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

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J Eley, U Langner, CB Simone II and K Langen, Maryland Proton Treatment Center

Overview

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

Introduction: Proton Therapy

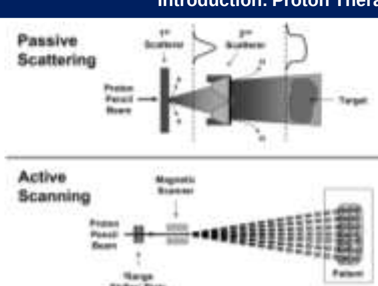

Figure from
Hall, IJROBP 65: 1-7 (2006)

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

Consensus Statement on Proton Therapy in Early-Stage and Locally Advanced Non–Small Cell Lung Cancer

Joe Y. Chang, MD, PhD, Salma K. Jabbour, MD, Dirk De Ruysscher, MD, Steven E. Schild, MD, Charles B. Simone, II, MD, Ramesh Rengan, MD, Steven Feigenberg, MD, Atif J. Khan, MD, Noah C. Choi, MD, Jeffrey D. Bradley, MD, Xiaorong R. Zhu, PhD, Antony J. Lomax, PhD, and Bradford S. Hoppe, MD, on behalf of the International Particle Therapy Co-operative Group (PTCOG) Thoracic Subcommittee

IJROBP 95: 505-516 (2016)

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- "*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*"

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Consensus Statement on Proton Therapy in Early-Stage and Locally Advanced Non–Small Cell Lung Cancer

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- "*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*"
- Trade-off between conformality of IMPT and robustness of passive scattering

Overall aim

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

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Background: Repainting

Planned | Delivered with motion | 10 x repainting

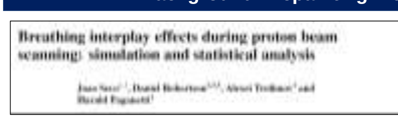
Liver SBRT example

Red contour = CTV

Color wash: >90% dose

Repainting helps, but is often inefficient

Background: Repainting methods


Breathing interplay effects during proton beam scanning: simulation and statistical analysis

PMB 54: N283-N94 (2009)

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

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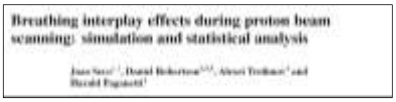
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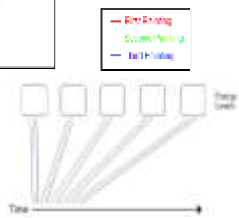

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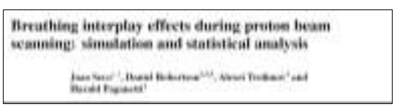
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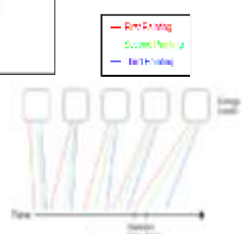

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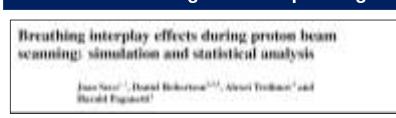
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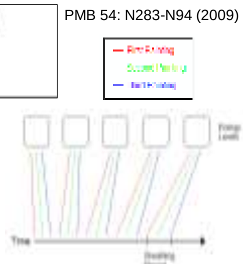

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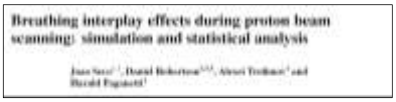
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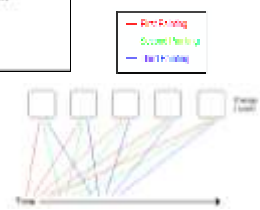

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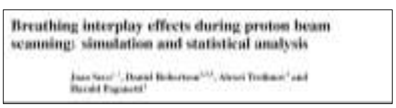
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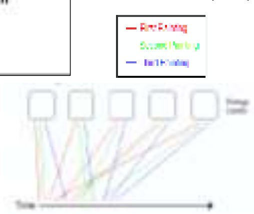

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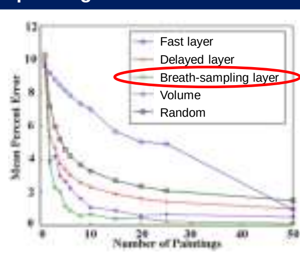
4. Volume repainting
5. **Random repainting**

Background: Repainting methods

- sin(x), $sin^4(x)$, $sin^6(x)$
- 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

Problems	Suggested solutions
Many spots cannot be repainted at all because they have too few MU	Use interlaced spot-adapted number of repaintings (1,2,4,8,16)

Breath-sampling repainting: Implementation problems

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The beam current cannot be reduced enough to stretch the layer delivery time to a full breathing cycle	Use waiting time between spots to extend the layer duration

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- Spot-adapted breath-sampling repainting

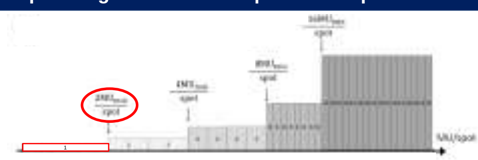
Spot-adapted breath-sampling repainting

- Repaint algorithm
- Investigate interplay effect mitigation in…
  - Experiments
  - Simulations
  - 4D dose reconstrutions

Spot-adapted breath-sampling repainting

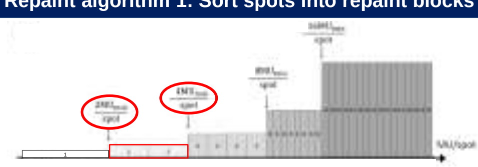
- Assume known regular breathing period, T = 4s
- Deliver each layer in T = 4s with evenly spread repaintings

Repaint algorithm 1: Sort spots into repaint blocks



- All spots with $<2MU_{min}$ are painted once

Repaint algorithm 1: Sort spots into repaint blocks

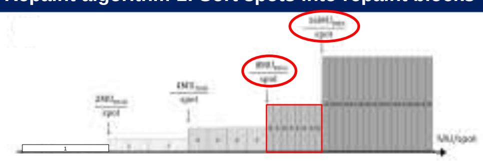


- All spots with $<2MU_{min}$ are painted once
- All spots with $\geq 2MU_{min}$ and $<4MU_{min}$ are painted twice

Repaint algorithm 1: Sort spots into repaint blocks

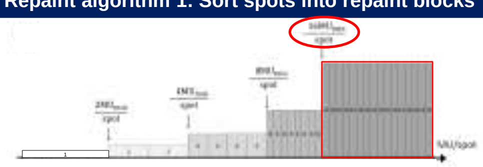
- All spots with $<2MU_{min}$ are painted once
- All spots with $\geq 2MU_{min}$ and $<4MU_{min}$ are painted twice
- All spots with $\geq 4MU_{min}$ and $<8MU_{min}$ are painted 4 times

Repaint algorithm 1: Sort spots into repaint blocks



- All spots with $<2MU_{min}$ are painted once
- All spots with $\geq 2MU_{min}$ and $<4MU_{min}$ are painted twice
- All spots with $\geq 4MU_{min}$ and $<8MU_{min}$ are painted 4 times
- All spots with $\geq 8MU_{min}$ and $<16MU_{min}$ are painted 8 times

Repaint algorithm 1: Sort spots into repaint blocks



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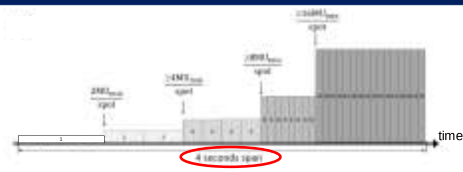
- All spots with $\geq 4MU_{min}$ and $<8MU_{min}$ are painted 4 times
- All spots with $\geq 8MU_{min}$ and $<16MU_{min}$ are painted 8 times
- All spots with $\geq 16MU_{min}$ are painted 16 times

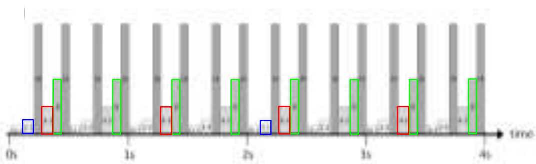
Repaint algorithm 2: Trim layer delivery time to exactly 4s



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

$$t_{wait} = \begin{cases} 0, & \text{if } \Delta x < 10\text{mm and } \Delta y < 10\text{mm} \\ \max\left(2.05\text{ms} + \frac{\Delta x}{6.9\text{mm/ms}},\ 3.52\text{ms} + \frac{\Delta y}{32.1\text{mm/ms}}\right), & \text{otherwise} \end{cases}$$

Repaint algorithm 3: Rearrange repaint blocks



- Evenly spaced repaintings over the whole breathing cycle

Spot-adapted breath-sampling repainting

- Repaint algorithm
- Investigate interplay effect mitigation in…
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Experiments

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

Experiments

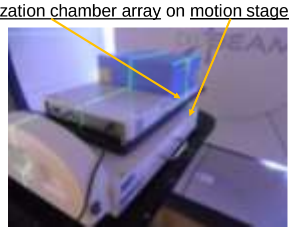
- Varian ProBeam facility at Maryland Proton Treatment Center
- Repainting algorithm in Matlab (manipulates Dicom RT plans)
- Five clinical plans (single-field optimization):

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

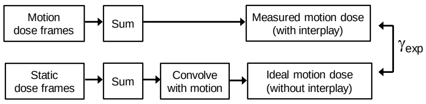
Experiments

- Each field delivered to Matrixx 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



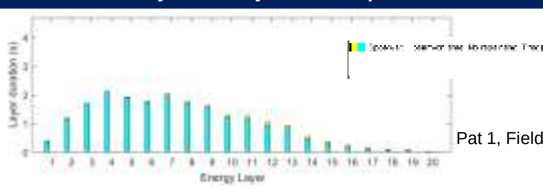
- 108 field deliveries in total (12 x 3 x 3)

Evaluation of experiments



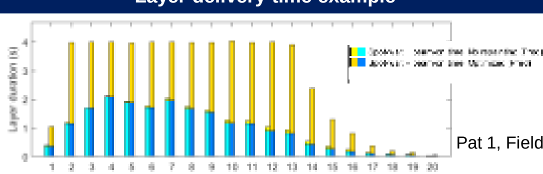
- Interplay effects quantified as 3%/3mm gamma pass rate γ_{exp}

Layer delivery time example



Pat 1, Field1

Layer delivery time example

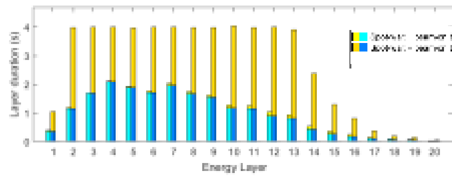


Pat 1, Field1

New repainting scheme:

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

Layer delivery time example

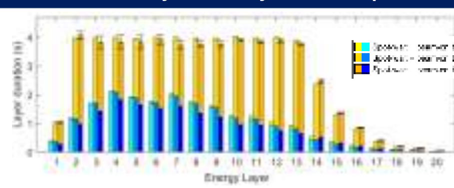


Pat 1, Field1

New repainting scheme:

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

Layer delivery time example



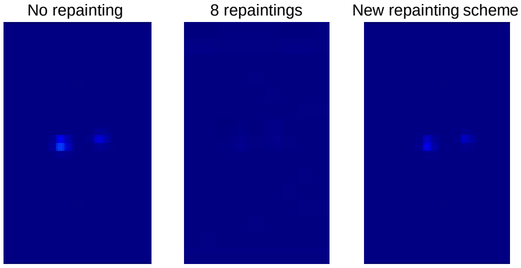
Pat 1, Field1

Mean absolute difference between actual and predicted layer duration:

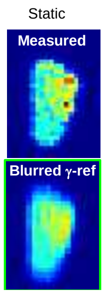
- 0.27 s

Example of measured doses (static target)

No repainting | 8 repaintings | New repainting scheme



Example of total measured field dose



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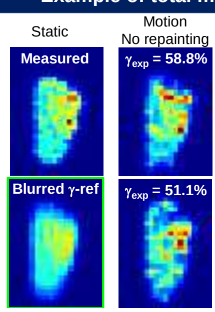

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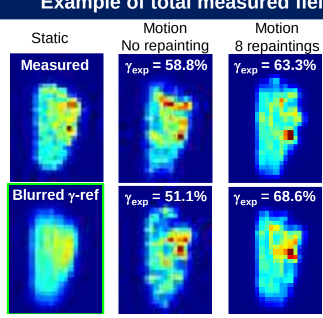

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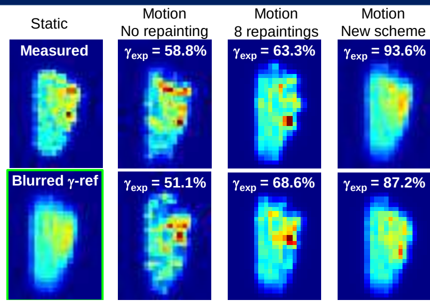


Gamma pass rates in experiments

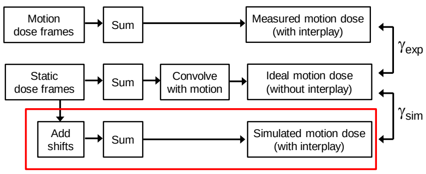
Repainting scheme	Experiments γ_{exp} (3%/3mm)
No repainting	59.6% ± 9.7%
8 repaintings	76.5% ± 10.8%
New repainting scheme	92.4% ± 3.8%

- Superior interplay effect mitigation with new repainting scheme

Spot-adapted breath-sampling repainting

- Repaint algorithm
- Investigate interplay effect mitigation in…
  - Experiments
  - Simulations
  - 4D dose reconstrutions

Simulations



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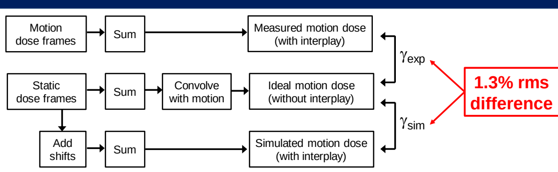
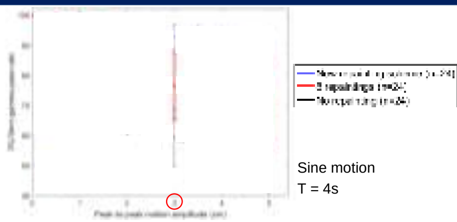


Simulations versus experiments

Repainting scheme	Experiments γ_{exp} (3%/3mm)	Sim of experiments γ_{sim} (3%/3mm)
No repainting	59.6% ± 9.7%	59.2% ± 9.6%
8 repaintings	76.5% ± 10.8%	76.4% ± 11.1%
New repainting scheme	92.4% ± 3.8%	92.8% ± 4.0%

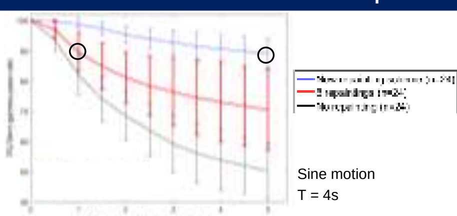
- Excellent agreement between simulations and experiments
- It justifies extension of the study to other motions with simulations

Simulations with different motion amplitudes



Sine motion
T = 4s

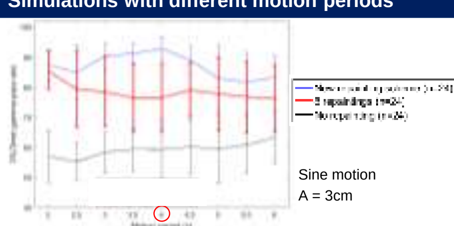
Simulations with different motion amplitudes



Sine motion
T = 4s

- 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%

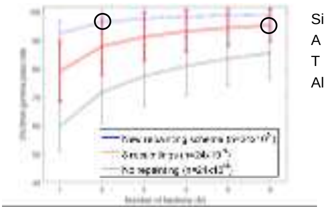
Simulations with different motion periods



Sine motion
A = 3cm

The new repainting scheme was best for 4s period, as expected,
but the degradation with other motion periods was quite modest

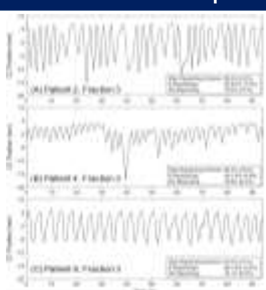
Simulations with 1-6 fractions



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

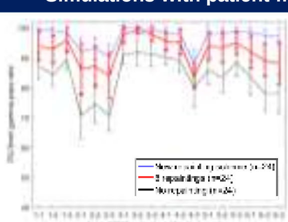
- 2 fractions with new repainting: Mean γ-pass rate = 96.3% ± 3.6%
- 6 fractions with 8 repaintings: Mean γ-pass rate = 95.3% ± 5.7%

Simulations with patient-measured liver motion



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

Simulations with patient-measured liver motion



Intra-treatment tumor motion for six liver SBRT patients (3 fractions each)

New repainting significantly better than 8 repaintings for all 18 trajectories

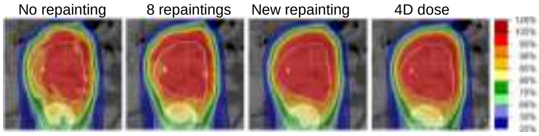
Spot-adapted breath-sampling repainting

- Repaint algorithm
- Investigate interplay effect mitigation in…
    - Experiments
    - Simulations
    - 4D dose reconstrutions

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



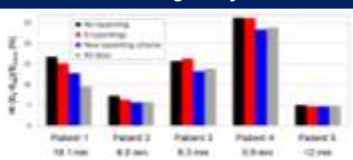
Patient 1:

- Pancreas, 3 fields, 2.25Gy/fx
- 19.1 mm motion in 4DCT

ICTV homogeneity index after 1 fraction

Homogeneity Index:
HI = $(D_2 - D_{98})/D_{mean}$

ICTV homogeneity index after 1 fraction



Homogeneity Index:
HI = $(D_2 - D_{98})/D_{mean}$

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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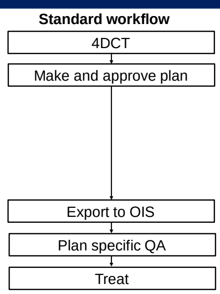
- Towards clinical implementation

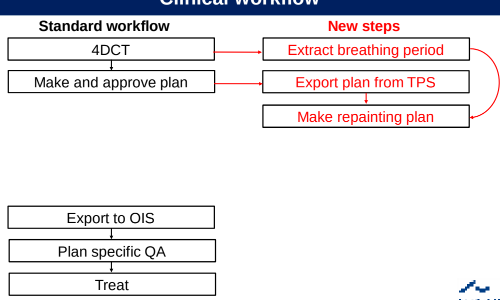
Clinical implementation

- 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

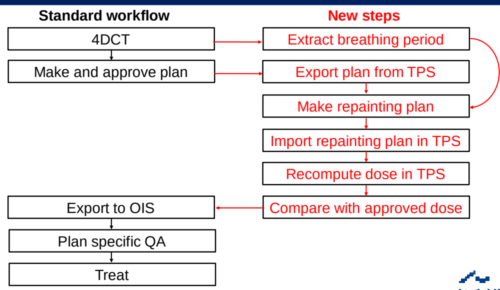
Clinical workflow



Clinical workflow



Clinical workflow



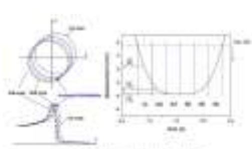
Summary: Spot-adapted breath-sampling repainting

- 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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