Disclosures

Ongoing Research Support from
• The National Institutes of Health (R01 CA169102, R01 CA202761)
• Varian Medical Systems
• Vision RT Ltd.

Respiratory-Correlated 4DCT

- Single, "reconstituted" average cycle
- Cycle-to-cycle variations not captured
- Subject to severe binning artifacts
  - Artifacts observed in 45/50 of 4D CT scans
  - Mean mag = 11.6 mm (range: 4.4 - 56.0 mm)
Respiratory motion patterns can vary cycle to cycle and day to day, causing variations in translation, rotation, and deformation of tumor and surrounding organs. 

- Shah et al., IJROBP 2013 46(3):477-82
- Amit Sawant, University of Maryland, Baltimore

Impact of baseline drifts and amplitude variability:

Maximum baseline drifts in the SI direction of 8.8 mm were observed in 30%, of 5-8 mm in 33%, and of 2-5 mm in 35% of the treatment fractions. In LR direction, maximum baseline drifts of 5-8 mm were seen in 3% and of 2-5 mm in 31% of the treatment fractions. In AP direction, maximum baseline drifts of 5-8 mm were observed in 3% and of 2-5 mm in 69% of the treatment fractions. These baseline drifts can also be seen in Fig. S1.

Compared to the magnitude of baseline drifts, the magnitude of amplitude variability was smaller with a mean intrafraction variability of 1.3 ± 1.0 mm, 0.4 ± 0.4 mm and 0.5 ± 0.4 mm in the SI, LR and AP directions, respectively. An interfraction amplitude variability of 1.2 ± 0.5 mm, 0.4 ± 0.3 mm and 0.5 ± 0.5 mm was observed for SI, LR and AP direction, respectively.

Steiner et al., Radiotherapy and Oncol, 135, 2019
67 year old female with NSCLC in right mid-lobe

- 1.5T GE Signa
- SSFP, ½ NEX
- TE/TR: 1.7/3.4
- Pixel: 2 x 3 mm^2
- Slice = 5 mm thick
- FOV = 240 x 240 mm
- Tacq = 0.152 s


80 year old male with NSCLC in left upper lobe

- 1.5T GE Signa
- SSFP, ½ NEX
- TE/TR: 1.7/3.4
- Pixel: 2.4 x 3.3 mm^2
- Slice = 5 mm thick
- FOV = 240 x 240 mm
- Tacq = 0.152 s


Surrogate-based vs. Target-based Monitoring
Volumetric motion management rather than "single-point" target-based motion management is ever more critical as we move towards increasingly potent forms of lung radiotherapy; e.g., SBRT, particle RT, dose escalation.

Comprehensive Review of Motion Models

Respiratory motion models: A review

Four "Example" Motion Models

4DCT-based
- UCLA 5DCT model (Dan Low)
- U Maryland surface photogrammetry-based model

4D cone-beam CT-based
- UT Southwestern SMEIR (Jing Wang)
- UCLA McSART (John Lewis)
UCLA 5DCT model

Acquisition protocol

Register Free Breathing Images to Measure Motion, Average to Reduce Noise
Current Motion Model

- Assume linear in variables (breathing amplitude and rate)
- Data that build the model are:
  - Deformation maps between CT scans
  - Surrogates measured during CT scan acquisition

\[
\tilde{X}(v, f) = X_0 + \alpha(X_0) v + \beta(X_0) f
\]

Position at \( v = f = 0 \): Breathing amplitude

Clinical Technique

New Technique

Early Clinical Implementation

- Replacing 4DCT with model-based CT workflow
- Provides 8 amplitude-based CT scans to the clinic
- Provide image of the model error


"Exhalation"
Volumetric Imaging Using Parameterized 4D Motion Model

Amit Sawant
University of Maryland, Baltimore

Research VisionRT Couch-mounted System With High-Speed Image Capture (HSIC)

Principal Component Analysis and Model generation

Establish relationship between 4DCT deformations and surface deformations

Relation between 1st and 2nd principal components of 4DCT DVF

Relation between 1st and 2nd principal components of surface deformations

Calculate affine transformation that maps these two spaces
Clinical Study – 18 patients accrued to date

Real-time Vision RT surface and ROI

4D Model – Volumetric Monitoring Over Multiple Respiratory Cycles

Building Model in PC Space

Validation: Comparing Model-generated Fluoro vs real Fluoro

Digitally reconstructed (model-generated) fluoroscopy

kV Fluoroscopy using Truebeam OBI

* For visible structures Dice coefficients were consistently > 0.8 (considered good)

Simultaneous Motion Estimation and Image Reconstruction (SMEIR) for 4D-CBCT
Simultaneous Motion Estimation and Image Reconstruction (SMEIR) for 4D-CBCT

- Motion compensated image reconstruction
- Update motion model directly from projections


Multi-organ Meshes to Model Sliding Motion

- Allow sliding motion between lung and thoracic cage
- More accurate reconstruction at peripheries of lung

Incorporate Biomechanical Modeling into 4D-CBCT reconstruction

Reconstruction results from 24 projections

More accurate DVF with biomechanical modeling


Lung Tumor Motion Simulation Error

FEM respiration simulation using predicted lung surface motion as the boundary condition

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<th>motion range RL (mm)</th>
<th>motion range SI (mm)</th>
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Teherani, ... and Wang, PMB, 60, 8833-8849, (2015)

Motion Compensated Simultaneous Algebraic Reconstruction (McSART)
McSART workflow

- 1. Projections
- 2. Motion-blurred SART images (8 bins)
- 3. Motion-compensated SAR (McSART) images
- 4. Iteration with DVF
- 5. Respiratory motion model

Retrospective patient study

- Use retrospective 5DCT patient data as ground truth in McSART process
- 8 patients
- Truebeam geometry used, including SID, SAD, detector size, resolution
First application to prospectively acquired patient data

Videos from first patient in coronal, sagittal, and axial planes.
CONCLUSION

• Volumetric motion models will become increasingly relevant and possible in the near future
• Barriers such as large image data handling, memory, processing power and rapidly becoming non-issues
• Monitoring the entire volume will create new treatment planning and delivery paradigms that focus more on normal tissue toxicity and post-RT function/QoL