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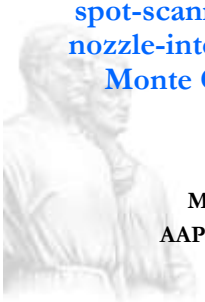
Efficient patient-specific QA for spot-scanned proton therapy using nozzle-integrated detectors and fast Monte Carlo dose calculations



Jedediah Johnson
Mayo Clinic Rochester
AAPM Annual Meeting 2018

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Disclosures

NONE!

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Designing a Patient-Specific QA (PSQA) Program

- Evaluate each element of the process
  - Modeling output of the machine
  - Calculating dose when that output hits the patient
  - Transferring plan instructions to delivery equipment
  - Machine performance
- Anticipate which steps in the process are most likely to cause problems
- Focus there!

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Historical Perspective

- Current proton PSQA practices have been influenced by the evolution of IMRT QA
- Understanding the issues associated with IMRT beam delivery, along with the measurements which detect dosimetric discrepancies, provides context for the proton QA discussion

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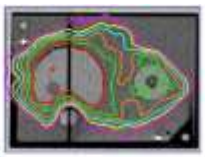
Evaluation of IMRT at Institutions Participating in NCI Sponsored Clinical Trials

Andrea Molineu, Paola Alvarez, Nadia Hernandez, David S. Followill, Geoffrey S. Ibbott



RPC

MD ANDERSON CANCER CENTER

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IMRT Head and Neck Phantom

- PTV 1 treated to 6.6 Gy
- PTV 2 treated to 5.4 Gy
- OAR limited to < 4.5 Gy

Criteria for credentialing

- Measured PTV doses must be within 7% of intended
- Distance to agreement in high gradient region near OAR: ≤ 4 mm

RPC

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IMRT Head and Neck Phantom Results

- 94 irradiations were analyzed
- 62 irradiations passed the criteria
  - 16 institutions irradiated multiple times
- 32 irradiations did not pass the criteria
- 74 irradiations are represented

Only 62% of institutions passed the criteria on the first irradiation.

Ibbott GS, Followill DS, Molineu HA, Lowenstein JR, Alvarez PE, Roll JE, Challenges in Credentialing Institutions and Participants in Advanced Technology Multi-institutional Clinical Trials. International Journal of Radiation Oncology Biology Physics 2008;71:S71-S5.

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IMRT Head and Neck Phantom Results

- 18 failed by TLD results only
- 5 failed by film results only
- 9 failed by both

	PTV 1	PTV 2	OAR	Displ. (mm)
Mean	1.01	1.00	1.09	-1.2
Std dev	0.054	0.050	0.27	3.5
Count	227	113	113	94
Range	0.78-1.13	0.85-1.22	0.42-2.24	(-15) - 8

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Explanations for Failures

- Incorrect output factors in TPS
- Incorrect PDD in TPS
- Inadequacies in beam modeling at leaf ends (Cadman, et al; PMB 2002)
- Not adjusting MU to account for dose differences measured with ion chamber
- Setup errors

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Designing a Patient-Specific QA (PSQA) Program

- Evaluate each element of the process
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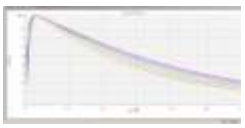
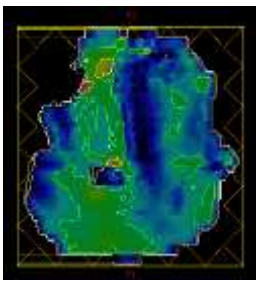
IMRT Process: Modeling Output

- Input Data



- IMRT Output



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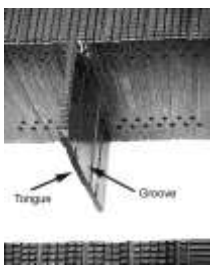
IMRT Process: Modeling Output



Rounded leaf ends

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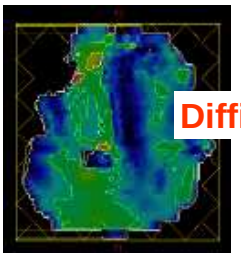
IMRT Process: Modeling Output



Difficult!

Actual Delivery Pattern

Modeled Delivery

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IMRT Process: Dose Calculation

- Once output is modeled, calculate dose:
  - Heterogeneities
  - External profile changes
  - Unusual scattering conditions (sinuses, gas, etc.)

Simple(ish)!

Input

Output

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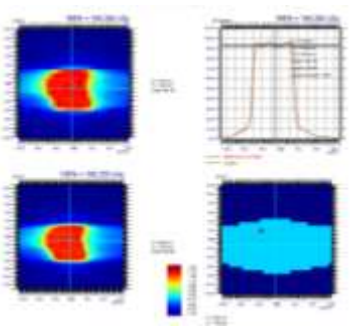
Dose Plane Comparison



Matrixx detector

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IMRT Process Summary

- Modeling the output is difficult, and the planning system often got it wrong
- Measuring the total dose distribution in phantom is a good way to check output
- Differences between patient and phantom (heterogeneities, contours, etc) are less important for x-rays

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Patient-Specific Beam Modifying Equipment

Scattered beam protons

- Compensators (shape distal end of range)
- Apertures (define field shape)

Spot scanning protons

- None (only magnetic steering)

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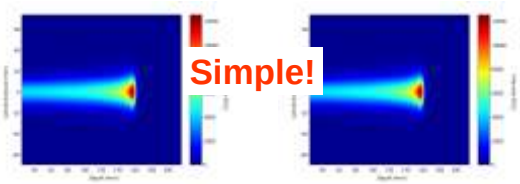
Proton Process: Modeling Output

- Input Data
- Output Calculation



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Proton Process: Calculating Dose

- Input Data
- Output Calculation

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GPU-based Monte Carlo Second Check

For more technical detail please see:
Wan Chan Tseung H, Ma J,Beltran C, A fast GPU-based Monte Carlo simulation of proton transport with detailed modeling of nonelastic interactions. Medical Physics 2015;42:2967-78

Beltran C, Tseung HWC, Augustine KE, Bues M, Mundy DW, Walsh TJ, et al., Clinical Implementation of a Proton Dose Verification System Utilizing a GPU Accelerated Monte Carlo Engine. International Journal of Particle Therapy 2016;3:312-9.

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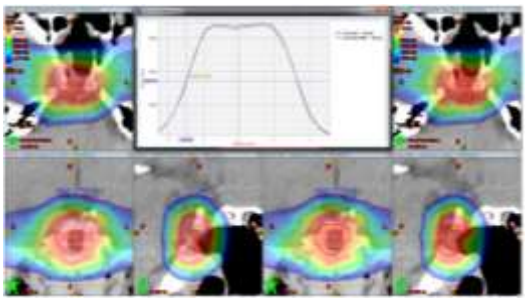
Analytical TPS Usually Does Fine



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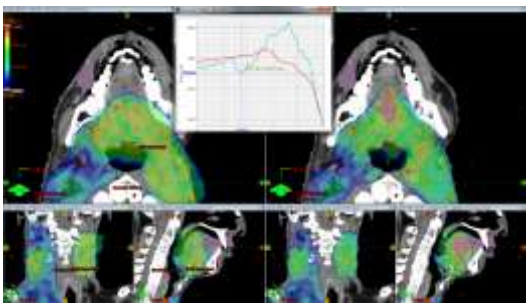
Analytical TPS Sometimes Fails



Analytical TPS Monte Carlo

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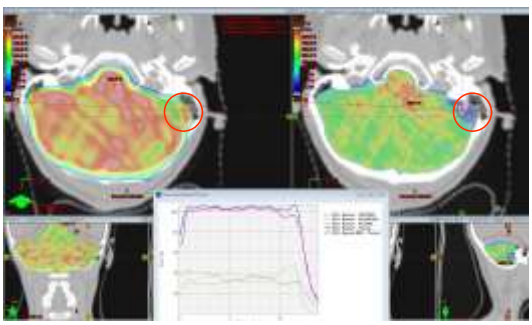
Analytic vs. Monte Carlo II



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Proton Process: Calculating Dose

- Input Data
- Output Calculation

Difficult!
Monte Carlo important

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Transfer of Plan Instructions to Delivery Systems

- IMRT: Dynamic MLC files are a list of discrete MLC shapes with dose indices.
- Protons: spot list parameterized by energy, location, and MU.
- These are data files, which computers are good at sending back and forth.
- Always QA patient file that will be used for treatment

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Transfer of Plan Instructions to Delivery Systems

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Summary: IMRT vs. Proton PSQA

	IMRT	Protons
Modeling Output	Difficult	Simple
Dose Calculation	Simple	Difficult
Data Transcription Verification	Very simple, but important	Very simple, but important

Since the needs are different, should the process also be different?

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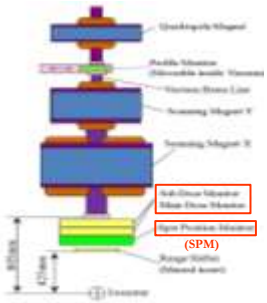
Nozzle Schematic



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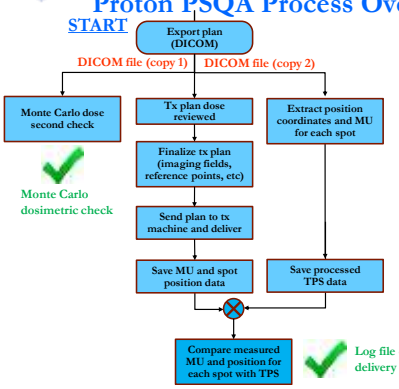
Proton PSQA Process Overview



IMPORTANT:

Delivery logs are compared to a treatment plan file which is explicitly tied back to the dosimetric second check!

The comparison verifies that the MC calculated plan is what was sent to the treatment machine.

Analysis demonstrates performance of the equipment

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Log File Use in Proton Therapy

- The use of log files in proton therapy is not new. Other institutions make use of this information
  - Example: Zhu X, Li Y, Mackin D, Li H, Poenisch F, Lee A, et al., Towards Effective and Efficient Patient-Specific Quality Assurance for Spot Scanning Proton Therapy. Cancers 2015;7:631.
- Log files have been used for:
  - supplementing more traditional ion-chamber based measurements at isocenter
  - re-calculating dose distributions in the planning system using actual delivered spot positions and weights
- Instead of using log files to supplement more traditional PSQA measurements, we have used them to partially replace these measurements

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Proton Process: Delivery

- Treatment plan delivered to water jugs
- One delivery per field at the same gantry angle as the actual plan.

Simple and efficient

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QA Tolerances

- The main purpose of our log file analysis is to ensure that the delivered plan is the same as the one reviewed in the treatment planning system
- Machine performance can also be assessed by analyzing log file data. QA tolerances match machine safety abort thresholds
- Machine abort thresholds were set during commissioning and are based on planning studies which assessed clinically meaningful dosimetric deviations.

Whitaker, T. J., Beltran, C. , Tryggestad, E. , Bues, M. , Kruse, J. J., Remmes, N. B., Tasson, A. and Herman, M. G. (2014), Comparison of two methods for minimizing the effect of delayed charge on the dose delivered with a synchrotron based discrete spot scanning proton beam. Med. Phys., 41: 081703.

Yu J, Beltran CJ,Herman MG, Implication of spot position error on plan quality and patient safety in pencil-beam-scanning proton therapy. Medical Physics 2014

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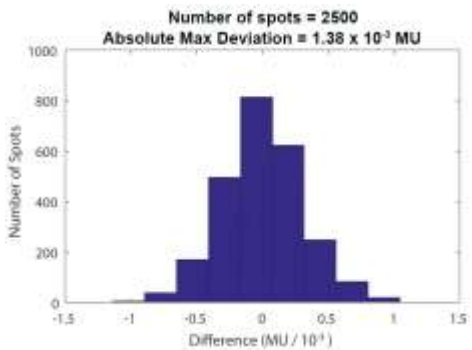
QA Report: MU Deviations



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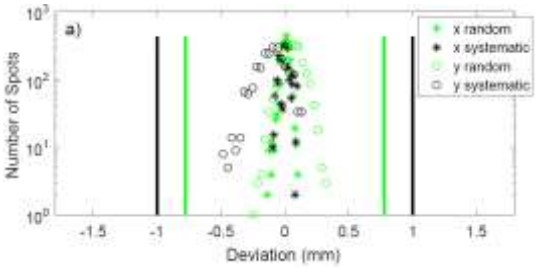
QA Report: Spot Position Deviation Histograms



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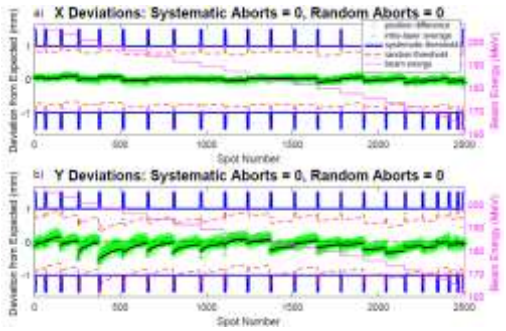
QA Report: Spot Position Deviations in the Time Domain



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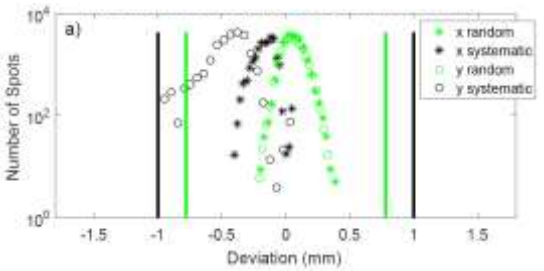
QA Report: Suboptimal Delivery



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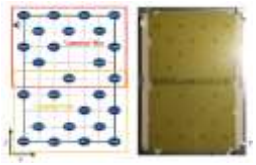
Beam Trajectory Commissioning/QA

- Rigorous connection between SPM readout and spot position at isocenter is crucial!
- Film measurements for a representative sampling of spot locations is performed at isocenter and correlated with the SPM.



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Regular Machine QA

- Essential for a log-file-based QA program
- Critical that SPM measurement remains an accurate surrogate for spot position at isocenter.
- Daily and monthly QA: spot position, output, energy
- Weekly SPM QA: field large enough to sample entire extent of SPM is delivered to ion chamber detector array (Matrixx, IBA). Measured dose is compared against both the calculated Monte Carlo dose distribution and previous weekly QA measurements using gamma analysis.

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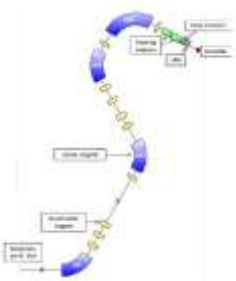
Patient-Specific Range Verification?

- Beamline optics act as spectrometer.
- Utilize dispersion to ensure correct beam energy: a change in beam energy will manifest as a detectable shift in spot position
- Worst case scenario (230 MeV):
  - 1 mm spot positional shift (interlock threshold) corresponds to 1.9% change in range.



Shiraishi S, Herman MG, Furutani KM, Measurement of Dispersion of a Clinical Proton Therapy Beam. Submitted to *Med Phys*, 2018.

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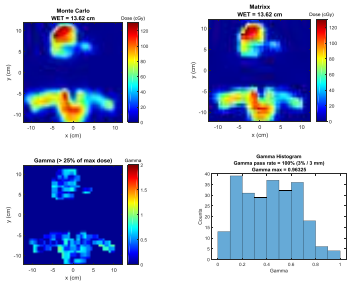
Matrixx

- Connection to historical standards and additional end-to end verification: first two plans per week are calculated on and measured on the Matrixx phantom



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Under Development: Detailed Treatment Log Database

- All important technical parameters of <u>every</u> beam delivery in our clinic will be recorded in an SQL database
- Enables detailed analysis of machine trends and patient-specific treatment records

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Summary

- PSQA needs between IMRT and IMPT are different
- Mayo Rochester QA protocols are very different for these two modalities, but specifically designed for sensitivity to important errors
- Our proton QA approach tends towards more holistic integration of patient-specific and machine QA.

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Acknowledgements

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