IMAGE GUIDANCE AND REGISTRATION – PARTICULAR CHALLENGES IN CASE OF RE-IRRADIATION

MARTIN F. FAST
ACKNOWLEDGEMENTS / SLIDE CREDITS

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CONFLICTS OF INTEREST

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• NKI-AVL is part of the Elekta Atlantic MR-linac Research Consortium

https://mrrt.elekta.com/
OUTLINE

THE FUTURE IS NOW – MRI-GUIDED RADIOTHERAPY

THE WORKING HORSE – CBCT-GUIDED RADIOTHERAPY

DOSE ACCUMULATION – READY FOR CLINICAL USE?

IMAGE REGISTRATION – CHALLENGES AND OPPORTUNITIES
ELEKTA UNITY MR-LINAC

- 1.5 T Philips magnet
- 7 MV linac
- 22x56 cm² treatment field
- Real-time cine-MR imaging
- MLC based on Agility design

Photo courtesy: Elekta AB
ELEKTA UNITY MR-LINAC AT NKI-AVL

INSTALLATION
• May 2016

INITIAL RESEARCH PHASE
• Phantom measurements
• Volunteer imaging
• Patient volunteer imaging

FINAL UPGRADE
• June-August 2018
ELEKTA UNITY MR-LINAC AT NKI-AVL

First patient treated TODAY
(September 6th, 2018)
Clinical focus
• Prostate cancer
• Rectal cancer
• Oligometastases (especially liver)

Technical focus
• EPID dosimetry
• Practical 4D solutions
• Quantitative imaging
NKI’S LIVER RT WORKFLOW FOR THE MR-LINAC

PRE-TREATMENT IMAGING
4D-CT + 4D-MRI

TREATMENT PLANNING

DAILY IMAGING
4D-MRI

IMAGE REGISTRATION & PLAN ADAPTATION

TREATMENT DELIVERY
MID-POSITION STRATEGY ON THE MR-LINAC

Simulation

Pre-beam

Simple Dose Shift
SELF-GATED 4D-MRI

2D SEQUENCE

DATA ACQUISITION
Data from arbitrary respiratory phases

RESPIRATORY SIGNAL

DATA SORTING
To amplitude or phase

3D SEQUENCE

Cartesian Radial

K-space
# 4D-MRI ACQUISITION: 2D VS 3D

<table>
<thead>
<tr>
<th>Acquisition</th>
<th>2D</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR (spatial resolution)</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Acquisition / reconstruction time</td>
<td>~minutes (3-15min)</td>
<td>&lt;minute ~hours / dedicated reconstruction server</td>
</tr>
<tr>
<td>Pulse sequences</td>
<td>Standard</td>
<td>Tailored</td>
</tr>
<tr>
<td>Contrasts</td>
<td>T1 or T2 - weighted</td>
<td>T1-weighted</td>
</tr>
</tbody>
</table>
## 2D-BASED 4D-MRI

<table>
<thead>
<tr>
<th>2D Orientation</th>
<th>Sagittal</th>
<th>Axial</th>
<th>Coronal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC-motion</td>
<td>In-plane</td>
<td>Out-of-plane</td>
<td>In-plane</td>
</tr>
<tr>
<td>FOV coverage / acquisition time</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

FOV: 25 slices of 5mm, Acq time: ~4min
A Self-Sorting Coronal 4D-MRI Method for Daily Image Guidance of Liver Lesions on an MR-LINAC

Tessa van de Lindt, MSc, Jan-Jakob Sonke, PhD, Marlies Nowee, MD, PhD, Edwin Jansen, MD, PhD, Vivian van Pelt, Uulke van der Heide, PhD, and Martin Fast, PhD

Department of Radiation Oncology, The Netherlands Cancer Institute, Amsterdam, The Netherlands

Received Jan 5, 2018, and in revised form May 4, 2018. Accepted for publication May 10, 2018.
RESULTS: SELF-SORTING SIGNAL ANALYSIS

Table 1: Image-based self-sorting signal vs navigator signal results

<table>
<thead>
<tr>
<th>ImS vs NavS</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation</td>
<td>0.95 – 0.97 (range)</td>
<td></td>
</tr>
<tr>
<td>RMSD (mm)</td>
<td>1.39 – 2.13 (range)</td>
<td></td>
</tr>
<tr>
<td>Time difference inhale positons (s)</td>
<td>0.06 ± 0.13 (mean ± SD)</td>
<td></td>
</tr>
<tr>
<td>Bin difference for amplitude-binning</td>
<td>0.41 ± 0.64 (mean ± SD)</td>
<td></td>
</tr>
<tr>
<td>Bin difference for phase-binning</td>
<td>0.23 ± 0.47 (mean ± SD)</td>
<td></td>
</tr>
</tbody>
</table>

van de Lindt et al (2018), IJROBP
RESULTS: AMPLITUDE VS PHASE SORTING

van de Lindt et al (2018), IJROBP
RESULTS: TUMOR VISIBILITY

Lesion: 15mm

van de Lindt et al (2018), IJROBP
MR-LINAC: DAILY PLAN ADAPTATION IS A MUST
MATERIALS & METHODS: EXPERIMENTAL VALIDATION

4D-MRI\(^1\)
- Unity MR-Linac
- Coronal multi-2D TSE

TREATMENT PLANNING
- Monaco v5.19
- 10-beam step-and-shoot IMRT
- 3x20 Gy

PHANTOM MOTION
- Periodic CC motion
  - A = 15 mm
  - T = 4 s
- CC baseline shifts
  - 0, 5, 10 and 15 mm

\(^1\) TN van de Lindt et al., IJROBP., 2018
## RESULTS

### GEOMETRIC AND DOSIMETRIC RESULTS

<table>
<thead>
<tr>
<th>Baseline shift (mm)</th>
<th>EPID</th>
<th>MRI</th>
<th>Film</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MidP (mm)</td>
<td>Cine (mm)</td>
<td>4D (mm)</td>
</tr>
<tr>
<td>5</td>
<td>5.0</td>
<td>5.3</td>
<td>3.8</td>
</tr>
<tr>
<td>10</td>
<td>9.8</td>
<td>10.6</td>
<td>10.0</td>
</tr>
<tr>
<td>15</td>
<td>15.0</td>
<td>15.5</td>
<td>14.3</td>
</tr>
<tr>
<td>Δ Mean±SD</td>
<td>0.1±0.1</td>
<td>-0.5±0.1</td>
<td>0.6±0.6</td>
</tr>
</tbody>
</table>

Delta Mean ± SD

Gamma analysis: 3%/2mm
NEXT FRONTIER: REAL-TIME ADAPTATIONS

Motion variability not captured by 4d imaging

Fast et al (2018), IJROBP
CINE MRI + AUTO-CONTOURING

- 6 patients
- 22 image series: sequence (bSSFE vs GRE) + image orientation
- Dice: 0.92 (median)
- Centroid distance: 1.5 mm (median)
- Multi-template matching (MTM) and deformable image registration (DIR) performed best

Fast & Eiben et al (2017), R&O
TUMOUR TRAILING

REGULAR MOTION
• High-frequency motion components
• Accounted for in mid-position planning strategy

IRREGULAR MOTION
• Low frequency motion components (slow baseline drifts)
• Following mid-position changes during treatment → Tumour trailing#

MR-LINAC: FEASIBILITY OF TRAILING

- 3x20 Gy liver SBRT
- Simulated delivery to midP CT (full consideration of interplay)
- Baseline drift: 0.5 mm/min (CC) & 0.25 mm/min (AP)
- Isocentre-shift‡ dose reconstruction
- Trailing vs Conventional vs Planned

MR-LINAC: TRAILING PROOF-OF-PRINCIPLE

Motion monitoring
- Sagittal b-FFE cine-MRI
- 1x1x10 mm³
- 3 Hz

Plan adaptation
- Triggers for motion ≥1 mm
- Adapts MLC to target in beam’s-eye-view

Trailing
- Starts with initial plan
- Pauses linac when needed
- Transfers adapted plan via iCom interface
RESULTS: DOSE AND GAMMA-DISTRIBUTION

Gamma analysis: 3%/2mm
Real-time 4D dose reconstruction for tracked dynamic MLC deliveries

The ROYAL MARSDEN
NHS Foundation Trust

The Institute of Cancer Research
The (adaptive) Radiotherapy Process

Pre-treatment imaging → Treatment-planning

Pre-treatment imaging

In-room imaging

Image registration & correction

Intervention (ART)

Treatment assessment
EPID dosimetry
Decision rules
Traffic-light protocol

Treatment delivery (~30/35 fx)
• EPID: *traffic-light* for dose differences with planned >> but what does it mean in the anatomy?

• IGRT: Decision rules & *traffic-light* protocol >> we see deformations, what does it mean?
  – Dual registration Lung
  – Multi-clipbox HNC

• Ad hoc assessment: editing the pCT for weightloss/deformations in Pinnacle ...
Example lung

Lung Cancer
60 Gy, 30 fx
Previously irradiated:
cord dose < 20 Gy
NTD (a/b=2)
Example HNC

- Nasopharynx
- SIB 70 Gy, 35 fxs
- Large PTV
- Many OARs: N. Opticus, Chiasm, Brainstem
- mROI with weights 1/0
What these examples show

Mental exercise...
- Isodose lines: is that what we delivered?
- Deformations: how does that change CTV/OAR dose?
- History: Systematic? Random? Trend?
- Timing: How much can we still gain with replanning?
- Upon replanning: what about dose already delivered?

→ We see geometry, we must think dose...

>> HEADACHE!
Alternative: dose accumulation

**compute the total delivered dose in the patient while accounting for dosimetrical and geometrical discrepancies**

2 important steps:

- Dose distribution delivered is different than planned
- Dose ends up at different location than planned
Dose accumulation

Step 1: Dose distribution delivered is different than planned

Planned dose in pCT

planned/recalculated dose in CBCT
Dose accumulation

Step 2: Dose ends up at different location than planned

Deformation & anatomy differences

CBCT warping
Dose accumulation

Step 2: Dose ends up at different location than planned

Deformation & anatomy differences
dose warping
Dose accumulation

After dose warping: common reference
Dose accumulation

Planned dose

Accumulated dose

Difference dose
Dose accumulation: DVH differences

DVH: accumulated dose vs planned dose

SPINAL_CORD
PAROTID
LARYNX
BRAINSTEM
CTV
CTVsd
ORAL VACITY

--- planned dose
--- accumulated dose
Challenges: prediction of final dose

Boost plan

ART @ fx 14
Challenges: DIR with limited Image Quality

• HNC: OK...
• Lung: WIP...

Example image quality rectum

Courtesy Sander Uilkema & Lisa Hartgring
DOSE ACCUMULATION: ENERGY-MASS TRANSFER

SUMMARY & OUTLOOK

• MRI-guidance provides excellent soft-tissue contrast

• Novel 4D-MRI radiotherapy solutions are being developed

• Margin reduction / active motion management will provide scope to allow for re-irradiations

• Away with the surrogate reality: start looking at dose in anatomy daily