4D CT Scanning: Imaging and Planning

Paul Keall, Ulrich Langer, and Yelin Suh

1 Stanford University
2 Virginia Commonwealth University

Notes

• See abstract
• See AAPM summer school talk, ICCR, ASTRO prep talk
• Add CBCT
• Get latest stuff from Ulrich
• Add grant/trofimov formalism
• Dimitre - images?
• Add table of 4D CT articles vs time

Conflicts-of-interest

• Advisory board: Calypso and Varian
• Intellectual property: Stanford and VCU
• Licenses: Standard Imaging
• Research grants: NIH, Varian
• Speaker: Philips and Varian
Educational objectives

1. Understand the principles of 4D CT image acquisition and reconstruction
2. Understand the limitations of current 4D CT technology
3. Understand the ongoing developments in 4D CT and 4D CBCT imaging
4. Understand the application of 4D CT to treatment planning

Overview

- 4D CT imaging
- 4D CT issues, applications and future directions
- 4D CT for planning
- Summary

4D CT imaging
4D thoracic CT imaging

Brief history of 4D CT

<table>
<thead>
<tr>
<th>Development</th>
<th>Year</th>
<th>First author</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single slice helical</td>
<td>2002</td>
<td>Ford, Vedam</td>
<td>MSKCC, VCU</td>
</tr>
<tr>
<td>Multi-slice cine</td>
<td>2003</td>
<td>Pan</td>
<td>GE/MGH/MSKCC</td>
</tr>
<tr>
<td>Cone beam (benchtop)</td>
<td>2003</td>
<td>Taguchi</td>
<td>Toshiba</td>
</tr>
<tr>
<td>Multi-slice cine</td>
<td>2003</td>
<td>Low</td>
<td>Wash U</td>
</tr>
<tr>
<td>Multi-slice helical</td>
<td>2004</td>
<td>Keall</td>
<td>VCU, MDACC</td>
</tr>
<tr>
<td>Multi-slice PET/CT</td>
<td>2004</td>
<td>Nehmeh</td>
<td>MSKCC</td>
</tr>
<tr>
<td>Cone beam (clinical)</td>
<td>2005</td>
<td>Sonke</td>
<td>NKI</td>
</tr>
<tr>
<td>Applications outside Rad Onc</td>
<td>Ongoing</td>
<td>Several</td>
<td>Several</td>
</tr>
</tbody>
</table>

Early 4D CT: single slice helical

Vedam et al PMB 2003

Brief history of 4D CT

- 8 respiratory phases
  - Peak inhale
  - Early inhale
  - Mid inhale
  - End inhale
  - Peak exhale
  - Early exhale
  - Mid exhale
  - Late exhale

Electrocardiogram-controlled image reconstruction has resulted in three-dimensional computed tomography scans of the heart.

Low et al ASTRO 2001

5 June 2007: 217 citations
(scholar.google.com)
What 4D CT is available?

- All major CT vendors
- Different respiratory signals
  - Optical abdominal tracking
  - Abdominal belt
  - Spirometer
- Different acquisition approaches
  - Helical
  - Axial/Ciné
- Different reconstruction methods
  - Image-based
  - Sinogram-based
- Do-it-yourself
- The limiting factor is the patient!
4D CT issues, applications and future directions

4D CT issues/future: Artifacts

Cause of artifacts?

• Irregular breathing correlates with artifacts

The impact of temporal inaccuracies on 4DCT image quality
Y.D. Moir, 3. A. Ahrab, and D. H. Edelman
Euroradiotherapy Department, Essen Clinic, 30145 Essen 10, Germany
Received 13 October 2002; revised 20 February 2003; accepted for publication 21 February 2003.

"A source of commonly observed inaccuracy is the misidentification of the respiration cycles and resulting respiration phase assignments used in the construction of the 4D patient model."
Irregular respiration with 4D CT scans

Systematic Error

4D CT improvement

- Replace post-processing with active control
- Include data sufficiency condition
- Current generation subset of next generation

Estimated improvement

Post-acquisition improvements
4D CT applications/future: Audiovisual biofeedback

Audio-visual biofeedback

- Studies at VCU, MGH, U Vienna and U Copenhagen have demonstrated a/v benefit
- Q. How best to train patients to breathe reproducibly?

Audiovisual biofeedback improves respiratory reproducibility

See also Neicu et al., Stock et al., Korreman et al.

George et al. IJROBP 2006

Variation of lung tumor motion

Breathing ‘regularly’

3 minutes later...

Courtesy Sonja Dieterich, Georgetown University
Step 1: Learn representative cycle

Step 2: Train patient-bar model

...or wave model?

Free breathing

Audiovisual biofeedback
### Results 10 volunteers

<table>
<thead>
<tr>
<th>Training type</th>
<th>RMS var in displacement (cm)</th>
<th>RMS var in period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free breathing</td>
<td>0.56</td>
<td>0.78</td>
</tr>
<tr>
<td>Bar model</td>
<td>0.30</td>
<td>0.33</td>
</tr>
<tr>
<td>Wave model</td>
<td>0.21</td>
<td>0.20</td>
</tr>
</tbody>
</table>

### Artifacts in 4D CT scans are due to:

- 3% Sorting in image not sinogram space
- 85% Irregular respiration
- 3% Inadequate respiratory monitors
- 3% Use of phase instead of displacement for reconstruction
- 2% Gantry rotation speed too slow

### Discussion of question: Artifacts are due to:

- Sorting in image not sinogram space
- Irregular respiration
- Inadequate respiratory monitors
- Use of phase instead of displacement for reconstruction
- Gantry rotation speed too slow

### Q2. Which of the following would be useful to reduce artifacts in 4D CT scans:

- 7% Breathing training
- 0% Improved acquisition techniques
- 0% Post processing methods
- 93% All of the above
Discussion of question: Methods to reduce artifacts

- Breathing training
- Improved acquisition techniques
- Post processing methods
- All of the above

4D CT applications/future: Ventilation assessment

4D CT ventilation

Source \( I(x_{\text{exh}}) \)

Target \( I(x_{\text{inh}}) \)

Source→Target \( I(u(x_{\text{exh}})) \)

Calculate DVF \( u(x_{\text{exh}} \rightarrow x_{\text{inh}}) \)

Difference \( I(x_{\text{inh}}) - I(u(x_{\text{exh}})) \)
4D CT ventilation

Courtesy Guerrero et al IJROBP 2005

4D CT issues/future:
Dose reduction

Dose reduction

Radiation dose reduction in four-dimensional computed tomography

T.L.E. Schelkesen, S. Thoson, G. Titter, A. Bonte
Department of Radiology, University of Ulm, Ulm, Germany
(2007)
(Received 2 February 2007, accepted for publication 21 September 2007, published 13 November 2007)

100 mAs
10 mAs
10 mAs with Deformable addition

4D CT applications/future:
5 degree freedom CT
Breathing Motion

• Separate airflow dynamics into two components:
  – Motion of diaphragm and other muscles that set the tidal volume (depth of a breath)
  – Variation of local pressure distribution caused by the dynamic process that causes air to flow into the lungs

Inhalation and Exhalation

‘5D’ CT

Courtesy Low et al IJROBP 2005

Courtesy Low et al IJROBP 2005

 Courtesy Low et al IJROBP 2005

Courtesy Low et al IJROBP 2005
What use are 4D CT scans?

- Determine tumor motion/screening
- Motion inclusive treatment
- Respiratory gated treatment
- 4D radiotherapy

4D CT in radiotherapy
Scenario 1: No respiratory motion management devices
4D CT in radiotherapy

Scenario 1: No respiratory motion management devices

- Acquire 4D CT
- Delineate GTV/CTV on each phase (or inhale/exhale)
- Create motion encompassing CTV
- Create PTV
- Plan and treat

![Exhale & inhale CT phases](image)

Motion inclusive treatment

4D CT in radiotherapy

Scenario 2: Respiratory gating
4D CT in radiotherapy
Scenario 2: Respiratory gating

- Acquire 4D CT
- Select respiratory phase(s)
- Delineate GTV/CTV on chosen phase(s)
- Create PTV
- Plan and treat with gating
4D CT in radiotherapy
Scenario 3: 4D radiotherapy

Tumor tracking delivery

4D CT applications in RT
- Quantify motion
- Treatment planning
  - Motion inclusive
  - Respiratory gating
  - Beam tracking
- Treatment delivery
  - Alignment
  - Verification
  - Build motion correlation model
  - Replanning/adaptation

Summary
Summary

• 4D thoracic CT developed in radiation oncology
• Rapid development and deployment
• Acquisition and images will improve
• Audiovisual biofeedback reduces irregularity
• Useful for a variety of treatment strategies
• Applications beyond radiation oncology