Benefits and Challenges of the 5D-CT Process

Going Beyond 4D with Breathing Motion Modeling

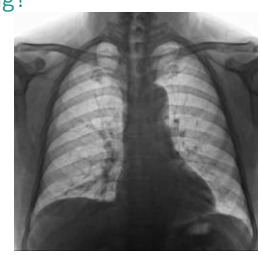
Daniel Low, Ph.D.

Disclosures

- Varian MRA
- ViewRay Stock

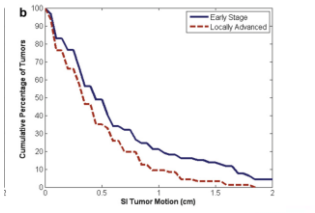
Why Is This Talk Happening?

- We need some form of 4DCT
- Commercial 4DCT
  - Low-Pitch Helical
  - Cine
- Adapted from Cardiac Imaging
- Cardiac cycle relatively uniform and regular
- Most often true with breathing
- Often not true



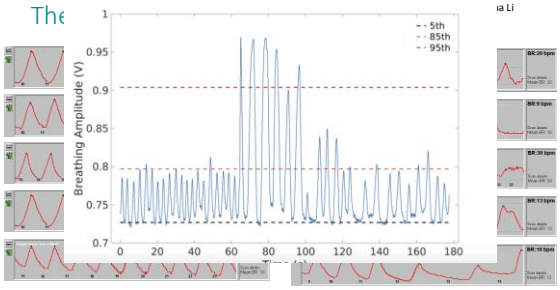
There is Motion

- Impacts targeting accuracy
- Impacts dosimetry



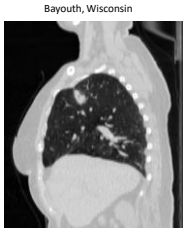
Zhu et al, Radiother Oncol 104 33-38 (2012)

The

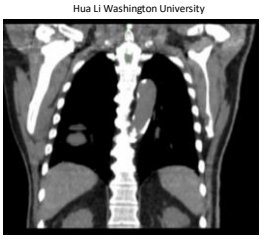


It's Not Just UCLA

Bayouth, Wisconsin



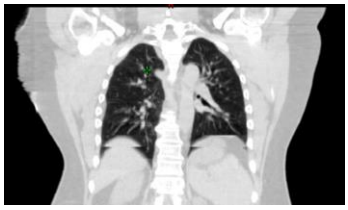
Hua Li Washington University



More Scans

Scott Hadley, University of Michigan

Laura Cerviño, UCSD



Still More Scans

Kyle Padgett, U. Miami

Rojano Kashani, Michigan

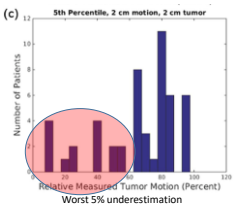
Tumor Motion Measurement Consequences

- Errors in tumor motion measurement simulated by Dou, et al.
- For 4DCT, irregular breathing causes errors in apparent motion magnitude, errors are “random”
- Look at worst 30% of patients
- Evaluate worst 10% of errors (5% most overestimated, 5% most underestimated)

Dou et al, Med Phys 42, 6084 (2015)

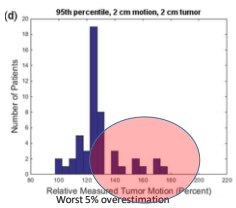
Irregular Breathing

Pitch 0.1 (Siemens low-pitch helical)



Worst 5% underestimation

Pitch 0.06 (Phillips low-pitch helical)



Worst 5% overestimation

Worse with Higher Pitch

Academic Need to Fix This

- 4DCT artifacts and lack of quantitation limit other research and clinical applications
- 2019 AAPM abstracts that have or use "4DCT", "4D-CT", "4DCBCT"

SU-E-SAN2-04
SU-F-221AB-01
SU-F-304-05
SU-I330-GePD-F5-06
TH-A-SAN2-01
TH-A-225BCD-03
TH-A-221AB-08
TH-D-304-02
MO-E115-GePD-F5-03
MO-E115-GePD-F5-05

PO-GePV-T-350
PO-GePV-T-351
PO-GePV-T-374
PO-GePV-T-381
SU-I330-GePD-F7-01
SU-I430-GePD-F5-02
SU-L-SAN2-03
SU-L-221CD-06
MO-I345-GePD-F4-01
TU-C1030-GePD-F9-03
TU-J345-GePD-F2-01

MO-E115-GePD-F5-01
MO-E115-GePD-F5-06
MO-E115-GePD-F7-01
MO-K-221AB-02
TU-AB-221AB-02
TU-C1030-GePD-F3-02
TU-C1030-GePD-F3-03
TU-C1030-GePD-F5-02
TU-C1030-GePD-F5-03
TU-C1030-GePD-F5-04
TU-C1030-GePD-F9-02
TU-F115-GePD-F2-05
TU-F115-GePD-F5-02

TU-HI-SAN2-07
TU-J345-GePD-F2-02
TU-J345-GePD-F2-03
TU-J345-GePD-F2-05
TU-J345-GePD-F7-03
TU-L-225BCD-02
WE-AB-221AB-04
WE-C1030-GePD-F6-06
WE-FG-SAN1-04
WE-FG-304-09
WE-HI-301-01
TH-A-SAN4-06
TH-A-SAN2-03
TH-A-SAN2-08
TH-A-225BCD-02
TH-A-225BCD-06
TH-A-221AB-09
TH-BC-303-03
TH-BC-303-11
PO-GePV-T-96
PO-GePV-T-99
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PO-GePV-T-138
PO-GePV-T-344
PO-GePV-T-371
PO-GePV-T-404

SU-F-221CD-03
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SU-KL-304-03
SU-L-SAN4-07
MO-AB-SAN1-07
MO-AB-221AB-07
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SU-I330-GePD-F5-05
TU-C-PinS-03
TU-C1000-GePD-F9-04
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SU-F-221AB-03
PO-GePV-P-99
PO-GePV-M-09
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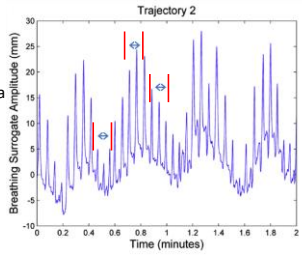
PO-GePV-T-137
PO-GePV-T-303
PO-GePV-T-316
TU-K430-CAMPUS-F3-02
WE-C930-GePD-F5-01

Why?

- Sampling and time
- Commercial sequences acquire approximately 8 seconds of data at any one location
- Formally assume regularity in amplitude or phase
- These two assumptions do not allow quantitative sorting-artifact free images or subsequent data

Low-Pitch samples over short time

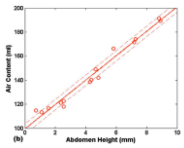


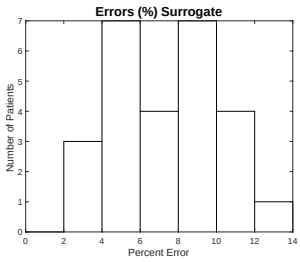
How to Manage Time?

- Prospective gating
- Change temporal distribution of data
  - Scan rapidly (minimal motion artifacts)
  - Images provide tissue positions
- Tie image data together using surrogate
- How? Through a **breathing motion model**

Surrogates

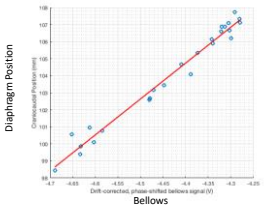
- Showed linear relationship between spirometry and abdomen height and bellows



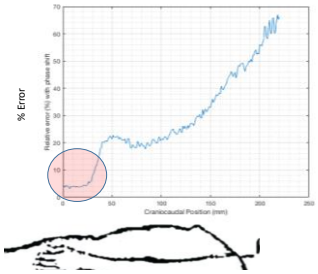


Lu et al, Med Phys 32, 2351 (2005)

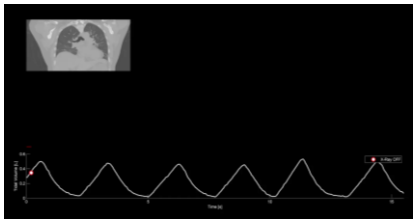
Diaphragm vs Bellows, mean relative error 7.4% (14 patients 27 lungs)

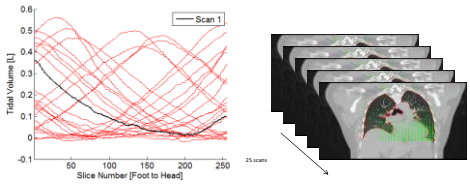


Where the Surrogate is Placed Matters



Fast Helical CT Protocol





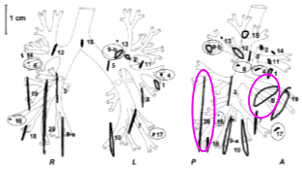
Motion Model

- Motion model will determine tissue positions as function of time
- Explicit variables are themselves functions of time, breathing irregularity resides within these variables
- Advantage in that image data are fast-helical CT scans that can be easily registered
- Data for the model are:
  - Deformation maps between CT scans
  - Surrogates measured during CT scan acquisition

Model Requirements

Seppenwoolde *et al*. Int. J. Radiation Oncology Biol. Phys., Vol. 53, No. 4, pp. 822–834, 2002

- Provide for hysteresis
- Couple position to surrogates
- Surrogate 1
  - Breathing amplitude (tidal volume *v*)
  - Manages overall lung inflation
  - Insufficient to model hysteresis
- Surrogate 2
  - Hysteresis assumed to be due to pressure imbalances
  - Pressure imbalances proportional to excess intra-tracheal pressure
  - Intra-tracheal pressure proportional to airflow *f*



Surrogate for Model?

- Started with spirometry-measured tidal volume/airflow
- Luckily Airflow is time derivative of Tidal Volume
- ANY surrogate proportional to tidal volume can be substituted for tidal volume! (That is most surrogates)
- We use pneumatic bellows

Model

- Assume linear in variables (amplitude and rate)
- This is not necessarily the ideal model, only the first model

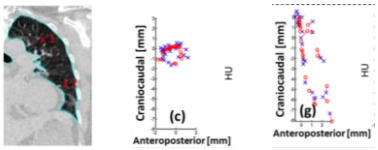
$$\vec{X}(v, f) = \vec{X}_0 + \vec{\alpha}(\vec{X}_0)v + \vec{\beta}(\vec{X}_0)f$$

Position at v=f=0 — Breathing amplitude — Breathing rate

Fit the Model

- Deformable image registration provides positions of each reference image voxel in other images
- Each has measured *v* and *f*
- Fit model parameters to positions

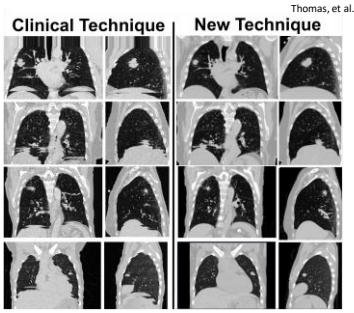
$$\vec{X}(v, f) = \vec{X}_0 + \vec{\alpha}(\vec{X}_0)v + \vec{\beta}(\vec{X}_0)f$$



Use the Model

- Deform images to reference image and average (reduced noise)
  - We changed to increasing mA of first scan
- Deform low-noise reference image to user-selected breathing "phase"
  - Select breathing amplitude and rate
    - Selections can be based on measured surrogates (e.g. make a video of breathing motion) or selected surrogates (e.g. for making scans for treatment planning)
  - Use model to deform low-noise reference image to desired phase

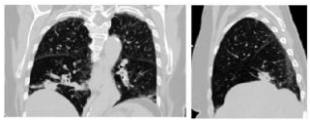
Thomas, et al. Red J 89, 191 (2014)



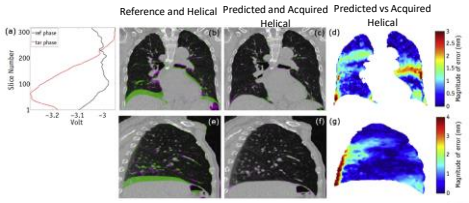
"Exhalation"

Very Pretty, But Are They Right?

- Images will always be pretty
  - No sorting artifacts
  - Low noise
- But are they correct?!
  - Computer bugs
  - Surrogate measurement errors
  - Model inadequacy
- How would the clinic know?
- Answer: The original free-breathing CT scans, reconstruct them with the model and compare

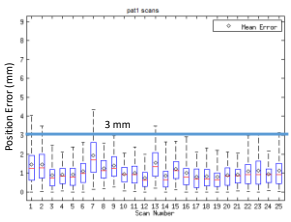


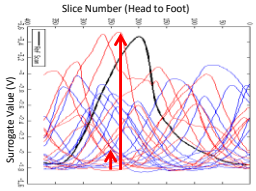
Verification example



Dou, et al. Red J 93, 925 (2015)

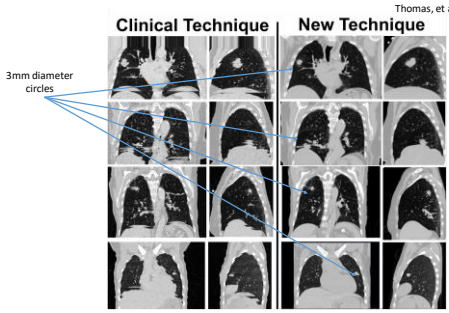
Irregular Breather





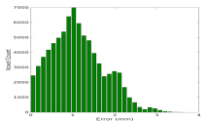
Factor of 8!

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



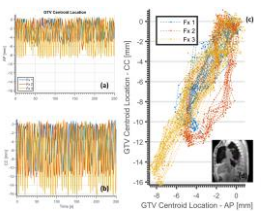
Clinical Implementation (2019)

- Replace 4DCT with model-based CT workflow (aka 5DCT)
- 5 patients
- 25 low-dose CT scans
- Provide 8 amplitude-based CT scans to the clinic
- Provide image of the model error
  - 75th percentile (of the 25 evaluations)



Model Instability

- How to remeasure the model at the treatment machine?
- Model-based CBCT
  - Provides better quality images and updated motion model



Conclusions

- We have been hampered for >15 years by an outdated and unnecessary process
- Based on an easy transition from cardiac to breathing
- Fundamentally inappropriate for irregular motion
- Change data sampling
- Use fast-helical CT to provide sorting artifact-free images
- Quantitation
- Potential for automation

Breathing Group

- Dylan O'Connell
- Michael Lauria
- Bradley Stiehl
- John Lewis
- Anand Santhanam
- James Lamb
- Katelyn Hasse
- Geraldine Chee
- Kamal Singharo
- Dan Ruan
- Percy Lee