4D Cone-Beam CT: Developments and Applications

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Outline

- Background
- Image acquisition approaches
- Projection sorting techniques
- Reconstruction techniques
- Imaging dose
- Clinical applications of 4D-CBCT
**Background: On-board X-ray based Imaging Techniques**

- **Radiograph**
  - Scan angle: 0˚
  - Scan time: <<1 s
  - Scan dose: <<1 mGy
  - Dimension: 2D

- **Cone beam CT (CBCT)**
  - Scan angle: 360˚~/200˚
  - Scan time: ~1 min
  - Scan dose: ~1-8 cGy
  - Dimension: 3D

- **Digital Tomosynthesis (DTS)**
  - Scan angle: 20˚ ~ 60˚
  - Scan time: < 10 s
  - Scan dose: < 1 cGy
  - Dimension: Quasi-3D

**Background - On-board X-ray based Imaging Techniques**

- **Radiograph**
- **CBCT**
- **DTS (30˚)**

**Background - Imaging for moving lung**

- **Static**
  - 3D CBCT

- **Moving phantom/patient**
  - 3D CBCT
  - 4D CBCT

4D imaging needed
Background: Challenges with 4D-CBCT

- Image acquisition:
  Unevenly distributed projections, slow gantry rotation (~1deg/s, 3-4min over 200deg)
- Projection sorting:
  robust, automatic, fast
- Reconstruction:
  under sampled projection data for each phase

Image acquisition approach

- \( \theta \): scan angle for a single phase in one cycle
- \( N_{cycle} \): number of cycles scanned
- \( \Psi \): total scan angle for a single phase

\[ G \]: gantry rotation speed (°/s)
\[ T \]: patient respiratory period
\( N_{phase} \): number of phase bins (typically 10)
\( \Omega \): total scanning angle (360° for half fan, 200° for full fan)

\[ \theta = \frac{G \times T}{N_{phase}} \]
\[ N_{cycle} = \frac{\Omega}{G \times T} \]
\[ \Psi = \theta \times N_{cycle} = \frac{\Omega}{N_{phase}} \]

Gantry rotation speed, projections more spread out

\[ G = 6°/s, T = 5s, N_{phase} = 10, \Omega = 360° ; \theta = 3°, N_{cycle} = 10, \Psi = 36° \]
Image acquisition approach

\[ \theta = \frac{G \times T}{N_{\text{phase}}} \]

\[ N_{\text{cycle}} = \frac{\Omega}{G \times T} \]

\[ \Psi = \theta \times N_{\text{cycle}} = \frac{\Omega}{N_{\text{phase}}} \]

θ = G \times T / N_{\text{phase}}

N_{\text{cycle}} = \Omega / (G \times T)

Ψ = θ \times N_{\text{cycle}} = \Omega / N_{\text{phase}}

G \downarrow \theta \downarrow N_{\text{cycle}} \uparrow

G = 3^\circ/s, T = 5s, N_{\text{phase}} = 10, \Omega = 360^\circ \rightarrow \theta = 1.5^\circ, N_{\text{cycle}} = 24, \Psi = 36^\circ

Slow gantry rotation for 4D-CBCT scan to spread out projections to reduce streak artifacts

Image acquisition approach

\[ T = 6.5s, N_{\text{phase}} = 10, \Omega = 360^\circ \]

G = 6^\circ/s

G = 3^\circ/s

G = 1^\circ/s

T = 6.5s

G = 2^\circ/s, T = 4.93s

T = 3.37s

Slower gantry rotation needed for longer respiratory period

Li et al., 67(4), 1211-1219, IJRBP, (2007)
Projection sorting techniques

- 4D-CBCT reconstruction requires sorting of projection images into different respiratory phases.

- Phase sorting methods:
  - External surrogates: bellow system, RPM system, spirometry
    - Require additional devices
    - External internal mis-correlation
  - Internal surrogates: Marker based and markerless methods
    - Marker based method: invasive implantation, marker migration
    - Markerless methods:
      - Tracking structures with respiratory motion
      - Tracking image intensity fluctuation with breathing
      - Motion modeling method

Projection sorting techniques: FT-Magnitude technique

- Acquire projections
- Perform 2D FT
- Extract resp signal
- Identify peak-insp
- Assign phase
- Sort/Bin projections
- Recon 4D-CBCT
Projection sorting techniques: Motion modeling based method

Prior Knowledge

Motion model
PC: 3.3

9 Deformation fields

4D-CT (10 phases)

On-board volume at time t considered as a deformation of CT

Projection sorting

On-board Projection

Motion model

PCF = \sum_{i=1}^{P} w_i(t)

3D Prior

DRR of deformed CT based on DVF(t)

w_i(t) for projection sorting

No

Self-fidelity Assessment Method

Yes

Lei Zhang et al, AAPM Annual Meeting, 2016

Projection sorting techniques: Motion modeling based method

PCA Coefficient

SI w1

PCA Coefficient based Phase Sorting

• Robust against changes in tumor size, location, and breathing pattern changes.
• This method could be used in both CBCT full fan and half fan mode, and for different gantry rotation speeds.

Lei Zhang et al, AAPM Annual Meeting, 2016

Projection sorting techniques: Motion modeling based method

<table>
<thead>
<tr>
<th>Patient Number</th>
<th>Average Phase Difference</th>
<th>Phase Difference within 10%</th>
<th>Phase Difference within 5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 (FF)</td>
<td>2.23%</td>
<td>99.4%</td>
<td>88.9%</td>
</tr>
<tr>
<td>P2 (FF)</td>
<td>1.81%</td>
<td>98.7%</td>
<td>93.4%</td>
</tr>
<tr>
<td>P3 (HF)</td>
<td>1.62%</td>
<td>100%</td>
<td>99.8%</td>
</tr>
<tr>
<td>P4 (HF)</td>
<td>1.82%</td>
<td>100%</td>
<td>96.2%</td>
</tr>
<tr>
<td>P5 (HF)</td>
<td>1.63%</td>
<td>98.4%</td>
<td>96.6%</td>
</tr>
</tbody>
</table>

Lei Zhang et al, AAPM Annual Meeting, 2016
Reconstruction techniques

- Feldkamp back projection
- Iterative method with compressed sensing
- Prior image based method: MKB, PICCS
- Motion compensated
- Prior knowledge with motion modeling

Reconstruction techniques: FDK Method

Cone Beam---Feldkamp-Davis-Kress (FDK) algorithm

- A 3D realization of the filtered-back projection algorithm
- Fast, easy-to-implement
- Streak artifacts

Reconstruction techniques: FDK Method

45 projections

90 projections

180 projections
Reconstruction techniques: Iterative method with TV

**ART, SART, SIRT + regularizations (TV)**

\[ TV(f) = \int ||\nabla f(x)||_1 dx \]

- Remove streak artifacts for sparse projection sampling in 4D-CBCT
- Computationally expensive
- Image over smoothed

**ART**: algebraic reconstruction technique
**SART**: simultaneous algebraic reconstruction technique
**SIRT**: simultaneous iterative reconstruction technique
**TV**: total variation

Reconstruction techniques: Iterative method with TV

<table>
<thead>
<tr>
<th>Projections</th>
<th>Images</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>![Image 1]</td>
</tr>
<tr>
<td>90</td>
<td>![Image 2]</td>
</tr>
<tr>
<td>180</td>
<td>![Image 3]</td>
</tr>
</tbody>
</table>

Reconstruction techniques: McKinnon-Bates (MKB) algorithm

- Less streaks, no over smoothing
- Residual motion artifacts

Reconstruction techniques: McKinnon-Bates (MKB) algorithm

Prior FDK MKB MKB+ truncation correction


Reconstruction techniques: prior image constrained compressed sensing (PICCS)

Construct prior image Xp by back projecting all phase projections

\[
\min\left[ \Psi_1(\mathbf{X} - \mathbf{X}_P)_{1,1} + (1 - \infty)\Psi_2 \mathbf{X}_{1,1} \right], \quad \text{s.t. } \mathbf{A}\mathbf{X} = \mathbf{Y}
\]

Reconstruction techniques: Motion compensated 4D-CBCT (MoCo 4D-CBCT)

Boston et al., RSNA, 2012
Reconstruction techniques: Simultaneous Motion Estimation and Image Reconstruction (SMEIR)

Dang et al., IJROBP, 2015

39 projections
200 projections

Dang et al., IJROBP 2015

Reconstruction techniques: prior knowledge based image estimation technique

1. $D \sim 10^7$ variables
2. limited-information acquired ($\sim 10^2$ projs)

ill-conditioned problem

need dimension reduction (modeling) or regularization of $D$

Reconstruction techniques: prior knowledge based image estimation technique

$\| \text{CBCT}_{\text{new}}(D, CT) - P \|^2 = 0$

Data fidelity constraint

(PCA)-based motion modeling

Fast, accuracy limited by modeling accuracy

Coarse estimation of deformation field

Data fidelity constraint

Free form deformation (FD) with energy constraint

Slower, accuracy not affected by modeling

Fine-tuned deformation field

Prior planning CT

FDK CBCT (200°)

Prior based CBCT (ortho 15°)

Prior knowledge based CBCT uses only 1/6 of imaging dose of FDK 40-CBCT scan

Harris et al, Med. Phys., 2017
4D-CBCT imaging dose

- 4D-CBCT protocol: 200º, 4min, 1320 projections, 20mA
- PMMA phantom with D=32cm, Length=45cm. TLD every 1.5cm

\[
CBDI = \frac{1}{L} \int_{-\pi/2}^{\pi/2} D(y)dy
\]

\[
CBDI_w = \frac{1}{3} CBDI_{\text{center}} + \frac{2}{3} CBDI_{\text{peripheral}}
\]

<table>
<thead>
<tr>
<th>Center</th>
<th>0º</th>
<th>90º</th>
<th>180º</th>
<th>270º</th>
<th>CBDLw</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBDI_{00} (mGy)</td>
<td>12.0±1.2</td>
<td>39.9±3.4</td>
<td>27.1±2.3</td>
<td>2.2±0.3</td>
<td>17.4±1.6</td>
</tr>
<tr>
<td>CBDI_{450} (mGy)</td>
<td>12.5±0.9</td>
<td>36.3±2.6</td>
<td>25.4±1.9</td>
<td>2.4±0.2</td>
<td>16.6±1.2</td>
</tr>
</tbody>
</table>

CBDI = Clinical applications: pretreatment 4D target localization

Courtesy of Edwin Sham

Clinical applications: pretreatment 4D target localization

Dual registration: 1. Register to the Clipbox

Courtesy of Edwin Sham
**Clinical applications: pretreatment 4D target localization**

Dual registration: 2. Register to the mask

Courtesy of Edwin Sham

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**Clinical applications: intra-fraction 4D target localization**

Limited-angle Intrafraction Verification (LIVE) System


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**Clinical applications: intra-fraction 4D target localization**

Concurrent kV-MV imaging scheme during treatment
Summary

- 4D-CBCT provides on-board 4D images of tumors with respiratory motion to minimize the motion artifacts for target localization.
- 4D-CBCT requires slow gantry rotation, automatic projection sorting and reconstruction algorithms using under sampled data.
- Applications for both inter- and intra-fraction 4D verification.

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