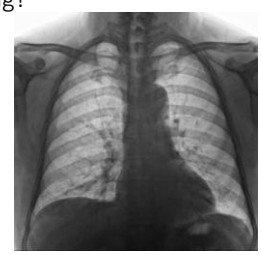
Disclosures

- MRA Varian
- ViewRay Stock

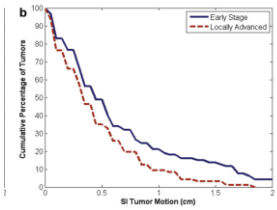
Why Is This Talk Happening?

- 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

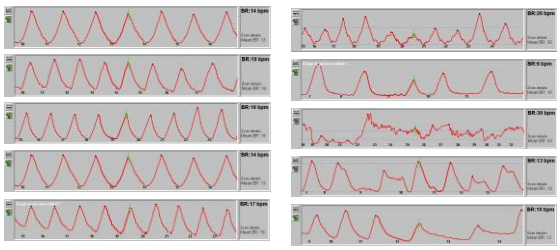
- Impacts targeting accuracy
- Impacts dosimetry
- Impacts motion



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

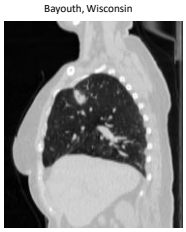
There is Irregularity

Thanks to Hua Li

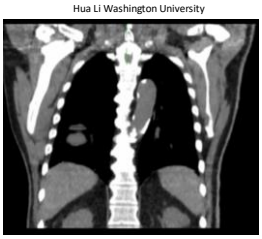


It's Not Just Us

Bayouth, Wisconsin



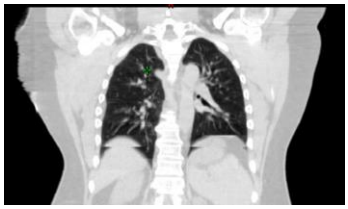
Hua Li Washington University



More Scans

Scott Hadley, University of Michigan

Laura Cerviño, UCSD



Still More Scans

Kyle Padgett, U. Miami

Rojano Kashani, Michigain

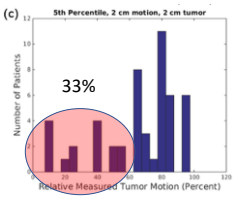
Tumor Motion Measurement Consequences

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

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

Irregular Breathing

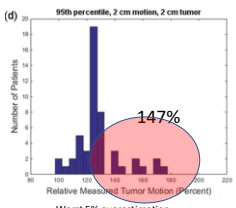
Pitch 0.1 (Siemens low-pitch helical)



Worst 5% underestimation

Worse with Higher Pitch

Pitch 0.06 (Phillips low-pitch helical)



Worst 5% overestimation

Academic Need to Fix This

- 4DCT artifacts and lack of quantitation limit other research and clinical applications
- Example abstracts that have or use "4DCT"

SU-H300-GePD-F5-05
SU-H300-GePD-F6-06
SU-K-202-01
SU-K-202-02
SU-K-202-04
SU-K-202-05
SU-L-202-04
SU-F-209-06
SU-F-KDBRC-03
SU-F-202-06
SU-F-207-02

SU-E-KDBRB1-02
SU-E-202-05
SU-K-202-01
SU-H300-GePD-F7-01
SU-H300-GePD-F8-02
SU-I-GPD-J-08
SU-I-GPD-J-66
SU-I-GPD-T-87
SU-I-GPD-T-377
SU-I-GPD-T-408
MO-C930-GePD-F5-01

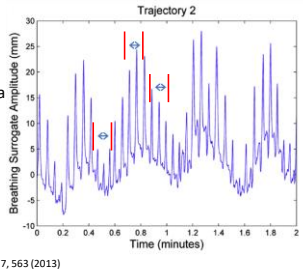
MO-E115-GePD-F5-03
MO-E115-GePD-F9-06
MO-I345-GePD-F4-03
TU-AB-KDBRC-03
TU-AB-205-03
TU-C1030-GePD-F9-03
TU-D-KDBRA1-01
TU-E115-GePD-F5-04
TU-GH-KDBRA1-06
TU-I345-GePD-F7-06
TU-I345-GePD-F8-05

WE-AB-KDBRC-02
WE-AB-KDBRC-05
TU-AB-205-05
WE-C1000-GePD-F5-06
TU-C1000-GePD-F9-02
TU-C1030-GePD-F9-01
TU-E115-GePD-F5-01
TU-E115-GePD-F5-02
TU-E115-GePD-F9-01
TU-I345-GePD-F3-03
TU-I345-GePD-F8-01
WE-AB-KDBRB1-04
WE-AB-KDBRC-04
WE-AB-KDBRC-07
WE-AB-KDBRC-08
WE-C1000-GePD-F6-03
WE-C1030-GePD-F2-01
WE-C1030-GePD-F2-02
WE-C1030-GePD-F2-04
WE-HI-KDBRB1-09
WE-HI-KDBRB1-10
WE-J-KDBRC-01
TH-AB-KDBRC-06
TH-D-KDBRA2-00
TH-EF-KDBRA1-07

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



Jani et al, Red J 87, 563 (2013)

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 model**

SU-H300-GePD-F8-02

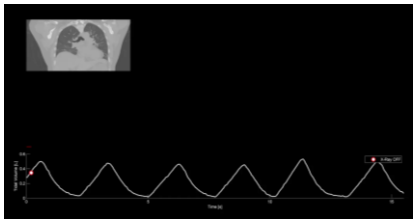
First Clinical Implementation of Respiratory Adaptive 4D-CT (REACT)

N Morton[1,6], J Barbour[2], J Sykes[2], J Kipritidis[3], C Hofmann[4], P Keall[5], R O'Brien[3], (1) University of Sydney, Sydney, NSW, (2) Blacktown Cancer And Haematology Centre, Sydney, NSW, (3) Blacktown Hospital, Blacktown, , Northern Sydney Cancer Centre, Sydney, (5) Siemens Healthcare GmbH, Forchheim, Bavaria, (6) University of Sydney, Camperdown, NSW, (7) University of Sydney, Camperdown, NSW

Purpose: Respiratory Adaptive Computed Tomography (REACT) system aims to mitigate motion errors which currently occur in up to 90% of 4DCT images. Errors are caused by inconsistent patient breathing, and have deleterious effects on tumor delineation and functional imaging. The REACT system identifies changes to a patient's breathing cycle and gates the beam in real-time. A method to implement REACT on a clinical CT scanner for the first time was developed and its effect on artifact reduction quantified. **Methods:** (a) Three free-breathing respiratory traces of high, average and low irregularity were run in-silico through our in-house REACT software. This resulted in a trace with 'Beam On'/'Beam Off' flags. (b) 'Beam Off' segments of each respiratory trace were retrospectively removed, leaving only regions of regular breathing. (c) Manipulated traces were simulated on CIRS dynamic thorax phantom and images acquired using standard 4DCT helical protocol (pitch = 0.09). (d) Each set of images were compared to conventional 4DCT images through visual inspection, total volume, false positive (FP) and false negative(FN) rates of the segmented moving phantom insert. **Results:** For the first time a phantom method simulating the integration of REACT system with a clinical scanner was successfully developed and real CT images acquired. All three traces ran without error. Image artifacts were found in all conventional scans. Total volume error was 28% for highly irregular trace which showed high FN rate of 25%, supporting severe overlapping visually inspected in images. Quantification of image artifact reduction is currently underway. **Conclusion:** First-time experimental implementation of REACT system and a clinical CT scanner was successful. Severe artifacts were found in conventional scans and continuing analysis of REACT images should demonstrate artifact reduction. This study represents the first step to complete implementation of a REACT real-time triggered CT system that should reduce not only imaging errors but imaging dose.

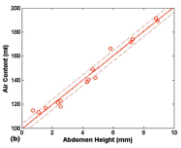
This work was supported in part by funding from Siemens Healthcare.

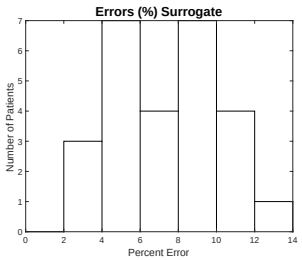
Fast-Helical Protocol



Surrogates

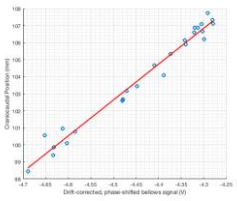
- Lu et al showed linear relationship between spirometry and abdomen height and bellows



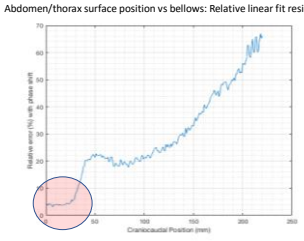


Lu et al, Med Phys 32, 2351 (2005)

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



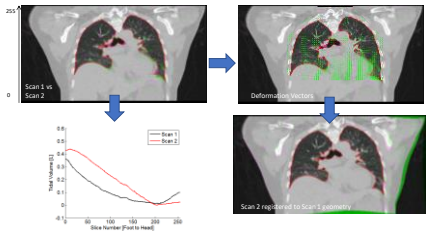
Where the surrogate is placed matters



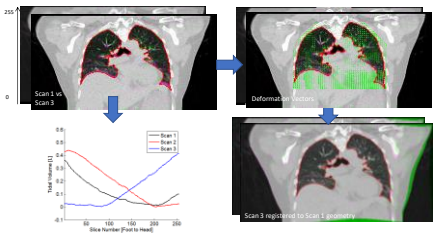
Motion Model

- Motion model will determine tissue positions as function of time
- Explicit variables are themselves functions of time, breathing irregularity lives within these variables
- Can add cardiac motion, eventually manage variations in chest and abdomen breathing
- Advantage in that raw data are fast-helical CT scans that can be easily registered and provide better raw data for analyses such as ventilation
- Data for the model are:
  - Deformation maps between CT scans
  - Surrogates measured during CT scan acquisition

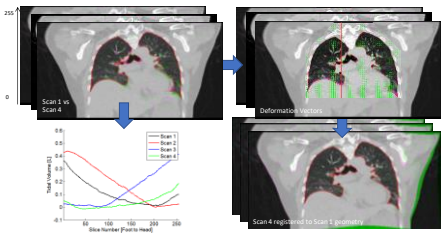
Registration

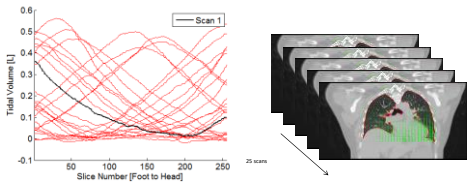


Registration



Registration





Surrogate for Model?

- Started with spirometry-measured tidal volume
- Motion function of tidal volume (lung expansion)
- Hysteresis assumed to be
  - Due to pressure imbalances
  - Pressure imbalances assumed to be proportional to excess pressure/vacuum in trachea
  - Excess pressure/vacuum in trachea assumed to be proportional to 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 + pressure transducer

Model?

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

Breathing rate

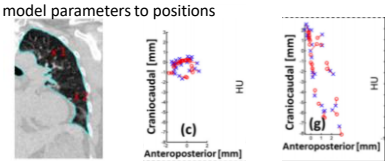
$$\vec{X}(v,f) = \vec{X}_0 + \vec{\alpha}(\vec{X}_0)v + \vec{\beta}(\vec{X}_0)f$$

Position at v=f=0 Breathing amplitude

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

Fit the Model

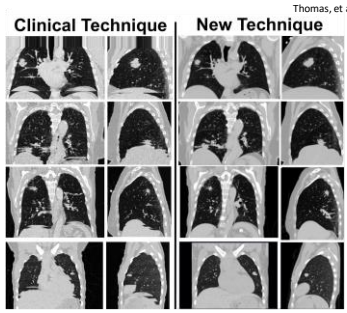
- Deformable image registration provides positions of each reference image voxel in other images
- Each has assigned *v* and *f*
- Fit model parameters to positions



Use the Model

- Deform images to reference image and average (reduced noise)
- 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

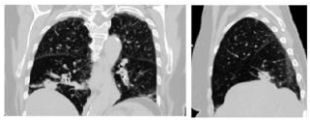
Thomas, et al. Red J 89, 191 (2014)



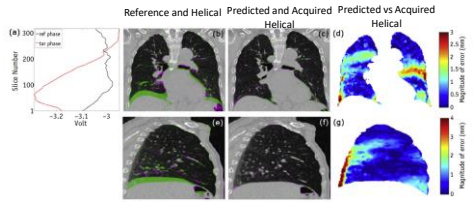
“Exhalation”

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

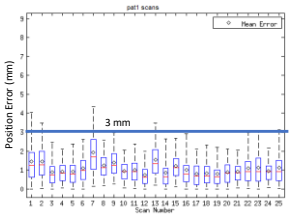


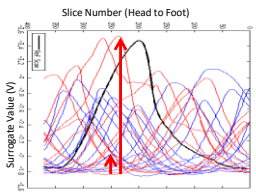
Verification example



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

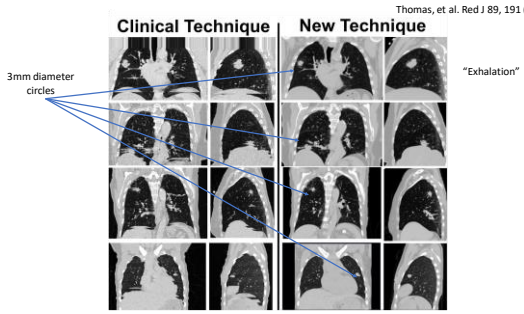
Irregular Breather





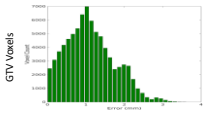
Factor of 8!

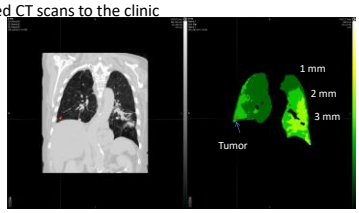
Thomas, et al. Red J 89, 191 (2014)



Clinical Implementation (August 2018)

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





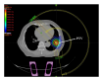
Motion-Mitigation Strategy Selection and Optimization

CT Simulation

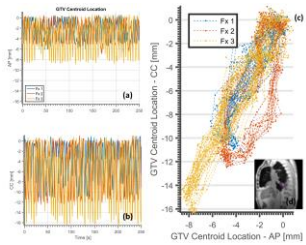
Model-based CT

Dosimetry

Automated Treatment Planning



Breathing Model (in) Stability?



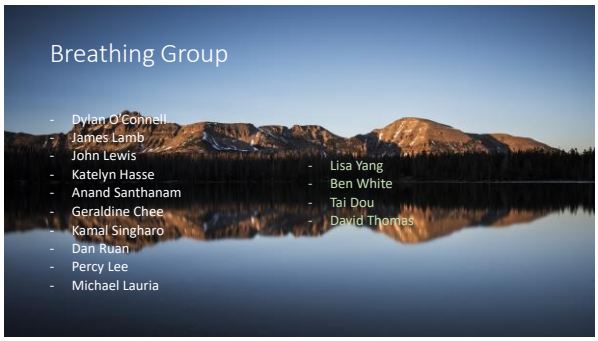
Model changed in fraction 2

Changing Breathing Models (not breathing pattern) Requires Adaptive RT

- 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
- James Lamb
- John Lewis
- Katelyn Hasse
- Anand Santhanam
- Geraldine Chee
- Kamal Singharo
- Dan Ruan
- Percy Lee
- Michael Lauria
- Lisa Yang
- Ben White
- Tai Dou
- David Thomas