Online Adaptive MR-Guided RT: Workflow and Clinical Implementation
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Disclosures
Funding:
- ViewRay Inc.
- Philips Medical Systems

Learning Objectives
• To understand the difficulties, challenges and available technologies for online adaptive RT.
• To understand how to implement online adaptive therapy in a clinical environment and to understand the workflow and resources required.
• To understand the limitations and sources of uncertainty in the online adaptive process.
Rationale for adaptive radiotherapy

- Anatomical changes
  - Tumor response
  - Change in normal anatomy
  - Weight gain / loss
- Systematic changes in patient setup and positioning relative to initial simulation
- Inter-fraction variations in shape / size of the target (bladder, cervix, ...)
- Variations in position and proximity of OARs relative to the target

Plan adaptation strategies

- Treatment adaptation strategies and the tools required depend on what type of anatomical change we want to correct for
  - Weight change (offline)
  - Tumor response (offline)
  - Variation in shape / size (online)
  - Variation in OAR proximity to target (online)

Online Adaptive Workflow

- Imaging
- Contouring
- Dose calculation
- Planning and Evaluation
- Patient QA
**Online Adaptive Workflow**

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**Volumetric imaging for plan adaptation**
- In-room CT, MR, CBCT
- Soft-tissue contrast for delineation of OARs and in some cases the target

**Volumetric imaging for plan adaptation**
- Large field of view
  - Encompass all regions where contouring is required
  - Allow for inclusion of patient’s external surface for dose calculation
Online Adaptive Workflow

Imaging  →  Contouring  →  Dose calculation  →  Planning and Evaluation  →  Patient QA

Inroom CT  
MR  
CBCT  
...

Fully manual Registration
Auto-segmentation

Contouring for online adaptation

- Planning image (CT / MR) are registered to the daily image after initial localization to the target
  - Rigid
  - deformable
  - Atlas based auto-segmentation

- Uncertainties in automatically generated contours
  - No deformable registration is perfect
  - Manually edit the contours if needed
  - Does not fix the deformation vector field

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Inroom CT  
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...

Fully manual Registration
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Electron density
Electron density map for dose calculation

- In-room CT
- CBCT – Some corrections needed
- MR – Transfer from original plan
  - The errors in deformation will propagate to the electron density map
  - Manually correct the errors

Online Adaptive Workflow

Imaging → Contouring → Dose calculation → Planning and Evaluation → Patient QA

- In-room CT
- MR
- CBCT
- ...

- Fully manual Registration
- Auto-segmentation
- Electron density
- Full reoptimization
- Adjusting the aperture
- Plan library

Dose prediction

- DVHs can be evaluated for the new contours
- Prescription templates highlight dose objectives that are violated
Plan Re-optimization

- Reoptimization with same beam angles and original set of optimization objectives
  - Preserving the beam angles of the original plan can simplify QA
  - Robustness of the original set of objectives is important

Plan Re-optimization

- Plan normalization – Normalize to cc or % of any structure
- Planning tools should be accessible in case modifications to the objectives are needed.

Plan Evaluation and QA

- Final plan is evaluated and approved by the physician
- Export for QA - Images, structure set, RED, dose, and beam parameters
### Online Adaptive Workflow

- **Imaging**
  - Inroom CT
  - MR
  - CBCT
  - ...

- **Contouring**
  - Fully manual registration
  - Auto-segmentation

- **Dose calculation**
  - Electron density

- **Planning and Evaluation**
  - Full reoptimization
  - Adjusting the aperture
  - Plan library

- **Patient QA**
  - Measurement
  - Secondary calculation

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### Patient QA

- **Primary limitation in proceeding to treatment is QA**
  - We cannot take the patient off the table to do phantom measurements.

### Is patient specific phantom measurement necessary?

- **Argument against measurement**
  - Measurement inaccuracies
  - Insensitivity of the QA devices
  - Measurements cannot separate the source of the error

- **Argument for measurement**
  - Measurement is the only way to test deliverability of the plan
  - Measurement can save us from catastrophic errors
Independent plan evaluation prior to delivery

- Independent Monte Carlo dose calculation

- Plan consistency check:
  - Gantry angles
  - Number of segments
  - Beam on times
  - Fluence calculation
  - Structure volumes

- Contour QA (in progress):
  - Boolean operations
  - Margin expansions

- 3D gamma calculation over the full volume with 3%, 3 mm criteria
Commissioning the online QA tool

- How do we trust this in place of actual measurements?
  - Dose calculated by this tool was compared to actual patient specific measurements – ArcCheck, ion chamber
  - Sensitivity of the analysis to errors in dose was verified by introducing known errors
    - Introducing a 3% error in dose results in gamma pass rate dropping to 76% from 93%.

Independent plan evaluation prior to delivery

- Measurement based QA performed results are similar between initial and adapted plans
- Original and adapted plans have similar passing rate when compared to the independent MC calculation
Contour QA

- Out of 195 adapted fractions, 5 errors or near misses
  - Contouring (3)
    - All were found by the user in post-treatment chart review
  - Density correction (1)
    - Caught by user at time of replanning
  - Beam decay (1)
    - Caught by the online patient-specific QA

Time and Resources

- How long does the process take?
  - Volumetric imaging and contour propagation: 1 - 4 minutes
  - Contour evaluation and manual edits: 5 to 15 minutes (or more)
  - Dose prediction: 1.5 - 3 minutes
  - Manual edits to the electron density: 2 minutes
  - Plan re-optimization: 2 - 4 minutes
  - Normalization or modification to the plan parameters: 3 - 5 minutes

**Total time: 20 – 30 minutes**
What happens to the anatomy while we replan?

Henke et al (MR in RT Symposium, Ann Arbor, June 2016)
- Repeat images at 45 – 60 minutes after the initial image
- Evaluated the contours and compared the magnitude of change to the changes observed in between fractions

Common challenges in online adaptation
- Contouring continues to be the most time-consuming part of the process
- Understanding the relative geometry of OARs / targets and the beam will allow us to focus manual contour edits to regions that matter
- Contour edits can be limited to a 2 – 5 cm ring around the PTV

How much contouring accuracy is needed
Common challenges in online adaptation

- Dose accumulation
  - Uncertainties in deformable registration translate into errors in dose accumulation
  - Regions with high dose gradient are most sensitive
  - Manual correction to the contours does not correct the deformation vector field.

- Daily dose evaluation instead of cumulative dose
  - More conservative approach as it ensures that each fraction meets the specified dose tolerances

Discussion

- Advancements in in-room imaging have enabled the clinical implementation of online adaptive RT.

- Time and resources required at the treatment machine continue to be the limiting factor in a more widespread implementation of these techniques

- Future work should focus on quantifying the sources of uncertainty in order to allow for automation of overall process

Acknowledgments

- Jeffery Olsen, MD
- Deshan Yang, Ph.D.
- Tianyu Zhao, Ph.D.
- James R. Victoria, CMD
- Virain Rodriguez, Ph.D.
- Lindsey Olsen, Ph.D.
- Tracey Hand, CMD
- Karl Tanderup, Ph.D.
- Olga Green, Ph.D.
- Omar Wooten, Ph.D.
- Sasa Mutic, Ph.D.
- James F. Dempsey, Ph.D.
Thank You