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

4D eXtended CArdiac-Torso (XCAT) Phantoms

Original Adult Models

Visible Human Data

Segmented

Converted to NURBS Surfaces

Segars et 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
Population of XCAT Phantoms

Segars et 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

Generate MT-XCAT using D-CGAN

Data Preparation
- Real Image
- Organ Map

Model training and validation
- Training Group
  - Real Image
  - Organ Map
- Validation Group
  - Orgain Map
  - Real Image
- DCGAN
  - Validation Group
  - Simulated Image
  - Evaluation: PSNR SSIM
  - Fine-tune

Testing and Evaluation
- XCAT
  - Real Image
  - Evaluation: Image Features
- MT-XCAT
  - DCGAN
  - Evaluation: PSNR SSIM

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

Generate XCAT Phantom with CT Texture

Generate XCAT Phantom with CBCT Texture

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

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

RADAR family of phantoms, Stabin et al.

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

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

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

- Radiation therapy: 4D imaging and treatment
- Patient database for model training (deep learning)
- Virtual clinical trial before the actual clinical trial

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

Abadi et al. Journal of Medical Imaging 7(4), 042805, 2020
Digital phantoms are valuable tools for addressing the challenges in patient studies.

Significant progress has 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.
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Image quality augmentation:
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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: reconstructed by FDK backprojection
- TV-CBCT: reconstructed by iterative algorithm with total variation (TV) constraint
- CT

72 half fan cone beam projections
4D-CBCT Image Enhancement

Training and testing workflow

4D-CBCT Image Enhancement

Ground truth CBCT using 900 projections

Iteratively reconstructed CBCT using 120 projections

Enhanced CBCT using 120 projections

4D-CBCT Image Enhancement

CT

CBCT using 72 simulated projections

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

Digital Tomosynthesis (DTS) Image Enhancement

DTS (30°)

Axial

Coronal

Sagittal

CBCT (200°)

DTS

CBCT
DTS Enhancement using Patient-specific Model

- **Prior CT deformrots**
- **Augment Data**
- **Patient-specific Model Training**
- **Testing**
  - Limited-angle projections
  - FDK

**Planning CT Scanning**

**Patient-specific DTS Enhancement Model**
DTS Enhancement

Simulated projections

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<thead>
<tr>
<th>Prior CT</th>
<th>DTS</th>
<th>Enhanced DTS</th>
<th>Ground Truth</th>
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Jiang et al, Wed, 11:30-12:30pm, Novel Imaging Technologies for IGRT, AAPM Annual Meeting, 2020
## DTS Enhancement

### Real projections

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<thead>
<tr>
<th>Prior CT</th>
<th>FDK-based DTS</th>
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<th>Reference CBCT</th>
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**Prediction time ~1s**

Prior Knowledge based Virtual CT Generation

Prior CT Volume → Deformation Field Map (DFM) → On-board Image

Data fidelity constraint: DRRs → Match → On-board Projections

Deformation field solved

Prior CT Volume → On-board Virtual CT

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
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.