Democratizing real-time image guidance and verification: Approaches implemented on conventional linacs
Agenda

- Introduction and scope
- Real-time IGRT methods
- Real-time dose reconstruction
- Conclusion
SBRT:

- Involves high fraction doses with steep dose gradients
- Requires high accuracy at each fraction
- Challenged by intra-fraction motion
Stereotactic Body Radiation Therapy

SBRT:

- Involves high fraction doses with steep dose gradients
- Requires high accuracy at each fraction
- Challenged by intra-fraction motion

Real-time motion adaptation:

- Could ensure high accuracy at each fraction
- Requires real-time motion monitoring
Real-time signals available on conventional linacs

Adopted from Keall et al. IJROBP 2018: 102: 922-31
Surveys: Use of in-room imaging

Simpson et al. Cancer 2010
Survey scope: 385 MDs in US

MV imaging
kV imaging
Respiratory signal
Surveys: Use of in-room imaging

Simpson et al. Cancer 2010
Survey scope: 385 MDs in US

Batumalai et al. J Med Im Rad Onc 2017
Survey scope: 132 linacs in Australia

MV imaging

kV imaging

Respiratory signal
Real-time signals available on conventional linacs

- Beam’s eye view
- Relatively poor contrast
- Field-of-view and time-of-view dictated by treatment plan

MV imaging

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**MV imaging**
- Beam’s eye view
- Relatively poor contrast
- Field-of-view and time-of-view dictated by treatment plan

**kV imaging**
- Decoupled from treatment plan
- Gives imaging dose to patient
- Perpendicular to treatment field

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**MV imaging**
- Beam’s eye view
- Relatively poor contrast
- Field-of-view and time-of-view dictated by treatment plan

**kV imaging**
- Decoupled from treatment plan
- Gives imaging dose to patient
- Perpendicular to treatment field

**Respiratory signal**
- Higher frequency, lower latency
- Compatible with couch rotations
- Only external monitoring
Scope

Real-time 3D image-guidance methods:

- Based on kV, MV and respiratory signals
- Used clinically during treatment delivery with conventional linacs
Agenda

- Introduction and scope
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Four real-time IGRT methods implemented on conventional linacs

- MV imaging
- kV imaging
- Respiratory signal
Four real-time IGRT methods implemented on conventional linacs

- MV imaging
- kV imaging
- Respiratory signal

- MV/kV
- Sequential stereo
- KIM
- COSMIK
MV/kV imaging

VMAT prostate SBRT with implanted markers:

- Memorial Sloan Kettering Cancer Center

MV/kV imaging

VMAT prostate SBRT with implanted markers:
- Memorial Sloan Kettering Cancer Center
- kV images triggered every 20° gantry angle

MV/kV imaging

VMAT prostate SBRT with implanted markers:

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- kV images triggered every 20° gantry angle
- Cine MV acquired continuously (9.5 Hz)
- Short-arc MV DTS (digital tomosynthesis, 3°) image reconstructed at kV image angles

MV/kV imaging

VMAT prostate SBRT with implanted markers:
- Memorial Sloan Kettering Cancer Center
- kV images triggered every 20° gantry angle
- Cine MV acquired continuously (9.5 Hz)
- Short-arc MV DTS (digital tomosynthesis, 3°) image reconstructed at kV image angles
- 3D localization by MV-kV triangulation

Marker visibility in MV DTS

- The markers are blocked by the MLC 60-80% of the time (*)
- TPS script used for automatic VMAT plan manipulation
- Ensures visibility of at least one marker during the MV DTS
- Minimal degradation of plan quality

Ensuring marker visibility during MV short-arc DTS

A

B

C

Original control points around DTS position

Ensuring marker visibility during MV short-arc DTS

Original control points around DTS position

Squeeze MU delivery to smaller angular span

Ensuring marker visibility during MV short-arc DTS

Original control points around DTS position

Squeeze MU delivery to smaller angular span

Insert DTS arc with MLC opened around at least one marker.

\[ \text{MU}_{\text{DTS}} = 1.5–2 \text{ MU} \]

Ensuring marker visibility during MV short-arc DTS

Original control points around DTS position

Squeeze MU delivery to smaller angular span

Insert DTS arc with MLC opened around at least one marker.

\[ MU_{DTS} = 1.5 - 2 \text{ MU} \]

Adjust MU for \( MU_{DTS} \)

VMAT prostate SBRT implementation:

- Tracking templates created at 1° intervals

Thank you: Laura Happerset, Pengpeng Zhang, Margie Hunt, Ping Wang, Hai Pham
MV/kV imaging at Memorial Sloan Kettering Cancer Center

VMAT prostate SBRT implementation:

- Tracking templates created at 1° intervals
- Registered with MV DTS and kV images by Sequence Reg software during treatment delivery
- Gate-off manually and correct if >1.5mm error in two consecutive images

Thank you: Laura Happerset, Pengpeng Zhang, Margie Hunt, Ping Wang, Hai Pham
MV/kV imaging at Memorial Sloan Kettering Cancer Center

VMAT prostate SBRT application:

- 594 5-fraction prostate cancer patients treated 2016-2020
- On average 1.2 interruptions per fraction
- Prostate motion >5 mm for 10% of patients
- Median treatment time 9 minutes (measured for subset of patients)

Thank you: Laura Happerset, Pengpeng Zhang, Margie Hunt, Ping Wang, Hai Pham
Four real-time IGRT methods implemented on conventional linacs

- MV imaging
- kV imaging
- Respiratory signal

Sequential stereo

- MV/kV
- KIM
- COSMIK
Sequential stereo

VMAT spine SBRT:

- VU University Medical Center, Amsterdam
- Continuous kV imaging (7 Hz)
- Match on spine with DRRs from planning CT

Hazelaar et al, IJROBP 2018
Sequential stereo

VMAT spine SBRT:
- VU University Medical Center, Amsterdam
- Continuous kV imaging (7 Hz)
- Match on spine with DRRs from planning CT
- Triangulation with 2-8 previous kV images
- Assume no motion along current ray line since the previous images

Hazelaar et al, IJROBP 2018
Sequential stereo

Selection of previous kV images for triangulation:

- acquired 14-72° prior to current image
- ray line <1mm from current ray line
- all 2-8 selected ray lines intersect in a small volume close to current ray line

Hazelaar et al, IJROBP 2018
VMAT spine SBRT implementation:

- Tracking templates (DRRs) created at 1° intervals
- Registered with streamed kV images during treatment delivery
- Gate-off manually and correct (by CBCT) if >1mm error in any direction

Hazelaar et al, IJROBP 2018
First clinical online real-time experiences(*):

- 10 spine SBRT fractions of 3 patients:
- Images analyzed at ~1Hz (limited by computing speed)
- 2 beam interruptions in total due to >1mm errors

(*) Hazelaar et al, IJROBP 2018
First clinical online real-time experiences(*):

- 10 spine SBRT fractions of 3 patients:
- Images analyzed at ~1Hz (limited by computing speed)
- 2 beam interruptions in total due to >1mm errors

Further clinical experiences with real-time sequential stereo(**):

- ~40 spine SBRT
- DIBH lung SBRT
- Airway tracking (proximal bronchial tree) for central lung SBRT

(*) Hazelaar et al, IJROBP 2018
(**) W Verbakel, private communication
Four real-time IGRT methods implemented on conventional linacs

- MV imaging
- MV/kV
- Sequential stereo
- KIM
- kV imaging
- Respiratory signal
- COSMIK
KIM (Kilovoltage Intrafraction Monitoring)

KIM:

- Continuous kV imaging (5-11 Hz)
KIM (Kilovoltage Intrafraction Monitoring)

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KIM:

- Continuous kV imaging (5-11 Hz)
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- Find the 3D Gaussian Probability Density Function (PDF) that best describes the target motion (by maximum likelihood estimation)

KIM (Kilovoltage Intrafraction Monitoring)

KIM:

- Continuous kV imaging (5-11 Hz)
- Use all previous images in >120° angular span
- Find the 3D Gaussian Probability Density Function (PDF) that best describes the target motion (by maximum likelihood estimation)
- Find the most likely target position along the ray line

Online real-time KIM

Online real-time application:

- Northern Sydney Cancer Center and four other Australian clinics
- Implemented on Varian Clinac, Varian TrueBeam, Elekta Synergy linacs
- 120 prostate cancer patients:
  - Gate-off and correct couch if >3mm error in >5s (~2000 fractions)
  - MLC tracking (49 fractions)
- 2 liver SBRT patients treated in breath-hold (7 fractions)

Prostate KIM at Northern Sydney Cancer Center

Video from Paul Keall, Doan Trang Nguyen, Jeremy Booth
Four real-time IGRT methods implemented on conventional linacs

- MV imaging
- kV imaging
- Respiratory signal

→ MV/kV
→ Sequential stereo
→ KIM
→ COSMIK

AARHUS UNIVERSITY
COSMIK (Combined Optical and Sparse Monoscopic Imaging with KV x-rays)

COSMIK:

- Continuous monitoring of external marker block
- Sparse kV imaging of implanted markers (every 3 sec)
- Only for respiratory motion

Bertholet *et al*, PMB 2018
COSMIK workflow (liver SBRT)

Pre-treatment setup CBCT:

1. Extract internal 3D marker trajectory using KIM
2. Establish correlation model between external and internal motion

CBCT projections (liver SBRT)

3D marker motion

External motion

External-internal motion correlation model
COSMIK workflow (liver SBRT)

Pre-treatment setup CBCT:
1. Extract internal 3D marker trajectory using KIM
2. Establish correlation model between external and internal motion

During treatment delivery:
- Continuous external optical monitoring (20 Hz):
  - 3D internal marker motion estimated from correlation model
- Sparse kV imaging (0.33 Hz):
  - 3D internal marker position estimated with KIM
  - Update correlation model to account for tumor drift

Bertholet et al., PMB 2018
Online real-time application:

- ~20 liver SBRT patients
- 1 lung cancer patient (markers in mediastinal lymph nodes)
- Real-time motion-including tumor dose reconstruction
Common characteristics of all four real-time IGRT methods

- Implemented clinically on conventional linacs
- Research software, not commercially available
- (Sub)-millimeter accuracy
- 3 of 4 methods currently rely on implanted markers
## Summary of clinically implemented 3D real-time IGRT methods

<table>
<thead>
<tr>
<th></th>
<th>MV/kV</th>
<th>Sequential stereo</th>
<th>KIM</th>
<th>COSMIK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principle</strong></td>
<td>MV short-arc DTS</td>
<td>Triangulation</td>
<td>Monoscopic imaging</td>
<td>Monoscopic imaging Breathing correlation</td>
</tr>
<tr>
<td></td>
<td>Triangulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tumor sites</strong></td>
<td>Prostate</td>
<td>Spine</td>
<td>Prostate, liver</td>
<td>Liver, mediastinal LN</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Treatment</strong></td>
<td>Gate-off and adjust</td>
<td>Gate-off and adjust</td>
<td>Gate-off and adjust</td>
<td>None (only real-time dose reconstruction)</td>
</tr>
<tr>
<td><strong>adaptation</strong></td>
<td>couch</td>
<td>couch</td>
<td>couch. MLC tracking</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Markers</strong></td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Non-coplanar</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>0.1-0.2 Hz (every 20°)</td>
<td>1 Hz (7Hz imaging)</td>
<td>5-11 Hz</td>
<td>20 Hz</td>
</tr>
<tr>
<td><strong>Motion type</strong></td>
<td>Small</td>
<td>Small (or periodic)</td>
<td>Any</td>
<td>Respiratory motion</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>• Low kV dose</td>
<td>• Requires prior images with same target position</td>
<td>• Requires learning</td>
<td>• Requires learning</td>
</tr>
<tr>
<td></td>
<td>• Prior imaging not needed</td>
<td></td>
<td>• Requires stable motion PDF</td>
<td>• Low kV dose</td>
</tr>
<tr>
<td></td>
<td>• Requires marker in MLC aperture</td>
<td></td>
<td>• Requires learning</td>
<td>• Continuous monitoring at Fx</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Requires learning</td>
<td>• Low latency</td>
</tr>
</tbody>
</table>


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Real-time motion-including dose reconstruction

Motivation:
- Dose errors from motion >> Dose errors from machine QA

Dose reconstruction during treatment delivery:
- Enabled by real-time IGRT
- Important tool for real-time verification
Real-time motion-including dose reconstruction

DoseTracker in-house software:

- Very simple dose calculation
  - Water density
  - Flat patient surface
  - Same phantom scatter in all depths

Ravkilde et al, PMB 2014, Med Phys 2018
Real-time motion-including dose reconstruction

DoseTracker in-house software:

- Very simple dose calculation
  - Water density
  - Flat patient surface
  - Same phantom scatter in all depths

- …but flexible and fast
  - Any set of calculation points
  - ~100ms for 20,000 calculation points in a tumor
  - Includes motion

Ravkilde et al, PMB 2014, Med Phys 2018
Real-time dose reconstruction

First online application:

- Aarhus University Hospital
- 7 VMAT liver SBRT patients (10 fractions)
- Tumor position (COSMIK) and linac parameters streamed to DoseTracker
- Dose reconstructed in the PTV (1700-4500 calculation points, ~9 Hz)

Skouboe et al, Radiother Oncol 2019
Example: Dose reconstruction in a single point

Planned dose to liver tumor
(95-107% shown)

Skouboe et al, Radiother Oncol 2019
Example: Dose reconstruction in a single point

Skouboe et al, Radiother Oncol 2019
Example: Dose reconstruction in a single point

Planned dose to liver tumor (95-107% shown)

DoseTracker (during treatment)

TPS, isocenter shift (post-treatment)

Skouboe et al, Radiother Oncol 2019
Planned and delivered dose distribution

Planned dose to liver tumor (95-107% shown)

Delivered dose (95-107% shown)

Skouboe et al, Radiother Oncol 2019
Motion-induced reduction in CTV $D_{95}$

Skouboe et al, Radiother Oncol 2019
Motion-induced reduction in CTV D$_{95}$

RMS error in real-time calculated $\Delta D_{95}$ for all 10 fractions: 1.3%-points

Skouboe et al, Radiother Oncol 2019
Agenda

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Conclusions: Real-time IGRT on conventional linacs

- Technologies are being developed by researchers
- Used for real-time treatment adaptation or tumor dose reconstruction
- Potential for widespread use
Conclusions: Real-time IGRT on conventional linacs

- Technologies are being developed by researchers
- Used for real-time treatment adaptation or tumor dose reconstruction
- Potential for widespread use
- Broad adoption requires commercial solutions closely integrated with the clinical workflow
- MR-linacs may become driving a force for broader adoption
- IMRT, VMAT, CBCT: Fast clinical implementation of new technology
- Further development of markerless localization and image dose reduction may facilitate broader adoption of real-time IGRT.
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