Management of Irregular Respiration in 4DCT

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
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

Academic Need to Fix This

• 4DCT artifacts and lack of quantitation limit other research and clinical applications

• Example abstracts that have or use “4DCT”

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

Jani et al, Radi 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

Fast-Helical Protocol

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

Surrogates

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

Scan 1 vs Scan 2
Deformation Vectors
Scan 2 registered to Scan 1 geometry

Registration

Scan 1 vs Scan 3
Deformation Vectors
Scan 3 registered to Scan 1 geometry

Registration

Scan 1 vs Scan 4
Deformation Vectors
Scan 4 registered to Scan 1 geometry
Surrogate for Model?

- Started with spirometry-measured tidal volume
- Motion function of tidal volume (lung expansion)
  - 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

\[
\dot{X}(v, f) = \ddot{X}_0 + \dddot{X}_0 v + \dddot{\ddot{X}}_0 f
\]

Breathing rate

Position at \( v = 0 \)  
Breathing amplitude
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
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


Irregular Breather

Factor of 8!
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
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