Minimizing dose uncertainty for spot-scanning proton therapy of moving tumors by optimizing the spot delivery sequence

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Purpose

- Minimize the motion-induced dose uncertainty by optimizing delivery sequence
  - Guided by a recently developed analytical model
- Evaluate the efficacy of spot delivery sequence by measurements and compare measurements to the model
Delivery Sequence (DS)

Nominal Plan

Nominal Spot Pattern

Nominal Target

T0

Target at the time of delivery

T50

Delivered spots
Optimized Delivery Sequence (ODS)

Nominal Plan

- Nominal Spot Pattern
- Nominal Target

T0

- Target at the time of delivery

T50

- Delivered spots
Spot Delivery Sequences

82 Spots delivered in 1st second

Worst sequence (WS)  Regular sequence (RS)  Optimized sequence (OS)

Same delivery time, different effective delivery time. Increasing effective delivery time will minimize interplay effects
2D Matrixx Measurement on 1D Moving Platform
Measurements

- Single layer (homegeneous)
- Multi layer single patient field (heterogenous)
- Different spot delivery sequences
- Varies motion conditions
  - Motion range: 0-4 cm
  - Motion period: 5-10 s
  - Motion pattern
  - Motion direction
- At least 3 measurements were made for each combination
Single Layer Spot Position (homogeneous dose distribution)

Nominal plan (spot positions) to be delivered

Nominal dose
Measurement Results

- Single layer
- 4 cm motion
- $\sigma = 6.75$ mm in air
- Uniform dose of 138 cGy at the depth of measurement

3D dose

4D dose (dose without interplay effects)

Worst sequence (WS)

Regular sequence (RS)

Optimized sequence (OS)
Measurement Results

- Max dose error
  - >90% for WS
  - >50% for RS
  - <5% for OS

- 3D dose with $\sigma = 6.75$ mm
- 4D dose with 4 cm motion
- Measured dose with WS
- Measured dose with RS
- Measured dose with OS
Result of 310 Measurements

- Analytical model
  - Assuming time interval between spots to be Poisson distributed
  - Worst case scenario
  - Dose error as a function of effective delivery time
- All measurements were bounded by the model
2D Measurement with Variation of WET

- ITV
- Deform Vector Field
- Proton Beam
- $\Delta WET$ ($\Delta x, \Delta y$)

P. Park, PhD
Patient Field Measurement with Variation of WET

- Single liver patient field
- Uniform dose of 360 cGy (RBE) to patient
- Proton range of 16.4 cm to 5.6 cm
- 4 cm motion
- \( \Delta \) WET up to 4.8 cm
Patient Field Measurement with Variation of WET
36 Patient Field Measurements with Variation of WET

- All measurements were bounded by the model
- With OS
  - Maximum dose error < 10%
  - Mean dose error < 5%
Optimizing Spot Delivery Sequence for Patient Field

- Blue solid line – original plan
- Green dash line – OS with machine delivery constrains
- Black solid line – theoretical OS without delivery constrains
Summary

- Measurements in a single fraction
  - Extreme motion conditions
- With WS
  - Max dose error could be up to >90%
- With OS
  - Max dose error <5% for single layer measurements
  - Max dose error <10% for patient field measurements
- Poisson model bounds all measured dose errors
Conclusion

- Optimized delivery sequence was generated based on analytical model to minimize motion-induced dose uncertainty.
- With the optimized delivery sequence, it is feasible to limit the maximum dose error in patients to <10% in a single fraction.
- Gating, BH, tracking could still be valuable.
Scanning beam timing chart

Irradiation Time: 4.4 s max.
Spill Change: 2.1s
Proton Charge: 3-5 nC/spill

Proton Charge: typically 1-10 pC/spot
Irradiation Time: typically 1-10 ms/spot
Spot Interval: typically 3 ms/spot

Smith et al. Med Phys 2009
Scanning Beam Delivery at PTCH

- Beam on max 10 ms for max MU 0.04
- Beam off 3 ms

Pulse max 4.4 s (hundreds of beam on/off)

Pulse off 2.1 s

Energy switch 2.1 s

For MU > 0.04, spot is repainted

Y. Li et al.
Med Phys 2014