Clinical Implementation of Pencil Beam Scanning (PBS) Proton Therapy

Commissioning PBS dose calculation algorithms and understanding their limitations

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Particles contributing to doses

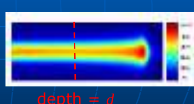
- Primary protons
  - Elastic interactions with electrons
  - Elastic proton-nucleus scattering
- Secondary particles
  - Non-elastic nuclear interactions
  - Secondary protons and other fragments (deuterons, tritons, alphas, neutrons, etc.)

Dose Algorithms

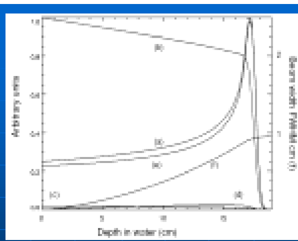
- Monte Carlo Simulation
  - Becoming available for clinical uses in commercial TPS
- Analytical calculation – pencil beam algorithms

  $D(x,y,z) = I[d(z)] \times LAT[x,y,d(z)]$

  - $I(d)$ – integral depth dose
  - $LAT(x,y,d)$ – lateral dose profile



Integral Depth Dose

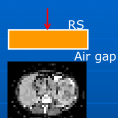


Pedroni *et al*. PMB 2005

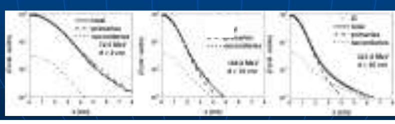
(a) Total dose
(b) Beam flux attenuation
(c) Dose locally deposited
(d) Dose from "beam halo" or low dose envelope
(e) Dose from primary protons
(f) Beam width σ broadening due to MCS in water

Lateral Dose Profile

- Multiple Coulomb Scattering (MCS)
  - In the patient
  - In the range shifter propagating through the air gap to the patient
  - Some devices in beamline
- Nuclear interaction
  - beam "halo" due to large angle inelastic nuclear fragments

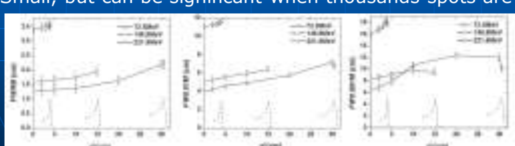


Sawakuchi *et al*. PMB 2010



Low dose envelope

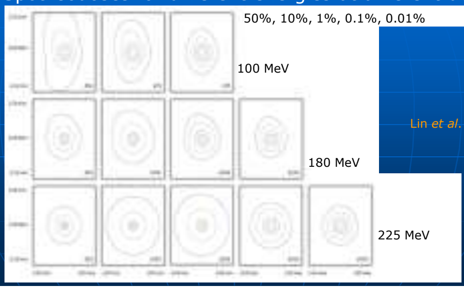
- High E – nuclear fragments
  - Depends on energy & depth
- Low E – MCS
  - In the devices and phantom/patient
- Small, but can be significant when thousands spots are used



Sawakuchi *et al*. PMB 2010

Low dose envelope

- Spot isodoses for different energies at different depths

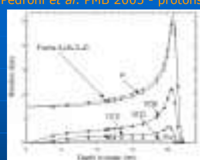


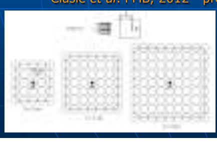
Lin *et al.* PMB 2013

Low dose envelope

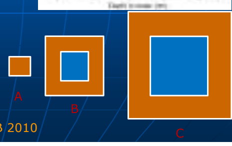
- Methods of measurements:
  - Concentric square frames:
    Pedroni *et al.* PMB 2005 - protons
  - Field size factors:
    Sawakuchi *et al.* PMB 2010 - protons
    Inaniwa *et al.* Med Phys 2009 - carbons
  - Concentric circles:
    Clasie *et al.* PMB, 2012 - protons

Pedroni *et al.* PMB 2005 - protons





Sawakuchi et al PMB 2010



Commissioning - Example

Zhu *et al.* Med Phys 2013

- Total dose: Fluence x Beamlet dose

$$D(x,y,z)=\sum_{E_k}\left\{\sum_{Beamlet\ j}\left[\Phi_{E_k}(x_j,y_j,z)D_{E_k}^{Beamlet}(x-x_j,y-y_j,d(z))\right]\right\}$$

- Beamlet dose: IDDs x Kernel

$$D_{E_k}^{Beamlet}(r,d(z))=\frac{1}{\rho_{H_2O}}\left[S(d)\times K(r,d)\right]$$

$$D_{E_k}^{Beamlet}(r,d(z))=\frac{1}{\rho_{H_2O}}\left[S_{pp}(d)K_{lat,prim}(r,d)+S_{sp}(d)K_{lat,sec}(r,d)\right]$$

pp – primary photons	$K_{lat,prim}$ – MCS, Moliere theory, 2 Gaussians
sp – secondary particles	$K_{lat,sec}$ – secondary particles, nuclear interaction

Input Data Requirements by Treatment Planning Systems

- In air profiles:
  - At 3 to 5 different positions from isoceter (e.g., ±200, ± 00, and ±0 mm) for every 10-20 MeV in both directions.
  - If a range shifting device is used, 2~3 complete data sets for 2~3 different thicknesses.

Input Data Requirements by the Treatment Planning System

- Integrated depth doses (IDDs):
  - Depth dose to be measured with a large p-p chamber with the radius *R*,

$$R \geq 3\sigma_{spot} = \sqrt{\sigma^2_{fluence} + 2(0.0307 \times Range)^2}$$

  - IDDs are in unit of Gy•mm²/MU or Gy•mm²/Gp (Gp = 10^9 ,giga protons)
  - The p-p chamber might be too "small" and requires a correction for dose deposited outside of the p-p chamber

Clasie et al PMB 2012

Correction factors for IDDs

- MC simulation to determine CFs

$$CF(E, d = 2cm) = \frac{IDD_{MC}(E, d = 2cm; r_2)}{IDD_{MC}(E, d = 2cm; r_1)}$$

- Convert MC IDDs to Gy•mm²/MU or Gp

$$IDD(E, d; r_2) = \frac{IDD_{MC}(E, d; r_2)}{IDD_{MC}(E, d = 2cm; r_2)} \times IDD_{meas}(E, d = 2cm; r_1) \times CF(E, d = 2cm)$$

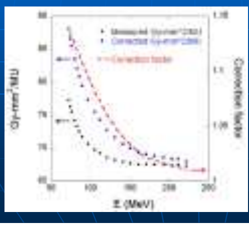
Normalized MC IDD at 2 cm depth

Measured IDD at 2 cm depth

Zhu et al Med Phys 2013

Measurement of single pencil beam

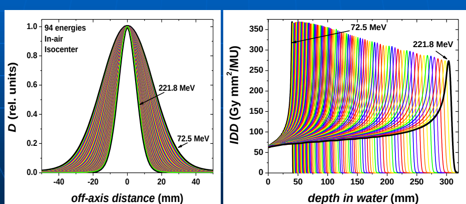
- Selected Pencil beams at CAX,
  - Bragg Peak Chamber (81.6 mm diameter chamber)
  - Physical depth = 1.6 cm, Effective depth 2.0 cm
  - 50 MU were delivered in physics mode



Gillin *et al.* Med Phys 2010

Input data

- Monte Carlo simulated input data (validated experimentally - Sawakuchi *et al.* Med Phys 2010)
- IDDs are in units of Gymm^2/MU or Gp



Zhu *et al.* Med Phys 2013

Fluence Model with Gaussians

- Fluence for individual spot:

$$\phi_{E_k}(x,y;x_m,y_m,z)=\phi^m_{E_k}\sum_i\left[\frac{w_i(E_k)}{2\pi\sigma_i^2(E_k,z)}\exp\left(-\frac{(x-x_m)^2+(y-y_m)^2}{2\sigma_i^2(E_k,z)}\right)\right]$$

Gaussians

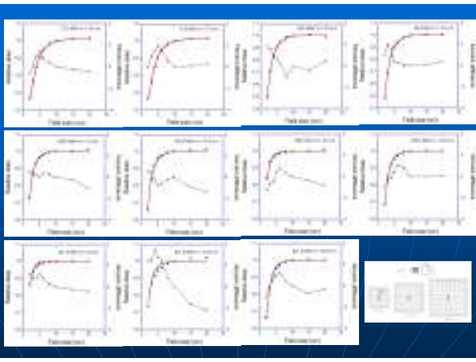
$w_1(E_k) + w_2(E_k) = 1$

$$\sigma_i(E_k,z)=\sqrt{\left(\frac{A_i(E_k)}{2}+B_i(E_k)z+\frac{C_i(E_k)}{2}z^2\right)}$$

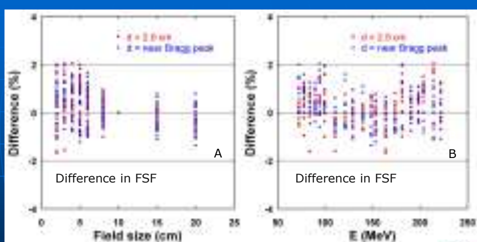
A, B & C phase space parameters

- Parameters were initially determined fitting input data to analytical formula
- Adjusted based on field size factors

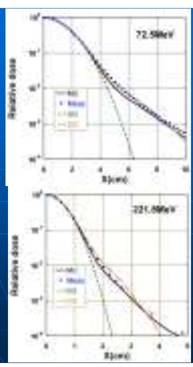
Zhu et al Med Phys 2013

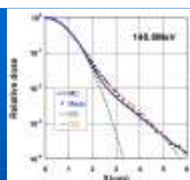


Difference in field size factors



20 mono-energetic fields
Avg ± Stdev = 0.2% ±0.7% (-1.7% to 2.1%)



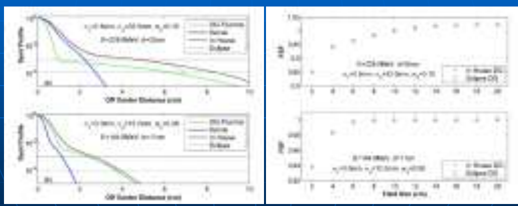


- In air lateral profiles: Comparison of Measurements, Monte Carlo and TPS calculated by single- and double Gaussian fluence model

Zhu et al Med Phys 2013

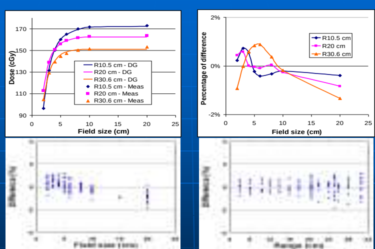
Fluence Model with Gaussians

- Colleagues at Mayo Clinic developed a in-house method to determine Gaussian fluence parameters



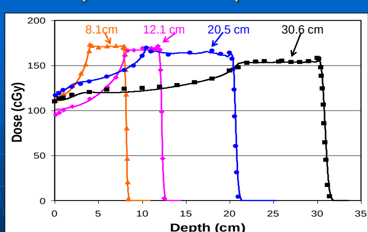
Shen et al Med Phys 2016

Dose at the center of SOBPs



The SOBP widths: 2 to 24 cm.
Avg ± Stdev = 0.0% ±0.6% (range, -1.9% to 1.2%)
Zhu et al Med Phys 2013

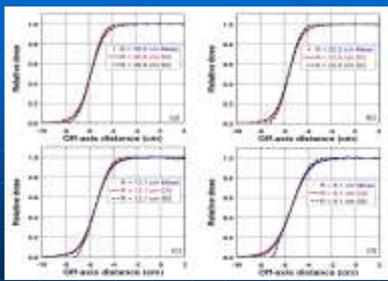
Comparison of depth doses



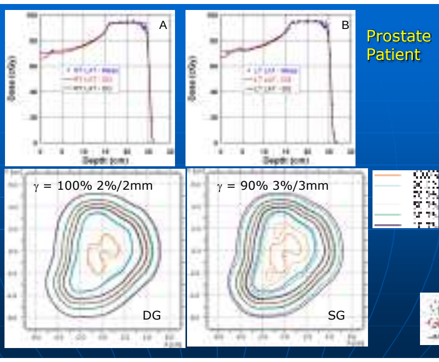
Field size of 10 cm × 10 cm,
SOBP width of 4 or 10 cm.

Zhu et al Med Phys 2013

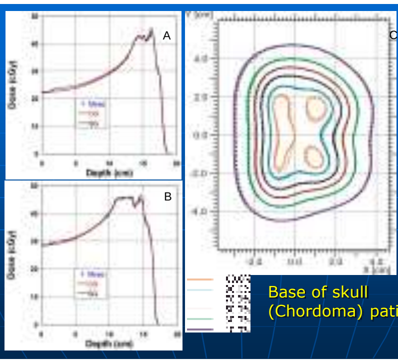
Comparison lateral dose profiles



Zhu et al Med Phys 2013

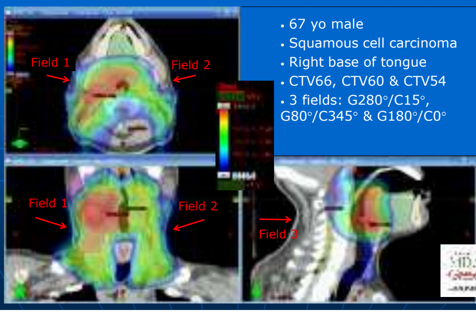


Prostate Patient



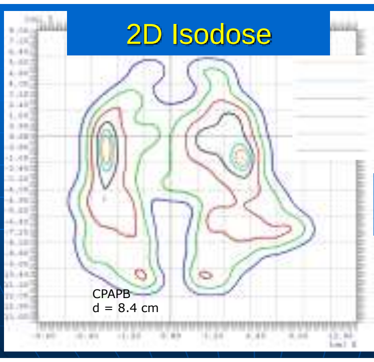
Base of skull (Chordoma) patient

Head & Neck – MFO/IMPT



- 67 yo male
- Squamous cell carcinoma
- Right base of tongue
- CTV66, CTV60 & CTV54
- 3 fields: G280°/C15°, G80°/C345° & G180°/C0°

2D Isodose



99.9 % passes for 2% dose/2-mm criteria γ-index

It is not perfect

- Commissioning will not exhaustively test all clinical scenarios
- Patient QA including dose measurements is desirable

Table 2: Summary of the gamma index passing percentages from the patient specific quality assurance of 2,187 treatment fields.

(a)

	[2%, 2-mm]	[3%, 3-mm]
Overall	85.3±0.8%	96.2±0.4%
CNS	85.9±1.9%	95.0±1.2%
HN	82.7±1.2%	94.9±0.7%
Prostate	100.0%	100.0%
Thoracic/GI	80.1±1.9%	97.2±0.8%

(b)

	[2%, 2mm]	[3%, 3-mm]
SFO	81.5±1.5%	95.2±0.8%
MFO	83.3±1.1%	95.6±0.6%
RS	81.9±1.0%	94.8±0.6%
NRS	86.1±2.0%	99.0±0.0%

Mackin *et al*. IJPT 2014

Summary

- Accurately modeling the low dose envelope is one of the most important elements during PBS commissioning
- Analytical dose models have limitations
- Patient specific QA should include dose measurements to continue validating the dose model.
- Better dose calculation methods such as Monte Carlo simulation are becoming available in commercial TPS
- Methods presented here could be used for the basic validations of Monte Carlo dose calculation as well
- Inhomogeneity phantoms (e.g., IROC phantoms) should be used for end-to-end validations of imaging, planning and delivery.

Acknowledgements

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Many others

Thank you!

Core, Halo, Aura and Spray

- Gottschalk et al have a more precise definition for the dose distribution of a proton beam stopping in water - Basic physics component and others from beam contaminations
  - *Core* – for the primary beam
  - *Halo* – for the low dose region from charged secondaries
  - *Aura* – for the low dose region from neutrals
  - *Spray* – for beam contamination

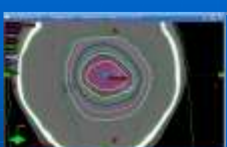
*Gottschalk et al PMB 2015

Basic Information about Bragg Peak Chamber

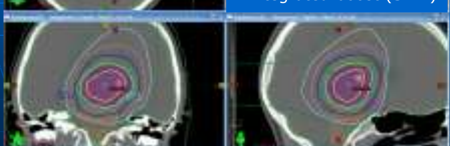
- Nominal sensitive volume: 10.5 cm^3.
- Sensitive volume: r = 40.8 mm, t = 2 mm.
- Nominal response: 325 nC/Gy.
- Reference point 3.5 mm front chamber surface.
- Entrance window: 3.47 mm PMMA.
- WET window: 4 mm.
- $N_{D,W}k_p$ = (3.181±0.023)x10^6 Gy/C*
  - Average 3 inter-comparison

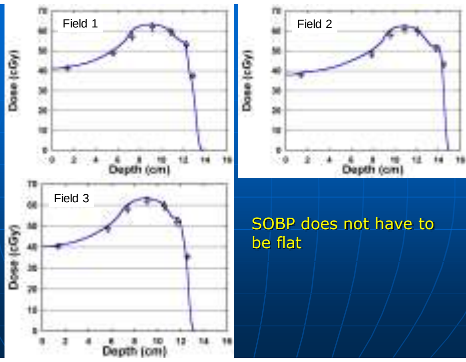
*Gillin *et al*. Med Phys 2010

Brain - SFIB



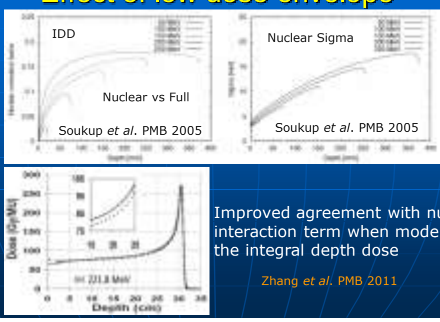
- 11 year old boy
- Glioma of tectal plate
- Single field (Simultaneous) integrated boost (SFIB)





SOBP does not have to be flat

Effect of low dose envelope

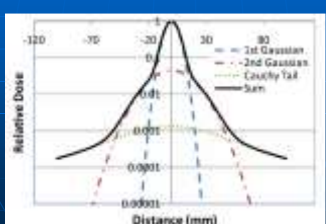


Improved agreement with nuclear interaction term when modeling the integral depth dose

Zhang *et al.* PMB 2011

Effect of low dose envelope

- Modified Cauchy-Lorentz function is a better choice than Gaussian for lateral profile modeling



Li *et al.* PMB 2012