4D signal processing for lung cancer treatment by radiotherapy

Nicolas Gallego-Ortiz
Respiratory motion

- Breath in, breath out
- What moves and how does it moves?
Respiration dynamic relations

Treatment: patient setup critical

4D CT: four dimensional computed tomography
Agenda

• Why respiratory motion in RT?
• Imaging technologies
• Tumor and lungs motion modeling
  – Finite Element Method
  – Deformable Image Registration
Why study respiratory motion?

• Correct for image artefacts
• To reduce tumor position uncertainty margins

GTV Gross Tumor Volume
CTV Clinical Target Volume
ITV Internal Target Volume
PTV Planning Target Volume
OAR Organ At Risk

E.B. Podgorsak
RADIATION ONCOLOGY PHYSICS.
Variations

• Intra-fraction variations
  – Short time changes in a regular respiratory pattern
  – Coaching to keep respiration regular

• Interfraction variations
  – Day to day changes. Organ fillings, weight loss / gain etc. Changes in respiratory pattern from one day to the other

• Constraints to have real-time tumor tracking
  – Need to model
Agenda

• Why respiratory motion in RT?
• **Imaging technologies**
• Tumor and lungs motion modeling
  – Finite Element Method
  – Deformable Image Registration
Imaging technologies

- Computed tomography
- 4D Computed Tomography
- 4D Magnetic Resonance
- … multimodality solutions with fluoroscopy, Cone-beam CT.
- Optical surface scanning technologies
Concept of 4D CT

• (3D + t) Computed Tomography

Low et al.: Breathing motion measurements
Medical Physics, Vol. 30, No. 6, June 2003
A sagittal slice of a lung tumor in motion
Optical surface technologies

Agenda

• Why respiratory motion in RT?
• Imaging technologies
• **Tumor and lungs motion modeling**
  – Finite Element Method
  – Deformable Image Registration
Lung and tumor motion modeling

• Biophysical models

• Deformable registration (data-driven)
  – Internal deformations related to surface
  – Surface deformation -> motion field
Agenda

• Why respiratory motion in RT?
• Imaging technologies
• Tumor and lungs motion modeling
  – Finite Element Method
  – Deformable Image Registration
What is Finite Element Method?

- Numerical method
- Solve boundary problems
- Partial differential equations
- On a discrete finite element set (discretized solution domain)
Dynamic model: simplified geometry

- Finite element model: Rectangle driven by a piston. Sinusoidal displacement profile


- Slipping boundary
- Non-slipping boundary
Dynamic model:

lungs material:

hookean linear and viscoelastic

Kyriakou et al.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>1.3 x 10^{-9} m^2</td>
<td>West (2005)</td>
</tr>
<tr>
<td>Density</td>
<td>200 kg</td>
<td>West (2005)</td>
</tr>
</tbody>
</table>

Resistence flow of air

Permeability of medium

$R = \frac{P_{\text{alveolar}} - P_{\text{atm}}}{Q}$

$\kappa = \frac{Q \mu L}{A(P_{\text{alveolar}} - P_{\text{atm}})} = \frac{Q \mu L}{ARQ} = \frac{\mu L}{AR}$

Variations
Explore effects

ADINA (commercial software for Automatic Dynamic Incremental Nonlinear Analysis).
Dynamic model: Assessment: 4DCT data

Kyriakou et al.
Dynamic model: Parameters tuning

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What is image registration?

http://www.itk.org/ItkSoftwareGuide.pdf
How does it work?
Image Registration

Fixed Image → Metric → Optimizer → Transform

Moving Image

pixels  →  fitness value  →  Transform parameters

pixels  →  points

Interpolator
What is the difference between Rigid Registration and Deformable Registration?

http://www.itk.org/ItkSoftwareGuide.pdf
Surface Volume Model
Deformable registration

Data
10 patients with 4D CT
“reference”
2 patients with repeated
(2 weeks after first acquisition)
for each case:
- Reference CT (full expiration)
- each frame of 4D CT
- Resp. signal
- External surfaces
  segmented from 4D CTs

Methods
- PCA: Principal component analysis

Results
1. Leave one out
2. on reapeated 4D CTs
   Full inspiration and
   Full expiration

- local profiles
- difference images
- Correlation Coefficient (CC)
- Clinical Expert

Fayad et al.
Med. Phys. 39 (6), June 2012
Principal Component Analysis
Approximated relation surface volume

\[ d_j = [u_{1,1,j}, u_{1,2,j}, u_{1,3,j}, \ldots, u_{M,3,j}, s_{1,j}, s_{2,j}, \ldots, s_{N,j}]^T, \]  

(4) \[ u_{m,i,j} \]

\[ D = [\tilde{d}_1, \ldots, \tilde{d}_j, \ldots, \tilde{d}_J], \]  

(5) \[ s_{n,j} \]

\[ \bar{d} = \frac{1}{J} \sum_{j=1}^{J} d_j. \]  

(6) \[ s_{n,j} \]

\[ DD^T(\text{DX}) = D(D^T\text{DX}) = \lambda \text{DX}. \]  

(7)

Take the K first eigen vectors

\[ d(t) \approx \bar{d} + \sum_{i=1}^{K} w_k(t) e_k. \]  

(8) \[ e_i \]

\[ \tilde{d} \approx E W, \]  

(9) \[ E = [e_1, \ldots, e_K] \]

\[ \tilde{u} \approx E_u W \]

\[ \tilde{s} \approx E_s W \]

\[ \tilde{d} = [\tilde{u}, \tilde{s}]^T \]

\[ \tilde{u}(t) = E_u E_s^{-1} \tilde{s}(t) = B \tilde{s}(t), \]  

(11) \[ \bar{d} = [\tilde{u}, \tilde{s}]^T \]

i th displacement of Voxel m at time j

Displacement nth Surrogate at time j

N = 1 amplitude

N = 1 phase

N = 2 ampl and phase

N = 10 (surface ROIs)

Fayad et al.
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Principal Component Analysis
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\[ d_j = [u_{1,1,j}, u_{1,2,j}, u_{1,3,j}, \ldots, u_{M,3,j}, s_{1,j}, s_{2,j}, \ldots, s_{N,j}]^T, \quad (4) \]

\[ D = [\tilde{d}_1, \ldots, \tilde{d}_j, \ldots, \tilde{d}_J], \quad (5) \]

\[ \tilde{u}(t) \approx E_u E_s^{-1} \tilde{s}(t) = B \tilde{s}(t), \]

Take the K first eigen vectors

\[ d(t) \approx \tilde{d} + \sum_{k=1}^{K} w_k(t) e_k. \quad (8) \]

\[ \tilde{d} \approx E W, \quad \text{and phase} \]

\[ \tilde{u} \approx E_u W \]

\[ \tilde{s} \approx E_s W, \quad W = [\ldots, w_k, \ldots] \]

\[ \tilde{d} = [\tilde{u}, \tilde{s}]^T \]

\[ \tilde{u}(t) = E_u E_s^{-1} \tilde{s}(t) = B \tilde{s}(t), \quad (11) \]

Fayad et al.
Med. Phys. 39 (6), June 2012
Reconstructed volumes  
Fayad et al.  
Med. Phys. 39 (6), June 2012
Surface + registration
Measuring respiratory patterns

J Schauer et al.
Surface + registration
Measuring respiratory patterns

J Schaefer et al.
Surface + registration
Measuring respiratory patterns

J Scharer et al.
Surface + registration
Measuring respiratory patterns

J Schaerer et al.
Patient surface motion
Summary

• Modeling + Simulation
  – Very simplified model approaches real tumor trajectories
• Deformable registration (motion field)
  – Typical breathing cycle motion (4D CT data)
  – Given a surfaces -> reconstruct volumen
  – Sensing + registering surfaces -> extract external motion field
Discussion

• Still no evidence that monitoring skin thoraco-abdominal area can improve tumor position estimation
  – Initial condition for tumor trajectories
  – Breaking correlation -> changes in respiratory pattern
  – Same tumor size and position DONT => same trajectory

• Will a model based on planning data hold for delivery fractions? (Time invariance)
Thank you!
What is your opinion?
Lung cancer

• Mortality rates
• Categories
• Treatment options
• Radiotherapy
  – Margins
death rates
US data 1930-2007

CA: A Cancer Journal for Clinicians
Volume 62, Issue 1, pages 10-29, 4 JAN 2012
death rates
US data 1930-2007

CA: A Cancer Journal for Clinicians
Volume 62, Issue 1, pages 10-29, 4 JAN 2012
Two categories

- Small cell lung cancer (SCLC)
  15 – 20 % of lung cancers
  Aggressive
- Non-small cell lung cancer (NSCLC)
Patient setup

• Registration
• Surface Matching
Margins

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4D CT
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