Improved Repainting for Interplay Effect Mitigation in Pencil Beam Scanning Proton Therapy

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Overview
- Introduction
  - Background: Repainting
  - Spot-adapted breath-sampling repainting
  - Towards clinical implementation

Introduction: Proton Therapy

Figure from Hall, IROBP 65: 1-7 (2006)
Introduction: Proton Therapy

Proton Pencil Beam Scanning (PBS):

- Good dose conformality in 3D (incl. target thickness variations)
- Allows intensity modulated proton therapy (IMPT)
- Interplay effects for moving tumors

Trade-off between PBS and Passive Scattering

- "IMPT [with PBS] generally provides better conformality than passive scattering"
Trade-off between PBS and Passive Scattering

- IMPT [with PBS] generally provides better conformality than passive scattering.
- For early-stage and locally advanced non-small cell lung cancer, “IMPT can almost always spare all critical organs even with complicated anatomy.”

Overall aim

Make proton PBS as robust to motion as passive scattering proton therapy.
Overview

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- **Background: Repainting**
- Spot-adapted breath-sampling repainting
- Towards clinical implementation

Background: Repainting

Liver SBRT example

Red contour = CTV

Color wash: >90% dose

Repainting helps, but is often inefficient

Background: Repainting methods

1. Fast layer repainting
2. Delayed layer repainting ($\geq 0.25s$)
3. Breath-sampling layer repainting
4. Volume repainting
5. Random repainting

PMB 54: N283-N94 (2009)
Background: Repainting methods

1. Fast layer repainting
2. Delayed layer repainting ($\tau \geq 0.25s$)
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PMB 54: N283-N94 (2009)
Background: Repainting methods

PMB 54: N283-N94 (2009)

1. Fast layer repainting
2. Delayed layer repainting (t ≥ 0.25s)
3. Breath-sampling layer repainting
4. Volume repainting
5. Random repainting

- sin(x), sin^2(x), sin^3(x)
- 1 - 3 cm motion
- 3.3 - 5.2s period
- 6.5cm x 6.5cm x 10cm target

Seco et al. PMB 2009
Summary so far

- Proton PBS allows superior dose conformality
- Highly susceptible to interplay effects
- Interplay effects cannot be mitigated by margins
- Breath-sampling repainting:
  - Ensures even distribution of repaintings over the breathing cycle
  - Very efficient after few repaintings
  - Has not yet been implemented clinically

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Breath-sampling repainting: Implementation problems

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Breath-sampling repainting: Implementation problems

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<td>The beam current cannot be reduced enough to stretch the layer delivery time to a full breathing cycle</td>
<td>Use waiting time between spots to extend the layer duration</td>
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- Spot-adapted breath-sampling repainting

Spot-adapted breath-sampling repainting

- Repaint algorithm
  - Investigate interplay effect mitigation in...
    - Experiments
    - Simulations
    - 4D dose reconstructions
Spot-adapted breath-sampling repainting

- Assume known regular breathing period, $T = 4s$
- Deliver each layer in $T = 4s$ with evenly spread repaintings

Repaint algorithm 1: Sort spots into repaint blocks

- All spots with $<2\text{MU}_{\text{min}}$ are painted once
- All spots with $\geq2\text{MU}_{\text{min}}$ and $<4\text{MU}_{\text{min}}$ are painted twice
Repaint algorithm 1: Sort spots into repaint blocks

- All spots with ≤2MU<sub>min</sub> are painted once
- All spots with ≥2MU<sub>min</sub> and <4MU<sub>min</sub> are painted twice
- All spots with ≥4MU<sub>min</sub> and <8MU<sub>min</sub> are painted 4 times
- All spots with ≥8MU<sub>min</sub> and <16MU<sub>min</sub> are painted 8 times
- All spots with ≥16MU<sub>min</sub> are painted 16 times
Repaint algorithm 2: Trim layer delivery time to exactly 4s

![Diagram showing trim layer delivery time](image1)

Exploit that $t_{\text{wait}}$ for each spot depends enormously on scan pattern

$t_{\text{wait}} = \begin{cases} 
0, \text{if } ax < 10 \text{mm and } dy < 10 \text{mm} \\
\max \left( 2.5 \text{ms} + \frac{ax}{6 \text{mm/sec}}, 3.52 \text{ms} + \frac{dy}{2.1 \text{mm/sec}} \right), \text{otherwise}
\end{cases}$

Repaint algorithm 3: Rearrange repaint blocks

![Diagram showing rearranged repaint blocks](image2)

- Evenly spaced repaintings over the whole breathing cycle

Spot-adapted breath-sampling repainting

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Experiments

- Varian ProBeam facility at Maryland Proton Treatment Center
- Repainting algorithm in Matlab (manipulates Dicom RT plans)

- Five clinical plans (single-field optimization):
  1. Pancreas: 3 fields, 2.25 Gy/fraction
  2. Liver: 2 fields, 3.87 Gy/fraction
  3. Lung/bronchus neoplasm: 3 fields, 1.80 Gy/fraction
  4. NSCLC in RLL: 2 fields, 1.80 Gy/fraction
  5. Renal cell carcinoma: 2 fields, 4.50 Gy/fraction

- 12 fields in total

Experiments

- Each field delivered to Matrix ionization chamber array on motion stage
  - 1 x static
  - 2 x sine motion (SI, 4s, 3cm)
  - 2D dose frames @10Hz

- New repainting scheme
  - 8 x repainting
  - No repainting

- 108 field deliveries in total (12 x 3 x 3)
Evaluation of experiments

Motion dose frames → Sum → Measured motion dose (with interplay)

Static dose frames → Sum → Ideal motion dose (without interplay) → Convolve with motion

Interplay effects quantified as 3%/3mm gamma pass rate $\gamma_{exp}$

Layer delivery time example

Pat 1, Field1

New repainting scheme:

- 31.8% of all layers had shorter duration than 4s (6.5% of all MU)
Layer delivery time example

Pat 1, Field1

New repainting scheme:

- In mean, the field delivery time was prolonged with 91% [71–130%]

Mean absolute difference between actual and predicted layer duration:

- 0.27 s

Example of measured doses (static target)

No repainting  |  8 repaintings  |  New repainting scheme
Example of total measured field dose

Static

Measured

Blurred $\gamma_{ref}$

Example of total measured field dose

Static

Motion

No repainting

Measured

$\gamma_{exp} = 58.8\%$

Blurred $\gamma_{ref}$

$\gamma_{exp} = 51.1\%$

Example of total measured field dose

Static

Motion

No repainting

Motion

8 repaintings

Measured

$\gamma_{exp} = 58.8\%$

$\gamma_{exp} = 63.3\%$

Blurred $\gamma_{ref}$

$\gamma_{exp} = 51.1\%$

$\gamma_{exp} = 68.6\%$
Example of total measured field dose

<table>
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<th>Static Measured</th>
<th>Motion No repainting ( \gamma_{\text{exp}} = 58.8% )</th>
<th>Motion 8 repaintings ( \gamma_{\text{exp}} = 63.3% )</th>
<th>Motion New scheme ( \gamma_{\text{exp}} = 93.6% )</th>
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<td>Blurred ( \gamma_{\text{ref}} ) Measured</td>
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Gamma pass rates in experiments

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<td>59.6% ± 9.7%</td>
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<td>8 repaintings</td>
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<td>New repainting</td>
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- Superior interplay effect mitigation with new repainting scheme

Spot-adapted breath-sampling repainting

- Repaint algorithm
- Investigate interplay effect mitigation in...
  - Experiments
    - Simulations
    - 4D dose reconstructions
Simulations

\[ \text{Motion dose frames} \rightarrow \text{Sum} \rightarrow \text{Static dose frames} \rightarrow \text{Convolve with motion} \rightarrow \text{Ideal motion dose (without interplay)} \rightarrow \text{Add shifts} \rightarrow \text{Sum} \rightarrow \text{Simulated motion dose (with interplay)} \rightarrow \text{Measured motion dose (with interplay)} \rightarrow \text{Simulated motion dose (with interplay)} \rightarrow \text{Ideal motion dose (without interplay)} \rightarrow \text{Convolve with motion} \rightarrow \text{Static dose frames} \rightarrow \text{Sum} \rightarrow \text{Measured motion dose (with interplay)} \]

1.3% rms difference

Simulations versus experiments

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- Excellent agreement between simulations and experiments
- It justifies extension of the study to other motions with simulations
Simulations with different motion amplitudes

- 5 cm motion with new repainting: Mean γ-pass rate = 89.0% ± 5.0%
- 1 cm motion with 8 repaintings: Mean γ-pass rate = 89.6% ± 6.1%

Simulations with different motion periods

The new repainting scheme was best for 4s period, as expected, but the degradation with other motion periods was quite modest.
Simulations with 1-6 fractions

- Sine motion
  - A = 3cm
  - T = 4sec
  - All combinations of 10 starting phases

- 2 fractions with new repainting: Mean $\gamma$-pass rate = 96.3% ± 3.6%
- 6 fractions with 8 repaintings: Mean $\gamma$-pass rate = 95.3% ± 5.7%

Simulations with patient-measured liver motion

Liver tumor motion previously measured with Kilovoltage Intrafraction Monitoring (KIM) for six SBRT patients (3 fx each)

New repainting significantly better than 8 repaintings for all 18 trajectories
Spot-adapted breath-sampling repainting

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4D dose reconstruction

- Simulate plan delivery → 10 breathing phase specific plans
- Import and calculate on 10 4DCT phases in TPS (RayStation)
- Sum dose from all phases in end-exhale phase (using DIR)
- Compare with the interplay effect free 4D dose

4D dose reconstruction example

Patient 1:
- Pancreas, 3 fields, 2.25Gy/fx
- 19.1 mm motion in 4DCT
ICTV homogeneity index after 1 fraction

Homogeneity Index: $HI = \frac{(D_2 - D_{98})}{D_{\text{mean}}}$

Mean HI for all five patients:
- No repainting: 14.2%
- 8 repaintings: 13.7%
- New repainting: 12.0%
- 4D dose: 11.6%

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Clinical implementation

- Relevant for SBRT with large motion
- Could replace current practice of
  - Deliver entire field twice (2 x Volumetric repainting)
  - Increase spot size by range shifter

Clinical workflow

**Standard workflow**

- 4DCT
- Make and approve plan
- Export to OIS
- Plan specific QA
- Treat

**New steps**

- Extract breathing period
- Export plan from TPS
- Make repainting plan
- Export to OIS
- Plan specific QA
- Treat
Clinical workflow

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Summary: Spot-adapted breath-sampling repainting

- A practical repainting strategy for interplay effect mitigation was suggested and implemented at Maryland Proton Treatment Center
- Was shown to be superior to conventional repainting in experiments, simulations, and dose reconstructions
- Quite robust to breathing period variations
- Requires no monitoring or synchronization with beam delivery
- Will facilitate proton PBS for thoracic and abdominal SBRT
- We work at clinical implementation at MPTC
- Published in Poulsen et al., IJROBP 100: 226-34 (2018)

Alternatives

Gated phase-controlled rescanning:
- Spread repaintings over open-gate period instead of full breathing cycle
- Delivery must be synchronized with breathing
- Mitigates both interplay effects and motion blurring

Furukawa Med Phys 2007:
Gated phase-controlled repainting at CIRS for carbon ion therapy
Alternatives

Breath-hold gating:
- Fast field delivery important
- Mitigates both interplay effects and motion blurring

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