Digital Tomosynthesis for Target Localization

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- Grant support from NIH-R21 CA 128368
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- Researchers from other institutions who kindly shared their slides

Objectives

- To understand the technical challenges and clinical potential of using DTS for target localization in radiation therapy
- To understand the latest developments in DTS reconstruction and registration methods
- To understand the clinical feasibility and efficacy of kV DTS compared to kV CBCT
- To learn about the latest developments in MV DTS and brachytherapy DTS applications

Outline

- DTS Imaging Fundamentals
- On-board kV DTS for Image Guided Radiation Therapy
- MV DTS
- Unique registration challenges
- Clinical localization studies (H&N, prostate, liver, breast)
- DTS for managing respiratory motion
Outline

• Rapid Arc verification using DTS
• DTS-guided adaptive radiation therapy (ART)
• Applications in brachytherapy
• Alternative scan geometries
• Creating truly 3D volumetric DTS images using prior patient-specific 3D images

DTS Imaging Fundamentals

• Limited rotation (e.g. 40°)
• Moderate depth resolution
• Good soft-tissue contrast
• Low dose (10% CBCT?)
• Fast (<10 sec) = breath-hold!
Fourier Slice Theorem

X-ray projection  \( \rightarrow \)  Slice of object's Fourier spectra

Series of x-ray projections  \( \rightarrow \)  Sampled region of Fourier domain

On-board DTS Resolution Characteristics

DTS silhouette

- Pure x-frequencies fully sampled
- Pure y-frequencies not sampled at all

Sup-Inf in coronal DTS  \( \rightarrow \)  Superior-Inferior Rotation Axis (\( R_z \))

Low Res.  \( \rightarrow \)  High Res.

DTS and RDTS
Classic tradeoff! Decreased resolution in the plane-to-plane dimension means less dose is required to achieve equivalent image noise. This is one of the major advantages of DTS!

Devon Godfrey, 7/16/2009
**DTS Image Characteristics**

One benefit of reduced plane-to-plane resolution:
- less stochastic noise

\[ \text{DTS requires less dose than CBCT!} \]

Typical DTS/CBCT exposure ratio = 

\[ \text{~1/5th (sagittal DTS) to ~1/10th (coronal DTS)} \]

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**DTS Reconstruction Techniques**

- Filtered backprojection (e.g., Feldkamp)
- Iterative or direct frequency domain deblurring (e.g., MITS, or iterative restoration)
- Algebraic reconstruction (e.g., ART, SART)
- Statistical techniques (e.g., MLEM, TV-EM, etc.)
- Techniques using patient-specific prior 3D image data

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For more info, see Dobbins and Godfrey, "Digital x-ray tomosynthesis: current state of the art and clinical potential", PMB (2003)
IGRT with Onboard Imaging

Challenges for Onboard 2D Images

Challenges for Onboard CBCT

<table>
<thead>
<tr>
<th>Modality</th>
<th>Dose/Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orthogonal set of MV digital images</td>
<td>5-8 cGy</td>
</tr>
<tr>
<td>Orthogonal set of KV images</td>
<td>≤0.1 cGy</td>
</tr>
<tr>
<td>CBCT Body scan (Koch et al. 1995; Yoshizumi et al. 2006)</td>
<td>3-4 cGy</td>
</tr>
<tr>
<td>CBCT Brain scan Yoshizumi et al. 2006</td>
<td>8 cGy</td>
</tr>
<tr>
<td>MVCT of Tomotherapy (Shen et al. 2005)</td>
<td>1 cGy</td>
</tr>
<tr>
<td>CT simulation scan (Judy et al. 1977)</td>
<td>3-4 rads</td>
</tr>
</tbody>
</table>
Challenges for Onboard CBCT

Mechanical constraints

Breast setup

Immobilization

On-board Digital Tomosynthesis (DTS) for 3-D IGRT

Reference DTS (RDTS) Images

Planning CT volume

Simulated point sources

FDK cone-beam reconstruction algorithm

Reference DTS (RDTS) slices

Simulated projections

Godfrey et al IJROBP 2006

Reference DTS (RDTS) Images

Planning CT volume

Simulated point sources

FDK cone-beam reconstruction algorithm

Reference DTS (RDTS) slices

Simulated projections

Godfrey et al IJROBP 2006

Prostate

0°

44°

360°

Godfrey et al IJROBP 2006
E.g., Descovich et al (UCSF)

- Modified imaging beam line: (4.2 MV, low Z target, no flattening filter, 0.3 cGy/MU)
- Low dose MV DTS:
  - Examples: Lung (2 cGy), H&N (0.6 cGy), Prostate (0.7 cGy)

DTS Registration Characteristics

- Can we register on-board DTS volumes directly to the planning CT data, or do we need to compute reference DTS volumes?
- How sensitive is DTS to slight translations and rotations?
Evaluation of DTS reference volumes using 3D mutual information

- 3D Volume of interest (VOI) in a chest phantom (4 cm S-I, 10 cm R-L, 8 cm A-P)
- Sample coronal slice from VOI
- Computed 3D MI shared by CT-DTS and RDTS-DTS pairs for all six rigid-body translations and rotations

- Simulated translations of reference CT spanning +/- 5mm & +/- 5° in each direction
- Measured 3D MI (DTS-CT & DTS-RDTS)
  - Does peak MI occur when the on-board DTS data is correctly registered?
  - How quickly does MI fall off away from the correct registration pose (how sensitive is the data to misregistration)?

DTS to RDTS: Effect of scan angle

DTS to RDTS vs. DTS to CT:
**Autoregistration Scheme Using DTS**

- DRR
- DTS On-board
- OBI Images

Updated $\theta$, $\Phi$, $\Psi$, $\delta_x$, $\delta_y$, $\delta_z$  

Criteria for stopping loop:  

- YES  
- NO

**Clinical Feasibility Studies**

- Reference DTS  
- On-board DTS
- Reference CT  
- On-board CBCT

- Localization using DTS  
- Localization using CT

Localization Accuracy (DTS – CBCT)

Isocenter deviation

**Onboard H & N DTS Imaging**

- DRR  
- Onboard
- R-DTS  
- Onboard-DTS
- R-CT  
- Onboard-CBCT

**H&N DTS Bony Localization**

Pearson Correlation  

<table>
<thead>
<tr>
<th>Orientation</th>
<th>2D Radiograph</th>
<th>3D CBCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>20° DTS Coronal</td>
<td>0.81</td>
<td>0.94</td>
</tr>
<tr>
<td>40° DTS Coronal</td>
<td>0.81</td>
<td>0.95</td>
</tr>
<tr>
<td>20° DTS Sagittal</td>
<td>0.79</td>
<td>0.94</td>
</tr>
<tr>
<td>40° DTS Sagittal</td>
<td>0.80</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Wu et al IJROBP 2007
H&N DTS Localization Accuracy (bony)

<table>
<thead>
<tr>
<th></th>
<th>20° DTS Sagittal</th>
<th>40° DTS Sagittal</th>
<th>20° DTS Coronal</th>
<th>40° DTS Coronal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>0.08 (0.07)</td>
<td>0.07 (0.07)</td>
<td>0.07 (0.07)</td>
<td>0.07 (0.07)</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>0.07 (0.07)</td>
<td>0.06 (0.06)</td>
<td>0.09 (0.07)</td>
<td>0.08 (0.07)</td>
</tr>
<tr>
<td>Lateral</td>
<td>0.09 (0.08)</td>
<td>0.07 (0.06)</td>
<td>0.08 (0.07)</td>
<td>0.08 (0.06)</td>
</tr>
<tr>
<td>3D Vector</td>
<td>0.16 (0.09)</td>
<td>0.14 (0.08)</td>
<td>0.16 (0.08)</td>
<td>0.15 (0.08)</td>
</tr>
</tbody>
</table>

SD in parentheses. All values are in cm.

Location Accuracy - Prostate

Based on soft tissue

<table>
<thead>
<tr>
<th></th>
<th>CBCT:Cor-DTS</th>
<th>CBCT:Sag-DTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat</td>
<td>0.08 ± 0.07</td>
<td>0.15 ± 0.14</td>
</tr>
<tr>
<td>Lng</td>
<td>0.06 ± 0.06</td>
<td>0.09 ± 0.09</td>
</tr>
<tr>
<td>Ver</td>
<td>0.11 ± 0.12</td>
<td>0.17 ± 0.17</td>
</tr>
<tr>
<td>3D Vector</td>
<td>0.18 ± 0.11</td>
<td>0.29 ± 0.17</td>
</tr>
</tbody>
</table>

Onboard Prostate DTS Imaging

Onboard Liver DTS Imaging
### Onboard Liver DTS Imaging

<table>
<thead>
<tr>
<th></th>
<th>40° DTS Sagittal</th>
<th>40° DTS Coronal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>0.16 (0.35)</td>
<td>0.09 (0.31)</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>0.04 (0.33)</td>
<td>0.03 (0.28)</td>
</tr>
<tr>
<td>Lateral</td>
<td>0.03 (0.31)</td>
<td>0.03 (0.21)</td>
</tr>
</tbody>
</table>

SD in parentheses. All values are in cm.

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### Onboard Breast DTS Imaging

- **Average Positioning Difference between DTS and CBCT (unit: cm)**

<table>
<thead>
<tr>
<th></th>
<th>With Surgical Clips</th>
<th>Without Clips</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coronal DTS-CBCT</td>
<td>Sagittal DTS-CBCT</td>
</tr>
<tr>
<td>Lateral</td>
<td>0.07</td>
<td>0.15</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>3D Vector</td>
<td>0.19</td>
<td>0.22</td>
</tr>
</tbody>
</table>

- **Managing Respiratory Motion using DTS**
  - Breath-hold verification prior to breath-hold treatment (reduced ITV)
  - 4D verification prior to gated treatment
Breath-hold vs. Free-breathing

Breath-hold RDTS
Breath-hold DTS

Free-breathing DTS
Free-breathing CBCT

Godfrey et al
IJROBP May 2006

Unacceptable for breath-hold Tx setup
Target surrogate shifted 2cm superior

Breath-hold Planning CT
Free-breathing CBCT

Effective alternative for breath-hold Tx setup
Target correctly located

Breath-hold Reference DTS
Breath-hold On-board DTS
Liver Subject #2

Breath-hold CT  Breath-hold RDTS  Breath-hold DTS

Large low-contrast liver malignancy

Lung Subject #1

Free-breathing 45° DTS
Free-breathing 360° (CBCT)

Lung Subject #1

Breath-hold 45° DTS
Breath-hold 360° (CBCT)
**Lung Subject #2 (Breath-hold)**

Sample 45° DTS Slices

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**4D DTS**

- Disadvantages of 4D CBCT
  - Scan Time
    - Lu et al. (2007) 7 min
  - Imaging Dose
    - Lu et al. (2007) 4.4 – 7.1 cGy
  - Streaking Artifacts
    - Sonke et al. (2005) 50 – 80 Projections per Phase

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**Results: Patient Study**

Radiographic

Maurer et al
AAPM 2009
Scan data from
Tinsu Pan (MD Anderson)

Maurer et al
Med Phys July 2008
**Results: Patient Study**

Radiographic 30° 4D DTS

Maurer et al. AAPM 2009. Scan data from Tinsu Pan (MD Anderson)

**Results: Patient Study**

Radiographic 30° 4D DTS 200° CBCT

GRS = 0.75°/s FR = 7 fps

Maurer et al. AAPM 2009. Scan data from Tinsu Pan (MD Anderson)

**Summary**

- **Acquisition Time**
  - 0.65 to 1.52 minutes per 40°

- **4D DTS Dose Relative to 3D CBCT!**
  - 0.17 to 0.51 per 40°

- **4D DTS Allows On-Board Motion Analysis**
  - Lower Dose than even 3D CBCT
  - Scan time similar to 3D CBCT

**DTS for Rapid Arc Verification**

- Collect DTS scans during rapid arc treatment?
- Use to monitor intrafraction motion
Part II: Imaging + Adaptation + Delivery

• Results: Mestrovic et al PD 2009

DTS-guided online adaptive radiation therapy (ART)
• E.g., Mestrovic et al (PMB 2009):
  → kV DTS imaging while gantry is rotated to the next treatment angle, w/ simultaneous reconstruction
  → Auto-segmentation of anatomy
  → Adaptation of direct aperture optimization (DAO) plan. Adaptation of segment performed during delivery of previous segment.
  → Total time added to treatment: 70 sec

Brachytherapy DTS Applications
• Source/seed localization for real-time dose calculation

• Real-time volumetric imaging during brachytherapy procedure (in-suite DTS)
  ➢ Wake Forest University group (Baydush, McKee, et al)

Part III: Imaging + Adaptation + Delivery

- Results: Mestrovic et al PMB 2009

Brachytherapy DTS Applications
• Source/seed localization for real-time dose calculation

• Real-time volumetric imaging during brachytherapy procedure (in-suite DTS)
  ➢ Wake Forest University group (Baydush, McKee, et al)
Alternative Scan Geometries

- Improved sampling of frequency space = reduced DTS blur…
  - E.g., Early 2000s in radiology:
    - Simple: Linear tomosynthesis
    - More Complex: Circular tomosynthesis
  - Possible problem: Shape of blurring function can mimic patient anatomy
Stationary Tomosynthesis Array for Radiotherapy (STAR)

A carbon nanotube-based multielement source for intrafractional image-guidance


1 Siemens Medical Solutions USA, Inc., Oncology Care Systems Group, Concord, CA.
2 XiRay Systems LLC, Research Triangle Park, NC.
3 Siemens AG Healthcare, Components and Vacuum Technology, Erlangen, Germany.
4 University of North Carolina, Chapel Hill.

AAPM 2009

Alternative Scan Geometries

Cine DTS with a multi-source array of carbon nanotube cathodes...

Duke Medicine
Non-rigid deformation for Nanotube Stationary Tomosynthesis (NST) (University of North Carolina)

Overview

Maltz et al AAPM 2009

NST at EI phase

Fluid flow registration

NST at EE phase

Warp

Tumor volume at EE (delineated on planning CT)

Predicted tumor volume at EI shown on NST

Color Blend of EE and EI, showing large tumor motion (1.5cm)

Chang et al AAPM 2009

Truly volumetric DTS imaging?

CBCT

DTS

How can you identify volume in DTS?
-- Poor axial view in traditional DTS

DTS from prior 3D image data

CBCT

CT-360°

Deform Map

CBCT-60°

Ren et al Med Phys June 2008
**DTS using deformation field map from prior 3D image data**

Based on two constraints, the DTS reconstruction problem is converted into the following constrained optimization problem:

$$\min_{\mu} \mathcal{E}(D), \text{ s.t. } P \, DTS_{new}(D, \mu) = Y$$

The above constrained problem can be further converted into the following unconstrained optimization problem:

$$\min \left( \mu \cdot \mathcal{E}(D) + \left\| P \, DTS_{new} - Y \right\|^2 \right)$$

where $\mu$ is the relative weight of the bending energy.

---

**Prostate Patient Data**

<table>
<thead>
<tr>
<th>Prior CBCT</th>
<th>Prior based DTS&lt;sub&gt;new&lt;/sub&gt; (60°)</th>
<th>New CBCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial view</td>
<td><img src="image" alt="Axial view" /></td>
<td><img src="image" alt="Axial view" /></td>
</tr>
<tr>
<td>Coronal view</td>
<td><img src="image" alt="Coronal view" /></td>
<td><img src="image" alt="Coronal view" /></td>
</tr>
<tr>
<td>Sagittal view</td>
<td><img src="image" alt="Sagittal view" /></td>
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</tbody>
</table>

**Liver Patient Data**

<table>
<thead>
<tr>
<th>Prior CBCT</th>
<th>FBP based DTS&lt;sub&gt;new&lt;/sub&gt; (60°)</th>
<th>New CBCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial view</td>
<td><img src="image" alt="Axial view" /></td>
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</table>
**Summary**

- Digital tomosynthesis is a promising technology for onboard target localization as well as brachytherapy applications
- It offers substantial advantages for motion management (4-D and breathhold imaging)
- 3D volumetric DTS is feasible
- Further investigation on clinical efficacy is warranted

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**Liver Patient Data**

- Prior CBCT
- Prior based DTS\(_{\text{prior}}\) (60°)
- New CBCT

**Head-and-neck Patient Data**

- Prior CBCT
- FBP based DTS\(_{\text{prior}}\) (60°)
- New CBCT

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**Head-and-neck Patient Data**

- Prior CBCT
- Prior based DTS\(_{\text{prior}}\) (60°)
- New CBCT

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Thank you for your attention