Position Monitoring – Future Roadmap

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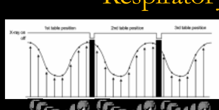
Disclosures

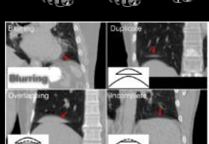
Ongoing Research Support from

- The National Institutes of Health (R01 CA169102, R01 CA202761)
- Varian Medical Systems
- Vision RT Ltd.

Respiratory-Correlated 4DCT



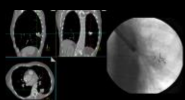
- Single, "reconstituted" average cycle
- Cycle-to-cycle variations not captured

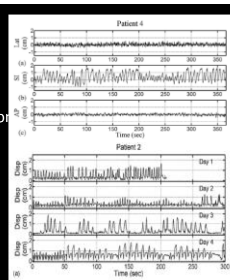


Yamamoto *et al.* IJROBP 2008

- 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
  - day to day
- Causing variations in translation, rotation and deformation of
  - tumor
  - surrounding organs





Shah et al.,IJROBP, 2013 86(3):477-83

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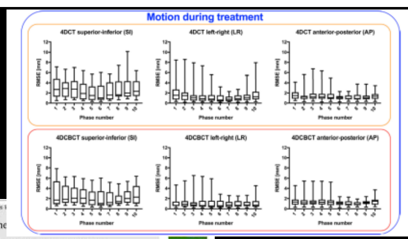
4DCT

4DCBCT



Original Article

Both four-dimensional computed tomography and four-dimensional cone beam computed tomography under-predict lung target motion during radiotherapy

Elisabeth Steiner, Chun-Chien Shieh, Vincent Caillet, Jeremy Booth, Ricky O'Brien, Adam Briggs, Nicholas Hardcastle, Dasantha Jayamanne, Kathryn Szymura, Thomas Eade, Paul Keall

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Impact of baseline drifts and amplitude variability

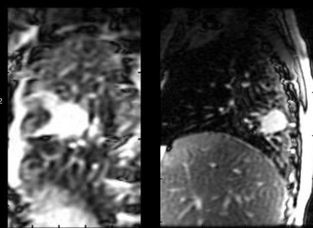
Maximum baseline drifts in the SI direction of >8 mm were observed in 10%, of 5–8 mm in 17% and of 2–5 mm in 35% of the treatment fractions. In LR direction, maximum baseline drifts of 5–8 mm were seen in 3% and of 2–5 mm in 31% of the treatment fractions. In AP direction, maximum baseline drifts of 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 0.6 ± 0.4 mm in the SI, LR and AP directions, respectively. An interfraction amplitude variability of 1.2 ± 0.9 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

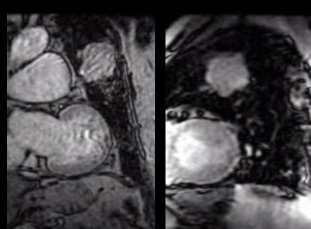
- 1.5T GE Signa
- b-SSFP, ½ NEX
- TE/TR: 1.7/3.4
- Pixels: 2 × 3 mm^2
- Slice = 5 mm thick
- FOV = 240 × 240 mm^2
- T_{acq} = 0.165 s



Sawant et al., BioMed Research International, 2014

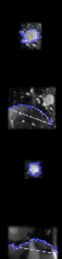
80 year old male with NSCLC in left upper lobe

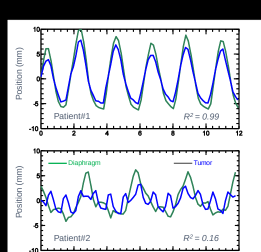
- 1.5T GE Signa
- b-SSFP, ½ NEX
- TE/TR: 1.7/3.4
- Pixels: 2.4 × 3.3 mm^2
- Slice = 5 mm thick
- FOV = 240 × 240 mm^2
- T_{acq} = 0.152 s



Sawant et al., BioMed Research International, 2014

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

ELSEVIER

Medical Image Analysis
Volume 17, Issue 1, January 2013, Pages 19-42

Survey Paper

Respiratory motion models: A review

J.R. McClelland [a], D.J. Hawkes [a], T. Schaeffter [b, c], A.P. King [b, c]

Show more

https://doi.org/10.1016/j.media.2012.09.005

Four “Example” Motion Models

4DCT-based

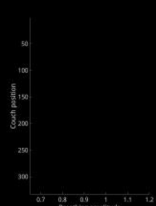
- UCLA 5DCT model (Dan Low)
- U Maryland surface photogrammetry-based model

4D cone-beam CT-based

- UT Southwestern SMEIR (Jing Wang)
- UCLA McSART (John Lewis)

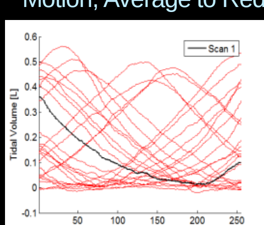
UCLA 5DCT model

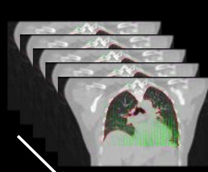
Acquisition protocol



Lu et al, Med Phys 32, 2351 (2005)

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





25 scans

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

Breathing rate

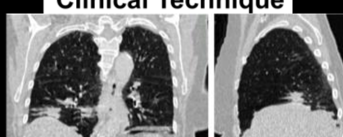
$$\vec{X}(v,f)=\vec{X}_0+\vec{\alpha}(\vec{X}_0)v+\vec{\beta}(\vec{X}_0)f$$

Position at v=f=0 Breathing amplitude

Clinical Technique

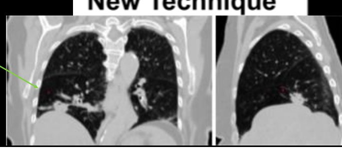
Thomas, et al. Red J 89, 191 (2014)

"Exhalation"



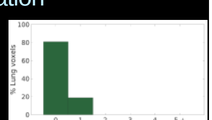
New Technique

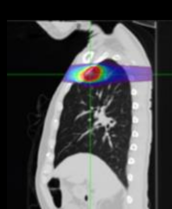
3mm diameter

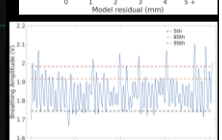


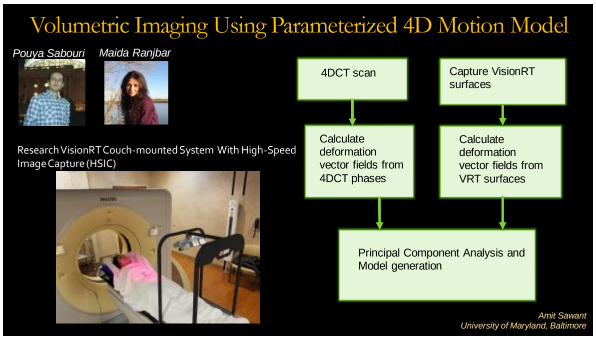
Early Clinical Implementation

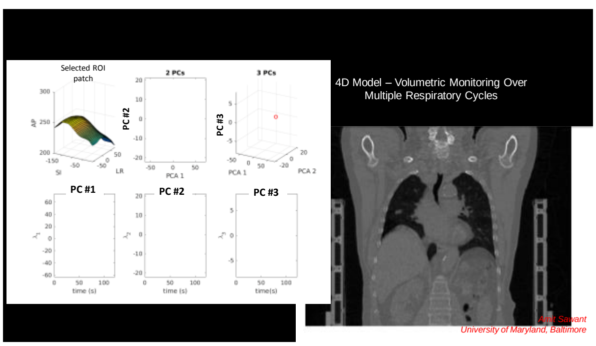
- Replacing 4DCT with model-based CT workflow
- Provides 8 amplitude-based CT scans to the clinic
- Provide image of the model error

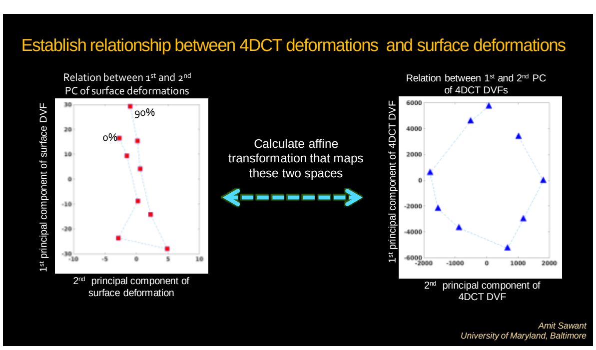







Volumetric Imaging Using Parameterized 4D Motion Model
Pouya Sabouri
Maida Ranjbar
Research VisionRT Couch-mounted System With High-Speed Image Capture (HSIC)
4DCT scan
Capture VisionRT surfaces
Calculate deformation vector fields from 4DCT phases
Calculate deformation vector fields from VRT surfaces
Principal Component Analysis and Model generation
Amit Sawant
University of Maryland, Baltimore


Selected ROI patch
2 PCs
3 PCs
PC #2
PC #3
PCA 1
PCA 2
PC #1
PC #2
PC #3
time (s)
4D Model – Volumetric Monitoring Over Multiple Respiratory Cycles
University of Maryland, Baltimore


Establish relationship between 4DCT deformations and surface deformations
Relation between 1st and 2nd PC of surface deformations
1st principal component of surface DVF
90%
0%
2nd principal component of surface deformation
Calculate affine transformation that maps these two spaces
Relation between 1st and 2nd PC of 4DCT DVFs
1st principal component of 4DCT DVF
2nd principal component of 4DCT DVF
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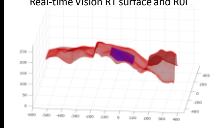
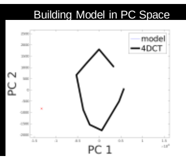
Clinical Study – 18 patients accrued to date

Real-time Vision RT surface and ROI



Building Model in PC Space



4D Model – Volumetric Monitoring Over Multiple Respiratory Cycles

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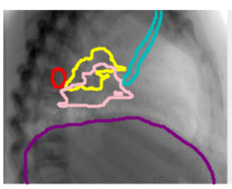
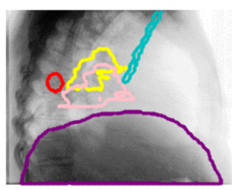
Validation: Comparing Model-generated Fluoro vs real Fluoro

Digitally reconstructed (model-generated) fluoroscopy



kV Fluoroscopy using Truebeam OBI



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

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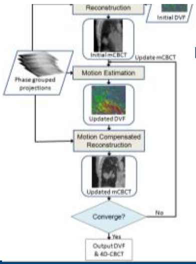
Simultaneous Motion Estimation and Image Reconstruction (SMEIR) for 4D-CBCT

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



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

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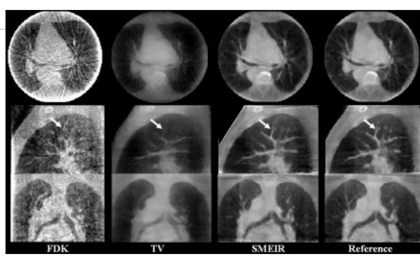

39 projections **200 projections**

J. Dang et al and J. Wang, IJRBP, vol. 91, pp. 410-418 (2015)

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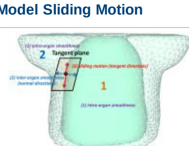
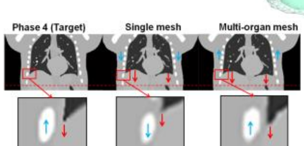
Multi-organ Meshes to Model Sliding Motion

Allow sliding motion between lung and thoracic cage





More accurate reconstruction at peripheral region of lung

Z. Zhong et al and J. Wang, PMB, vol. 61, pp. 996-1020 (2016)

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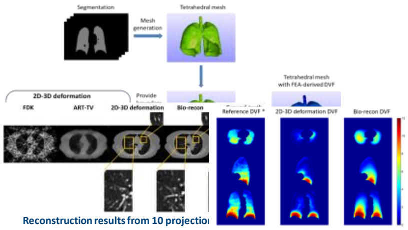
Incorporate Biomechanical Modeling into 4D-CBCT reconstruction



Reconstruction results from 10 projectio

More accurate DVF with biomechanical modeling

Zhang,..., Wang, IEEE-TMI, vol.36, pp. 641-652 (2017); Huang,..., Wang, PMB, 63, 045002 (2018)

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Lung Tumor Motion Simulation Error

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

#Patient	TCM motion range AP (mm)	TCM motion range RL (mm)	TCM motion range SI (mm)	TCM Euclid. Range (mm)	TCM Sim. error AP(mm)	TCM Sim error RL (mm)	TCM Sim. error SI (mm)	TCM Euclid. Error (mm)
1	1.23	2.43	1.12	2.94	0.53	1.02	0.68	1.33
2	0.58	1.17	0.30	1.33	0.59	0.63	0.28	0.90
3	1.65	1.56	4.35	4.90	0.71	0.82	1.43	1.79
4	1.50	3.75	12.00	12.66	0.41	1.11	2.12	2.42
5	1.21	2.90	0.45	3.17	0.31	0.84	0.44	0.99
6	1.49	4.96	3.30	6.14	0.98	2.32	1.34	2.85
7	1.38	0.87	1.50	2.21	0.36	0.78	0.51	0.99
8	1.07	1.66	5.70	6.03	0.40	0.46	1.78	1.88
9	0.85	0.70	5.40	5.51	0.39	0.52	1.21	1.37
10	0.68	2.53	14.23	14.46	0.34	1.01	2.22	2.46
Mean	1.16	2.25	4.83	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Teherani ... and Wang, PMB, 60, 8833-49, (2015); Teherani ... and Wang, 43, 5493-502Med. Phys., (2016)

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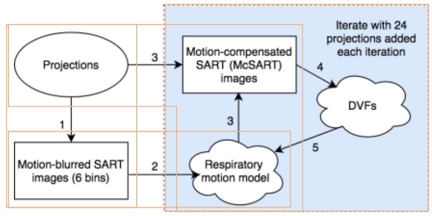
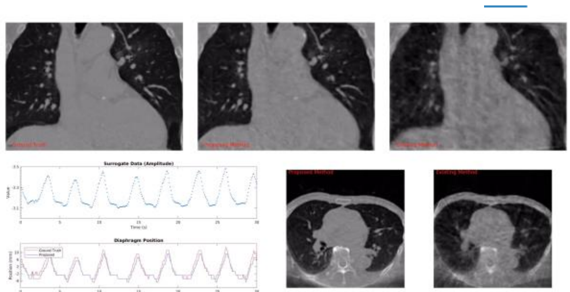
Motion Compensated Simultaneous Algebraic Reconstruction (McSART)

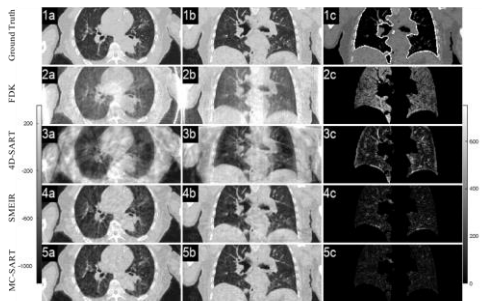
McSART workflow

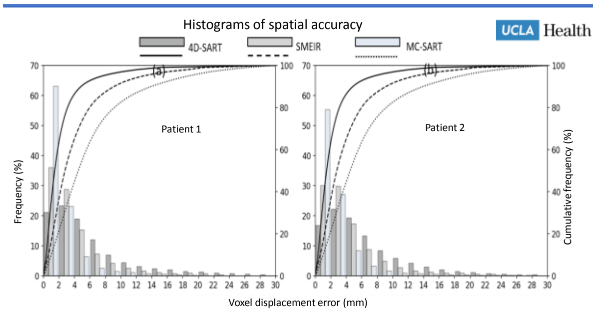


Retrospective patient study

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

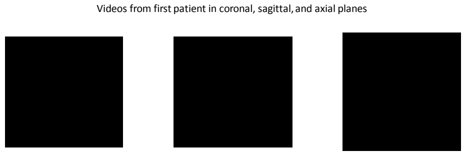






First application to prospectively acquired patient data

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



UCLA Health
Radiation Oncology

David Geffen School of Medicine

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

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