An automated replanning strategy for near real-time adaptive proton therapy

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Disclosures

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Dose degradation in IMPT

Inter-fraction variations

Intended dose

Degraded dose

Breathing

Gas in bowel

Tumor shrinkage

Figure courtesy of Mischa Hoogeman
Near real-time adaptive proton therapy
The situation

Planning CT scan

Daily CT scan
The aim

Planning CT scan

Daily CT scan
RPM adaptation

Prior plan (input) → Spot-location restoration → Addition of new spots and dose computation → Spot weight optimization → RPM adapted plan 1-2x (output)
Spot-location restoration

Prior plan (input) → Spot-location restoration → Addition of new spots and dose computation → Spot weight optimization → RPM adapted plan 1-2x (output)

To account for density changes

[Diagram showing gas and spot locations]
Spot addition & weight optimization

To account for changes in shape and location

Optimize the spot weights with the Reference Point Method (RPM) using a single optimization (fast)
The Reference Point Method (RPM)

Maintaining the multi-criteria trade-offs of the prior plan

Obtaining a Pareto optimal treatment plan

No objective value can be improved without worsening another

Figure courtesy of Rens van Haveren
The Reference Point Method (RPM)

Objective

Patient 1

Reference path

Objective 2

Objective 1

Patient 2

Patient 3

Trade-off curves
The Reference Point Method (RPM)

Objective

Patient 1

Patient 2

Patient 3

Reference path

Trade-off curves

Objective 1

Objective 2
Patient Materials

11 Prostate cancer patients
- 1 planning CT + 7-9 repeat CTs
- Total of 88 repeat CTs

Target volumes
- Prostate - PTVhigh (+2 mm)
- Lymph nodes + seminal vesicles - PTVlow (+3.5 mm)

Organs at risk - Rectum & Bladder
Results for Target

Criteria of success: $V_{95\%} \geq 98\% \ & \ V_{107\%} \leq 2\%$

- 1/88 scans without replanning
- 85/88 scans for the RPM adaptive method (1x)
- 88/88 scans for the RPM adaptive method (2x)
OARs – Compare to Benchmark

Benchmark is full automated multi-criteria optimized plans for repeat CT scans without time constraints (multiple iterations)
OARs – If we don’t adapt

Benchmark is full automated multi-criteria optimized plans for repeat CT scans without time constraints (multiple iterations)
OARs – If we don’t adapt

Deviation from benchmark (%-point or Gy(RBE))

- Rectum V75Gy (%)
- Rectum V60Gy (%)
- Rectum V45Gy (%)
- Rectum Dmean (Gy)
- Bladder V65Gy (%)
- Bladder V45Gy (%)
- Bladder Dmean (Gy)
OARs – If we do adapt
Time Results

Times for the new RPM adaptive method (on average):

Prior plan (input) -> Spot-location restoration: 7.3 seconds

Spot-location restoration -> Addition of new spots and dose computation: 0.6 minutes

Addition of new spots and dose computation -> Spot weight optimization: 1.1 minutes

Spot weight optimization -> RPM adapted plan 1-2x (output)
Non-Rigid Organ Motion in Cervical Cancer
Make ITV structures based on the bladder filling

Complete ITV

Full ITV (halffull – full)

Empty ITV (empty – halffull)

Account for Large Cervix Motion: Use a Plan-Library

Prior plan (input) → Spot-location restoration → Addition of new spots and dose computation → Spot weight optimization → RPM adapted plan 1-2x (output)

Plan Library

1-plan-library: Complete ITV

2-plan-library: Full ITV & Empty ITV
Patient Materials

6 Cervical cancer patients
- 2 planning CTs + 3-4 repeat CTs
- Total of 35 repeat CTs

Target volumes
- Cervix-uterus (+5 mm)
- Lymph nodes (+2 mm)

Organs at risk
- Rectum, Bladder & Bowelbag
Results for Target

Criteria of success: $V_{95\%} \geq 95\%$ & $V_{107\%} \leq 2\%$

- All plans fail without replanning
- At least 2 spot addition iterations are needed to have a 100% success rate
- A 2-plan-library performs better than a 1-plan-library
OARs – If we **don’t** adapt
OARs – If we _do_ adapt
Time Results

Prior plan (input) 6 seconds
Spot-location restoration 1.5 minutes
Addition of new spots and dose computation
Spot weight optimization 1.1 minutes
RPM adapted plan 1-2x (output)

Plan Library 14 seconds

With 1 iteration < 3 minutes ~50% is dose calculation

Benchmark plan took >1 hour
Fast Adaptation For Online-Adaptive IMPT is Possible

Clinically acceptable results can be achieved

With replanning (3 minutes)

- Pareto optimal result for the daily anatomy
- Even for large day-to-day variations
Fast Adaptation For Online-Adaptive IMPT is Possible

Prior plan (input) -> Spot-location restoration -> Addition of new spots and dose computation -> Spot weight optimization -> RPM adapted plan (output)

Plan Library

Thank you!

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