Clinical implementation of pencil beam scanning (PBS) proton therapy

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Penn Radiation Oncology
Penn Medicine

AAPM Education Session
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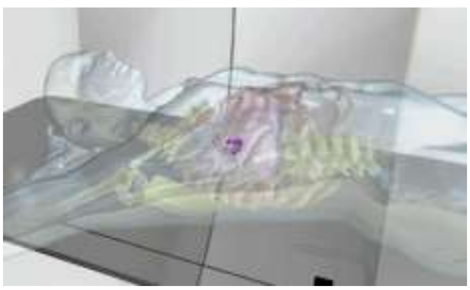
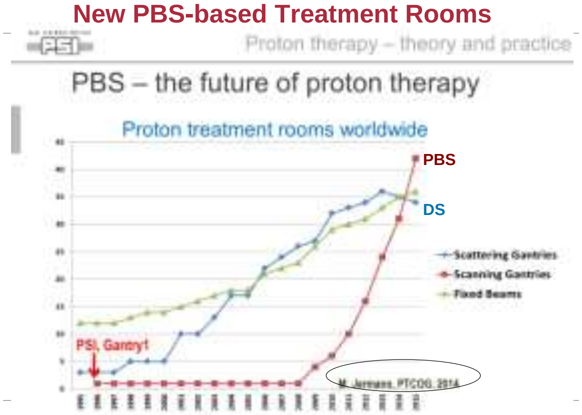
What is "PBS"?

Layer-by-Layer Energy Change with Lateral Beam Spreading Technology



Original Animation Provided by Varian

New PBS-based Treatment Rooms



Learning Objects

- ❑ Learn about essential steps for preparing and commissioning a PBS system (Dr. Dong)
- ❑ Understanding IMPT and delivery uncertainties (Dr. Pankuch)
- ❑ Understand dose calculation algorithms and their current limitations (Dr. Zhu)
- ❑ Staffing and Operation Issues (Panel discussion)

Disclosure: Lei Dong: Speaker Agreement with Varian Medical Systems;
Ron Zhu: None; Mark Pankuch: None

The nuances of PBS commissioning, machine QA, and patient QA

Lei Dong, Ph.D.

University of Pennsylvania

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Disclaimer: Varian Proton Advisory Board Member
IBA customer

Scope and Goals

- ❑ To learn about common tasks for commissioning a PBS based treatment room
- ❑ To discuss dose calibration in PBS implementation
- ❑ To discuss implementation strategies for machine QA and patient specific QA

General Definition of Clinical Commissioning

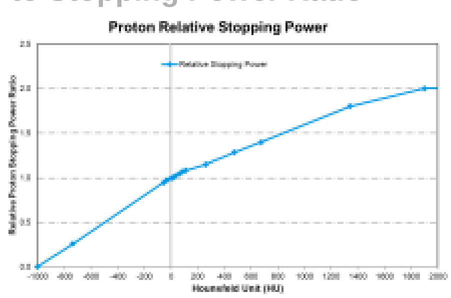
- Preparation to treat the first patient
  - Workflow
    - Procedures, treatment protocol development, documentation
  - Equipment purchase & commissioning
    - Vendor selections (immobilization to chamber selection)
  - TPS commissioning
  - Quality assurance procedures
  - Training

Two-Face (Phase) Process

- **Prior to room handover (90%)**
  - Any preparation that does not need beam time
  - Negotiate beam time for commissioning
- **After room handover (10%)**
  - Beam calibration
  - External peer review
  - Beam data acquisition
  - TPS validation measurements
  - End-to-end tests
  - QA setup
  - User training

Commissioning a CT Scanner

HU to Stopping Power Ratio

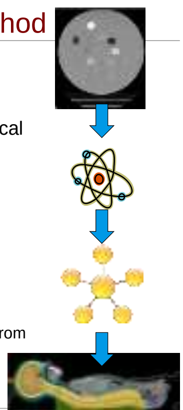


Phantom Composition is Different from Human Tissue!

Stoichiometric Calibration Method

✓Parametric based CT calibration:

- CT#: fitting specific parameters from **tissue substitutes** with known chemical composition and electron density.
- SPR: calculated based on the Bethe-Bloch equation
- Extrapolation with **Human tissue** compositions information
  - Based on the population average values from ICRP 23, ICRU 44, etc.

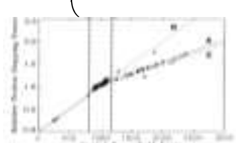


Schneider, U., E. Pedroni, and A. Lomax, Physics in Medicine and Biology, 1996. 41(1): p. 111-124.

Stoichiometric Calibration Method

- Two typical phantoms with known material composition
  - CRIS
  - Gammex
- Modeling

$$HU = \rho_e^{rel}\left(A\tilde{Z}^{3.62} + B\hat{Z}^{1.86} + C \right)$$



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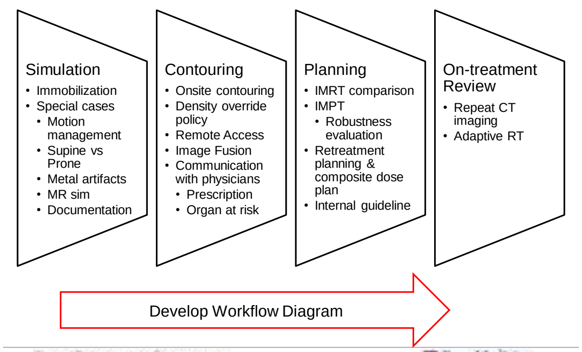
Additional Considerations

- **Patent Size Issue**
  - **Acquire phantom calibration in both head phantom and body phantom, and create an average table**
- **Peer Review**
  - **Similar CT models at other proton therapy centers**
- **Special material table**
  - Known materials and their SPRs
  - Dealing with metal artifacts
- **Documentation of CT recon parameters**
- **Metal artifact reduction algorithm**

Simulation and Planning Workflow



Develop Site-Specific Guidelines

(Clinical Protocol Development)

- **Simulation procedure**
  - Immobilization
  - Imaging requests
- **Treatment planning**
  - Prescription and normal tissue tolerances
  - Body contour (including treatment couch)
  - Density override policy
  - Planning techniques (class solution, beam angle selection)
  - SFO or MFO guideline
  - Plan report etc.

PBS Commissioning Measurements

- **Measurements**
  - Pencil beam IDD in water (all energies)
  - Pencil beam in-air fluence profiles at a few distances (at least three)
  - Normalization factor (output) at a fixed depth (all energies)
  - Pencil beam in-air profile at a few distances for each range shifter

Essential Equipment for Commissioning PBS

- **Dose Measurement**
  - Thimble Chambers or parallel plate chambers
    - TRS 398 compatibe
    - Suitable for high dose rate
  - Large "BraggPeak" chamber for IDD measurements
  - 3D scanning water tank
  - Specialized equipment
    - Multi-layer Large Ionization Chamber (IBA Giraffe)
- **Profile measurement**
  - High resolution 2D detectors

High-bias Thimble ionization Chamber Parallel Plate Chambers (preferred)

BraggPeak™ chamber

Water tank

2D detector For flatness & sym

IBA Giraffe Real-time IDD measurement

The First Week!

- **Evaluate measurement equipment**
- **Assess key commissioning measurements**
  - electrometer and ion chamber evaluation (leakage, linearity, end-effect, ion collection efficiency, etc.)
  - dose calibration
    - Challenging issues with high dose rate pencil beam
  - water tank and scanning hardware and software tests
  - detector tests for measuring beam profiles
  - gantry angle dependence (to ensure that measurement can be done, and measurements at one gantry angle would be adequate)
  - availability of accessories and other functions of the treatment unit

PBS Dose Calibration

IAEA TRS 398

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IAEA TRS 398

- **Establish the relationship between dose at reference condition to charge collected in the monitor chamber in the nozzle**
  - Dose / MU

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0}$$

- D_w,Q is the dose to water (Gy)
- M_Q is the corrected measurement (C)
- N_Dwq0 is ADCL calibration factor (Gy/C)
- K_QQo is chamber specific factor (unit less)

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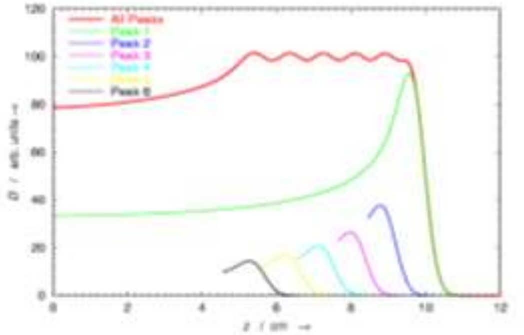
Making a Spread-Out Bragg Peak (SOBP)



Based on beam from HCL, Newhauser

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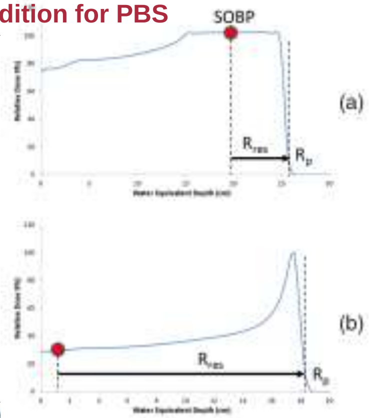
Calibration Condition for PBS

(a) Calibration at Mid SOBP (good for machines with built-in SOBP capabilities)

(b) Calibration at entrance region

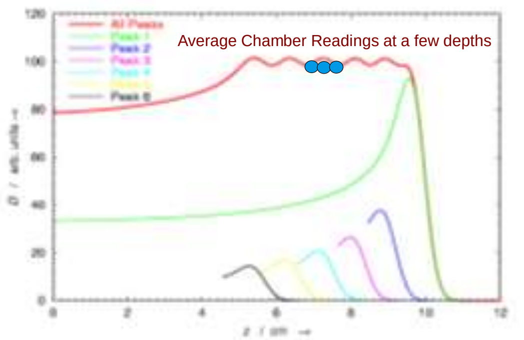
For single energy planar irradiation (PBS)

~ 160 MeV



TRS 398

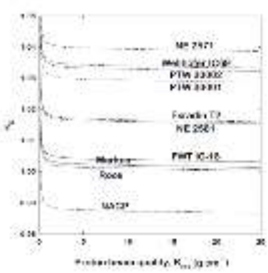
Making a Spread-Out Bragg Peak



Based on beam from HCL, Newhauser

Chamber specific perturbation factor, kQ

- Chamber perturbation correction factor
- Combines many corrections into one factor that is looked up in TRS 398 based on beam quality (Rres)
- Very stable number with Rres > 5cm (ie, 8cm+ SOBP)



$$k_{Q,Q_0} = \frac{(s_{w,air})_Q}{(s_{w,air})_{Q_0}} \frac{(W_{air})_Q}{(W_{air})_{Q_0}} \frac{p_Q}{p_{Q_0}}$$

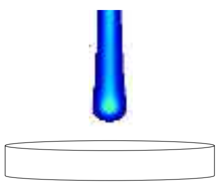
Chamber Selection

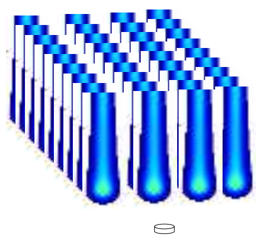
- **IAEA TRS 398**
  - Table 10

$$D_{w,Q} = M_Q \, N_{D,w,Q_0} \, k_{Q,Q_0}$$

PBS Calibration Pattern

Large Chamber + Pencil Beam vs. Small chamber + Large Field





PBS Calibration Pattern

Scripps: 70-250 MeV Beam
Calibration Energy: 160 MeV
Depth: 1.5cm SAD

Correction for recombination:
Pulsed scanned – 1.0062
*Pulsed – 1.0048
Continuous – 1.0017

"Avg Dose Rate"
60k MU/min

Instantaneous DR
~ 10Gy/s

Pion

- Corrects for recombination of ions in chamber. In other words, ions that are created but not collected.
- Two voltage technique with V1 and V2 differing by at least factor of 2.
- Our beam is pulsed scanned (pulsed for the chamber-eye-view)
- Generally this correction is less than 1%, but it is recommended to be less than 3%.

Simplified version:

$$k_s - 1 = \frac{M_1/M_2 - 1}{V_1/V_2 - 1}$$

Long form for pulsed or pulsed scanned:

$$k_s = a_0 + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2$$

[illegible]

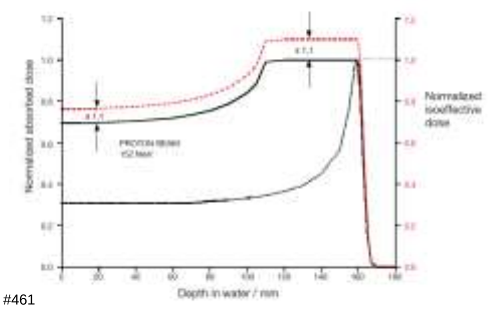
What am I missing?

If you calibrate cGy/MU correctly, you are still 10% off!

Dose Unit in TPS: Gy(RBE)

Current Standard RBE for Proton Therapy: 1.1

Proton Beam



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Peer Review

- **External review by a physicist**
  - Bring independent chamber and electrometer
- **IROC TLD measurements (at center of SOBP)**
  - TR4: 1.00
  - TR3: 0.99
  - TR2: 1.00

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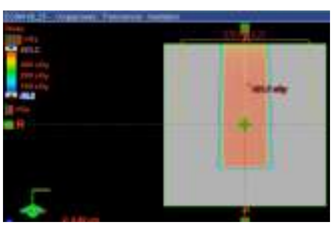
TPS Algorithm Commissioning

- **See Dr. Zhu's presentation**

Validation Plans for TPS Commissioning and Parameter Tuning

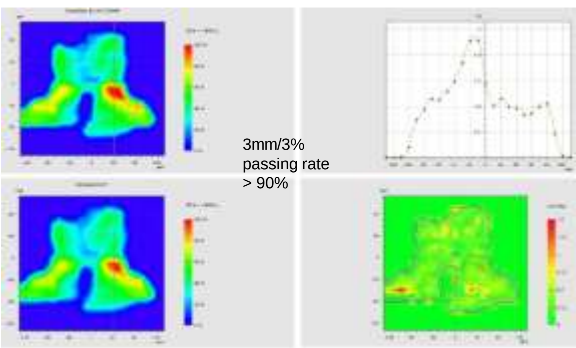
- **Systematic Plan Validation Approach**
  - Width of SOBP
  - Length of SOBP
  - Depth of SOBP
    - With and without Range Shifter
- Use animal tissue measurement to adjust output is not recommended
- **Patient specific QA**
  - QA results vs. beam model
- **End-to-end Tests**
  - Patient transfer
  - IGRT



Patient QA Comparison

- **IMRT**
  - Composite point dose measurement in phantom (ion chamber)
  - Fluence map (film; portal imaging device, 2D detector)
  - Analysis: absolute dose difference; gamma
- **IMPT**
  - Point dose in water or in phantom (ion chamber) measured **field by field**
  - 2D dose in phantom (2D detector)
  - Analysis: similar
  - **Range validation in water**

2D Array Measurement



Compare QA results at nearby depths

- A range error was discovered for a new 2-cm range shifter

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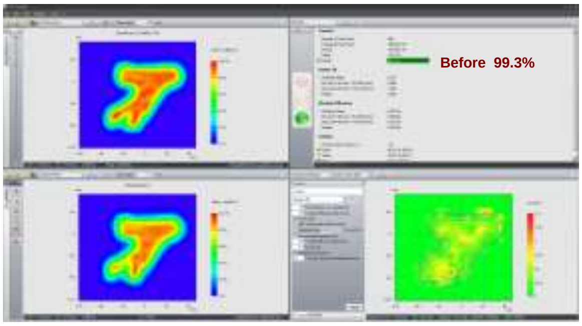


Develop a QA program

Assessing Risks Requires Knowledge

- **Relative risks for pencil beam delivery**
  - Spot Position (high risk)
  - Spot Intensity/dose (high risk/impact)
  - Spot Shape (intermediate risk)
  - Spot Energy (low risk)
  - Dose Rate (for raster scanning)

- **New ISO 9001:2015 promotes risk-based thinking in a quality management system due to the need for balancing operational efficiency and comprehensive quality management**

Machine QA Philosophy

- **Deciding what not to do are perhaps more important**
- **PBS (Spot Scanning vs. Raster Scanning)**
  - Spot intensity (dose/MU)
  - Spot position
  - Spot energy
  - Spot shape/size

  - ~~Dose Rate Stability?~~
  - Gantry dependence
  - Off-axis accuracy
  - Imaging & beam coincidence
  - Robotic couch

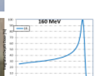
Creating Machine QA Baselines

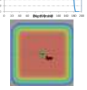
- **Timing to create monthly and daily QA baselines**
  - During commissioning when TPS is finalized
- **Machine QA design**
  - Verify the machine is in the same condition as your TPS predicts
  - Risk-based

Scripps

Daily QA

- End-to-end test run by therapists in the morning
- QA Phantom
- Imaging the block to verify:
  - Laser
  - couch position
- Dose pattern
  - Uniform spot pattern
  - 4 electron chambers to measure energy (~1mm resolution)
  - Central chamber for output
  - It can detect beam shape changes to some degrees

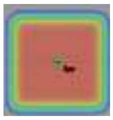




Monthly QA

Output measurement

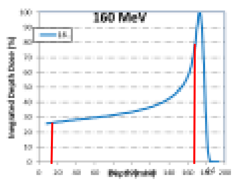
- Repeat at machine calibration condition
  - Parallel plate chamber
  - Depth: 1.5 cm
  - Single layer
  - 160 MeV
  - Spot spacing 2.5mm
  - Electrometer bias -400v



Monthly QA

Energy Check

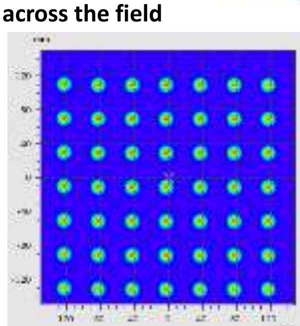
- Two-depth Technique
  - Ratio of ion chamber readings
  - Base: 1.5cm build-up
  - Deeper depth: 16.5cm build-up
- Alternative
  - IBA Giraffe™ (stacked parallel plate chambers with 2mm resolution)



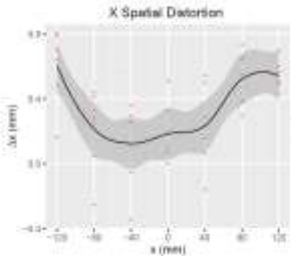
Monthly QA

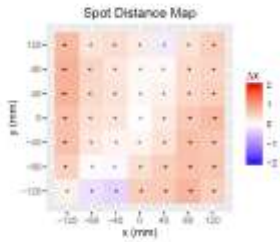
Spot Position Accuracy across the field

- Coarse Pattern
  - Geometric distortion
  - FWHM in all positions
    - Shape of spots



Monthly QA – Spot Off-Axis Position





Luis Perles
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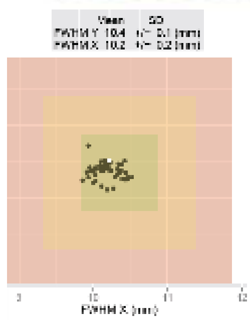
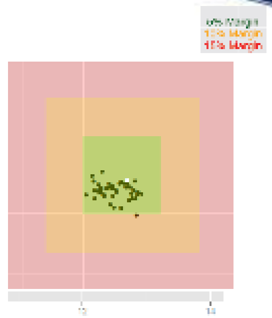
Monthly QA – Spot Size



160 MeV



90 MeV

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Monthly QA

- Center Spot Accuracy and agreement with imaging (kV or CBCT) and lasers

Logos Systems

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Scripps Annual QA – Repeat Commissioning

- What if the QA baseline was wrong or changed?
- Repeat selected commissioning measurements
  - Measure IDD in water tank for selected energies
  - Measure spot shape and size for selected energies
  - Measure the relative energy dependence factor
  - Confirm range shifter thickness, integrity, and snout position accuracies

Summary of Clinical Commissioning

- **Clinical commissioning is a multi-task project**
  - Get training early and prepared
  - Distribute work into smaller tasks
  - Get the right equipment
- **Intense commissioning tasks involving physics/dosimetry:**
  - Dose calibration
  - TPS commissioning
  - QA procedures
  - Workflow
  - End-to-end tests
  - Peer review