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)

There is Irregularity

Thanks to Hua Li

It’s Not Just UCLA

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”
- 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)*

*Pitch 0.06 (Philips low-pitch helical)*

**Worse with Higher Pitch**

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

**Academic Need to Fix This**

- **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
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

\[ \text{Errors (\% Surrogate)} \]

\[ \text{Percent Error} \]

\[ \text{Number of Patients} \]


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

- 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

\[ \hat{X}(v, f) = \hat{X}_0 + \alpha(\hat{X}_0)v + \beta(\hat{X}_0)/f \]

Position at v=f=0 Breathing amplitude

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

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
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

Clinical Technique | New Technique

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 Stehli
- John Lewis
- Anand Santhanam
- James Lamb
- Katelyn Hasse
- Geraldine Chee
- Kamal Singhroo
- Dan Ruiz
- Percy Lee