Real-Time Imaging and Tracking Techniques for Intrafractional Motion Management: Introduction and kV Tracking

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Motivation

• Target motion is a major complicating factor in the accurate delivery of radiation within the body
• Targets must not only be localized in space but also in time, i.e. space-time

Videos of thoracic target motion. Courtesy of R. Li
Motivation: Range of Tumor Motion

Sources of motion other than respiratory:

- Cardiac
- Skeletal Muscular
- Gastrointestinal
Introduction: Image Guidance

- Variety of delivery techniques:
  - Motion-encompassing irradiation
  - Compression
  - Breath-hold
  - Gating
  - Dynamic tracking delivery

Importance of intrafractional image-guidance and tracking
Survey of Imaging Techniques: Historical Trend

Simpson, et al., J Am Coll Rad, 6 (12), 2009
## Survey of Imaging Techniques: Summary

<table>
<thead>
<tr>
<th>Method</th>
<th>Examples</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megavoltage imaging</td>
<td>Electronic portal imaging device</td>
<td>Available on most linacs</td>
<td>Poorer contrast than kV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Imaging coordinate system same as treatment coordinate system</td>
<td>For modulated IMRT fields can only see part of anatomy</td>
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<tr>
<td></td>
<td></td>
<td>Can perform fluoroscopy and CBCT</td>
<td></td>
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<tr>
<td>kV imager</td>
<td>Dual imagers on Novalis, Cyberknife, Vero; single imagers on Elekta, Siemens, Varian linacs</td>
<td>Higher contrast than MV</td>
<td>Requires additional imaging dose</td>
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<tr>
<td></td>
<td></td>
<td>Can image independently of treatment beam</td>
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<tr>
<td></td>
<td></td>
<td>Can perform fluoroscopy and CBCT</td>
<td></td>
</tr>
<tr>
<td>Optical imaging</td>
<td>Brainlab, Varian RPM, VisionRT</td>
<td>Surface information without radiation dose</td>
<td>As sole modality cannot determine internal target positions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Can be combined with other internal positioning methods</td>
<td></td>
</tr>
<tr>
<td>Radio-frequency</td>
<td>Calypso, Micropos, Radpos</td>
<td>High accuracy</td>
<td>Only information about individual points</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High frequency</td>
<td>Requires implantation. Severe MRI artifacts.</td>
</tr>
<tr>
<td>γ-ray</td>
<td>Navotek</td>
<td>High accuracy</td>
<td>Additional radiation dose</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High frequency</td>
<td>Requires implantation</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>Nomos, Resonant</td>
<td>Volumetric images</td>
<td>Poorer image quality</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No implanted markers</td>
<td>Limited to some anatomic sites</td>
</tr>
<tr>
<td>Magnetic resonance imaging</td>
<td>IMRIS, U Alberta, U Utrecht, Viewray</td>
<td>Volumetric imaging</td>
<td>Mutual compatibility with linac</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No implanted markers</td>
<td>Cost</td>
</tr>
</tbody>
</table>
Survey of Commercial Systems with Intrafractional Motion Imaging (a) TrueBeam STx (d) CyberKnife robotic system (c) VERO gimbaled system (d) ViewRay MR guided system (Images courtesy of Varian, BrainLab, Accuray, ViewRay)
Outline of Symposium

Real-Time Imaging and Tracking Techniques

Intro. & kV Tracking
B. Fahimian

MR Tracking
D. Low

EM Tracking
P. Keall

MV Tracking
R. Berbeco

Acknowledgments:
Prof. Ruijiang Li, PhD
Prof. Billy Loo, MD, PhD
Prof. Lei Wang, PhD
Prof. Lei Xing, PhD
Stanford University
Kilovoltage Imaging

- Capabilities: kV planer (stereoscopic and monoscopic), kV fluoro, kV volumetric guidance (CBCT, 4D-CBCT, gated CBCT), triggered during treatment imaging

- Advantage: Better contrast / image quality (photoelectric interactions) than MV, triggered imaging independent of beam, flexibility and availability

- Disadvantage: Imaging dose, different isocenter than treatment beam, scatter / HU inaccuracy in volumetric implementations
Combination with Optical Imaging

- **Capabilities:** tracking of patient surface or external markers
- **Advantage:** No imaging dose, continuous tracking of surface or surrogate
- **Disadvantage:** Cannot determine internal motion
- **Utility:** Combine with other techniques such as periodic x-ray imaging to correlate external with internal motion. Gate and track based on optical signal.
Tracking Techniques

- Fiducial based techniques
  - Passive fiducials:
    - Gold markers and coils
    - Stents
    - Surgical clips
  - Active fiducials:
    - Radiofrequency (Calypso)
    - $\gamma$-ray (Navotek)
- Fiducial-less tracking:
  - Anatomical landmarks
    e.g., diaphragm, GTV
Tracking Techniques: Stereoscopic vs. Monoscopic

- **Stereoscopic**: two images from different directions
  - Floor mounted (robust decoupling of treatment head and imaging) - examples: CyberKnife, BrainLab ExacTrac
  - Ring mounted (Vero)
  - Triangulation used to determine 3D target position

- **Monoscopic**: image from a single direction.
  - Example: Conventional linac OBI
• Depth ambiguity: position cannot be determined from a single image
• Triangulation: 3D position of point-like objects can be estimated using backprojection of two images at different angles.

Schematic of localization using the process of triangulation.
Tracking: Correlation Based Techniques

CyberKnife Synchrony
- External surrogates continuously tracked
- Periodic x-ray stereoscopic imaging of target Correlation model used between external surrogate and internal target motion
- Dynamic tracking delivery using correlation model
- Advantage: lower imaging dose relative to RTRT
- Disadvantage: based on model estimate with limitations accuracy limitations
Tracking: Stereoscopic Correlation Based Techniques

Continues

External Surrogate Position

Periodic (Stereo X-ray)
Internal Target Position

Least Square Fit → Marker / Imager
Correlation Vectors $a, b$

$$\hat{(a, b)} = \arg \min_{i=1}^{n} \| T(t_i) - (aR(t_i) + b) \|^2$$

Estimated Target Position from Correlation Model

$$\hat{T}(t) = \begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{pmatrix} = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} R(t) + \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix}$$

Cardiac Tracking: Stereotactic Arrhythmia Radioablation (STAR)

- First in-human radioablation of ventricular tachycardia (25 Gy in 1 to 75% isodose line)
- Temporary fiducial (pacing wire) placed on the ventricular for tracking
- Continuous tracking of three LED markers, in conjunction with the time-dependent radiographic fiducial positions

Figure 1. Stereotactic arrhythmia radioablation (STAR) treatment plan. A, Simulated cardiac ablation contours (dark blue); B and C, Final target volume (blue/yellow) treated with 25 Gy (Green isodose line) with higher dose (Red 29 Gy isodose line) centered within the mid-myocardial layer.

Loo, et al., Circ Arrhythm Electrophysiol. 2015;8:748-750
Fahimian, et al., IJRBP Proceedings, V. 93,
Correlation models guide robot’s compensation of the first-order target motion due to respiration.

- 178 stereoscopic images defining the true target position with the 496 model points.
- Mean radial 3D was 3.2 mm with a standard deviation of 1.6 mm.
- 90% of points had less than 5.5 mm radial deviation.
Tracking Techniques: Monsocopic

- **Monsocopic**: image from a single direction.
- **Example**: Conventional LINAC on-board imager
During Treatment / Beam Level Imaging

- A number of imaging is now available during beam delivery:
  - MV imaging during treatment
  - Triggered kV at prior to or after gate
  - Continuous / fluoro kV during treatment
  - Combined kV and MV imaging

- Simultaneous delivery and imaging: electronic interference and scatter artifacts may be present if both kV and MV are on simultaneously
An intrafractional monoscopic image from a kilovoltage on-board imager can be used to

A. Determine the 3D position of targets
B. Image the beam’s eye view during delivery
C. Verify the expected 2D positions of targets at particular points in the respiratory cycle
D. Provide superior localization relative to stereoscopic images
E. Readily visualize soft tissue targets
An intrafractional monoscopic image from a kilovoltage on-board imager can be used to

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• Monoscopic: image from a single direction.
  • Example: Conventional LINAC OBI

• How do you deal with depth ambiguity
  • Option 1: Sequence of images + modeling
  • Option 2: Tomosynthesis of images from different angles
  • Option 3: Don’t! Use for 2D beam level verification only
• Monoscopic tracking:
  • *A priori* probability density function is from projection images acquired during patient setup
  • Update likelihood function from beam-level images
    \[ L(x) = f(c_k|x) = \alpha \cdot \exp\left[-||T_k(x) - c_k||_2^2/\beta_k^p\right] \]
  • 3D position by maximizing posterior probability distribution
- Reconstruction of intrafractional fluoroscopic images during arc delivery
- Advantages: Potential for markerless tracking, and more robust localization
- Disadvantages: Not truly real-time, dose from multiple projections
Beam-Level Imaging: Software Markers

- Software Markers can be placed at time of planning to delineate intended fiducial position.
- Placed at location of approximate phase that beam-level imaging occurs.
- Alternatively, placement could indicate boundaries of motion.
- Example: if gating 30-70%, and beam-level imaging prior to gate, place markers at the locations corresponding to the 30% 4DCT set.
Beam-Level Imaging During Gated Delivery

- Gantry rolls back and forth during gated VMAT
- Beam-level images taken prior to each gate
- Software markers projected on beam-level images

Images courtesy of R. Li
Beam-Level Imaging: Intrafraction Motion Verification

Beam Level Imaging: Accuracy

3D position (circles) of markers estimated from the beam-level kV images during gated VMAT.
Horizontal line = reference position on planning CT
Summary of Clinical Workflow for Monoscopic Tracking

**Planning stage**
- Contour tracking structure for desired gating window at time of planning

**Pre-treatment setup**
- Optically track of external surrogate
- Fluoro fiducial GTV, or anatomical landmark
- Adjust gating window so motion under fluoro is encompassed in projected structure

**During treatment**
- Beam level imaging to monitor intrafraction motion
Planar radiographic image entrance dose levels per intrafractional image range from

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>A. 0.01-0.05 mGy</td>
</tr>
<tr>
<td>38%</td>
<td>B. 0.25-0.5 mGy</td>
</tr>
<tr>
<td>30%</td>
<td>C. 1-5 mGy</td>
</tr>
<tr>
<td>10%</td>
<td>D. 10-50 mGy</td>
</tr>
<tr>
<td>2%</td>
<td>E. 50-100 mGy</td>
</tr>
</tbody>
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Planar radiographic image entrance dose levels per intrafractional image range from

A. 0.01-0.05 mGy
B. 0.25-0.5 mGy
C. 1-5 mGy
D. 10-50 mGy
E. 50-100 mGy

**Imaging Dose: CK and Brainlab Examples**

<table>
<thead>
<tr>
<th>Site</th>
<th>kV</th>
<th>mA</th>
<th>ms</th>
<th>mAs</th>
<th>mGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranium and C-spine</td>
<td>105–125</td>
<td>100</td>
<td>100</td>
<td>10</td>
<td>0.25</td>
</tr>
<tr>
<td>T-spine</td>
<td>120–125</td>
<td>100–150</td>
<td>100–125</td>
<td>10–20</td>
<td>0.25–0.50</td>
</tr>
<tr>
<td>L-spine</td>
<td>120–125</td>
<td>100–200</td>
<td>100–150</td>
<td>10–30</td>
<td>0.25–0.75</td>
</tr>
<tr>
<td>Sacrum</td>
<td>120–125</td>
<td>100–300</td>
<td>100–300</td>
<td>10–90</td>
<td>0.25–2.00</td>
</tr>
<tr>
<td>Synchrony</td>
<td>120–125</td>
<td>100–300</td>
<td>50–75</td>
<td>5–22.5</td>
<td>0.10–0.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site</th>
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<th>mA</th>
<th>ms</th>
<th>mAs</th>
<th>mGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranium and C-spine</td>
<td>120</td>
<td>125</td>
<td>100</td>
<td>12.5</td>
<td>0.335</td>
</tr>
<tr>
<td>Body</td>
<td>140</td>
<td>125</td>
<td>125</td>
<td>15</td>
<td>0.551</td>
</tr>
</tbody>
</table>

- Combined with continuous surrogate tracking to allow to limit dose
- Motivation for emphasis on alternative techniques for the remainder of Symposium