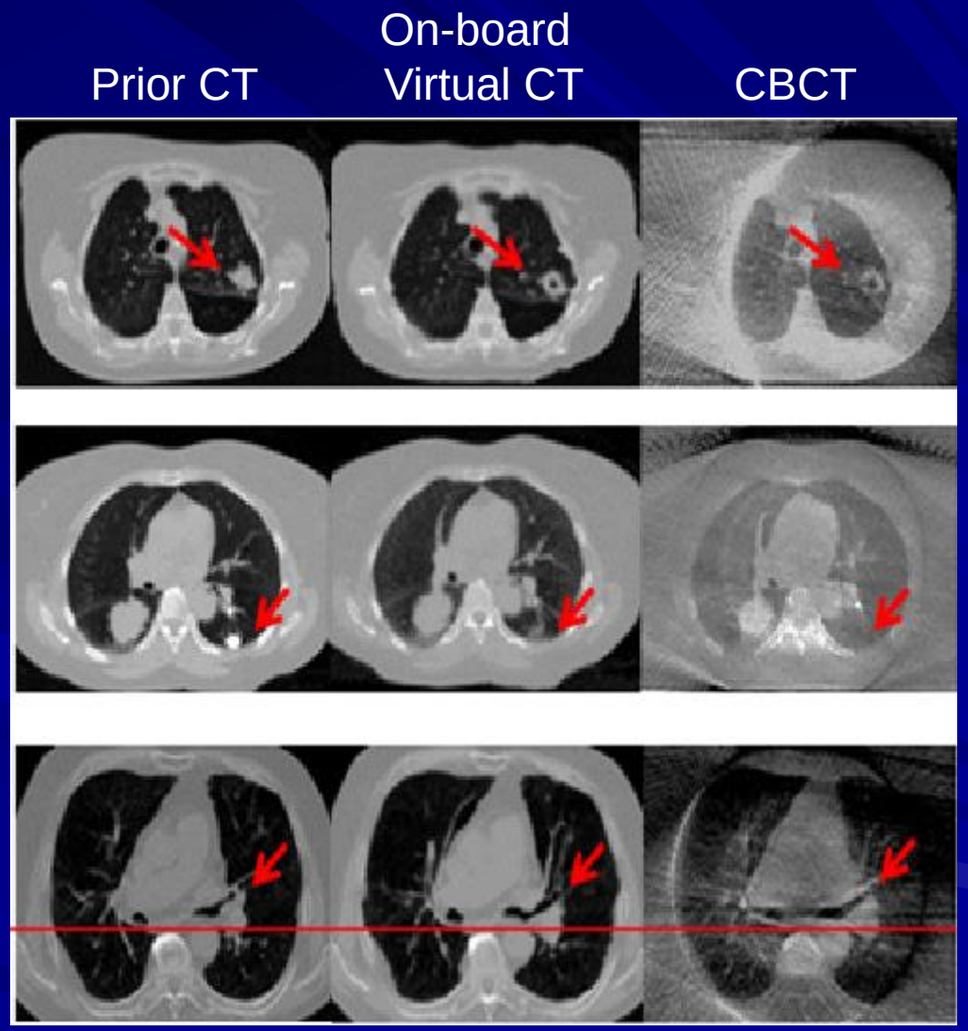


Ren et al, Med Phys, 41(2), 020701, 2014

Prior Knowledge based Virtual CT Generation

Reconstructed using projections acquired in orthogonal-10° scanning angles





Harris et al, Med Phys, 44(3), 1089-1104, 2017
Zhang et al, Phys Med Biol, 64(10), 10NT01, 2019

Summary

- Medical image synthesis is valuable for enhancing the image quality or synthesizing virtual images for different modalities.
- Medical image synthesis has a wide variety of applications in image guided radiation therapy, and can substantially improve the efficiency and precision of the imaging techniques for target localization or adaptive therapy.