Dose Calculation Algorithms and Commissioning

The Status of Intensity Modulated Proton and Ion Therapy

AAPM Symposium 2014

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Particles contributing to dose

- 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.)

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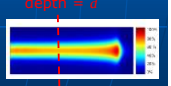
Dose Algorithms

- Monte Carlo Simulation
  - Not routinely used in the clinics yet
- Analytical calculation – pencil beam algorithms

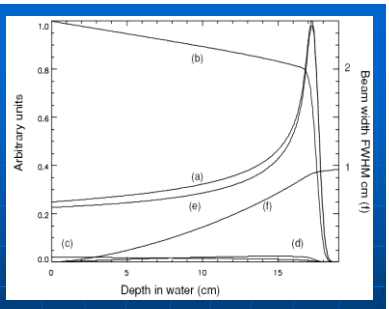
$D(x,y,z) = I(d) \times LAT(x,y,d)$

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



$$I(d) \propto \iint_{-\infty}^{\infty}$$

Integral Depth Dose



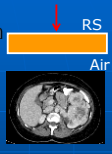
(a) Total dose
(b) Beam flux attenuation
(c) Dose locally deposited
(d) Dose from "beam halo" or low dose envelope
(e) Dose from primary protons

Pedroni *et al*. PMB 2005

Lateral Dose Profile

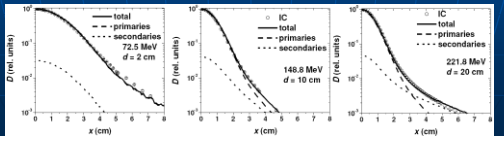
- Multiple Coulomb Scattering
  - In the range shifter propagating in the air gap to the patient
  - In the patient

Pedroni *et al*. PMB 2005

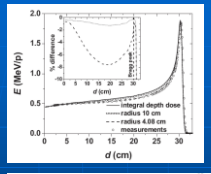


- Nuclear interaction
  - beam "halo" or low dose envelope due to large angle scattered protons and nuclear fragments

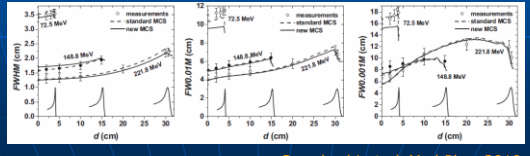
Sawakuchi *et al*. PMB 2010



Effect of low dose envelope



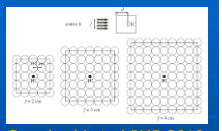
- Depends on energy & depth.
- Small, but can be significant when thousands spots together



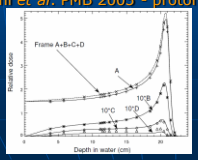
Sawakuchi *et al*. Med Phys 2010

Effect of low dose envelope

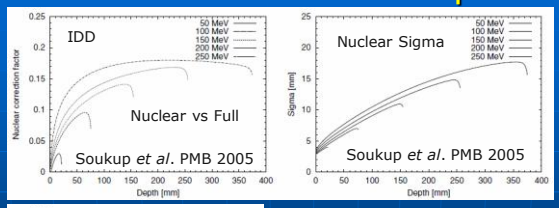
- Methods of measurements:
  - Field size factors:
    - Sawakuchi *et al*. PMB 2010 - protons
    - Inaniwa *et al*. Med Phys 2009 - carbons
  - Concentric circles:
    - Clasie *et al*. PMB, 2012 - protons
  - Concentric square frames:
    - Pedroni *et al*. PMB 2005 - protons

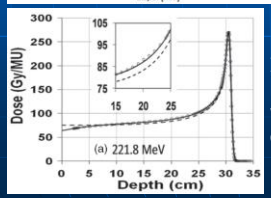


Sawakuchi et al PMB 2010



Effect of low dose envelope

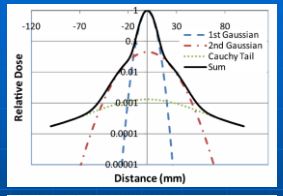




Improved agreement with nuclear interaction term when modeling the integral depth dose

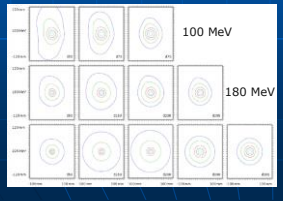
Zhang *et al*. PMB 2011

Effect of low dose envelope



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

Li *et al*. PMB 2012



Spot isodoses for different energies at different depths

Lin *et al*. PMB 2013

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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

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

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

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 the Treatment Planning System

- 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

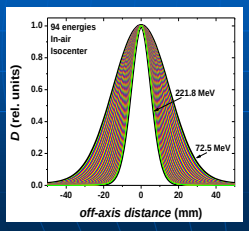
- Integrated depth doses (IDDs):
  - Depth dose to be measured with a large p-p chamber and suggests

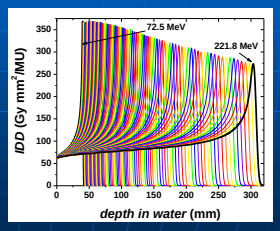
$$R=3\sigma_{spot}=\sqrt{\sigma_{fluence}^2+2(0.0307\times Range)^2}$$

  - IDDs are in unit of Gy•mm²/MU.

Input data

- Monte Carlo simulated input data (validated experimentally - Sawakuchi *et al.* Med Phys 2010)
- IDDs are in MeV/cm^3 and need to be converted to Gy/MUmm^2





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•mm^2/MU

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

Normalized MC IDD at 2 cm depth

Measured IDD at 2 cm depth

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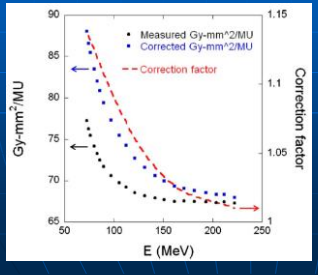
Measurement of single pencil beam

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



Gillin *et al.* Med Phys 2010

Fluence Model with Gaussians

- Fluence for individual spot:

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

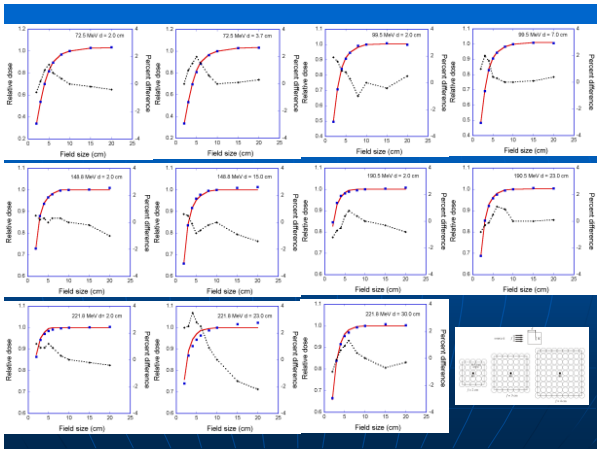
Gaussians

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

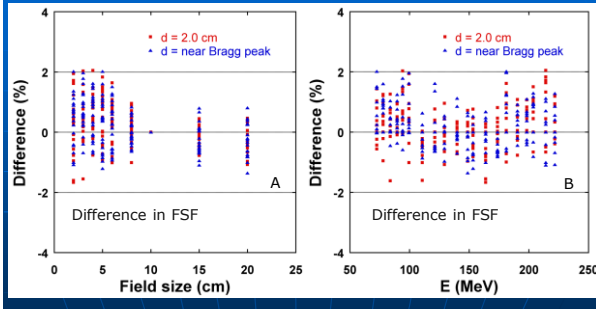
$$\sigma_i(E_k,z)=\sqrt{\left(\frac{A_i(E_k)}{2}+B_i(E_k)z+\frac{C_i(E_k)}{2}z^2\right)}$$

A, B & C phase space parameters

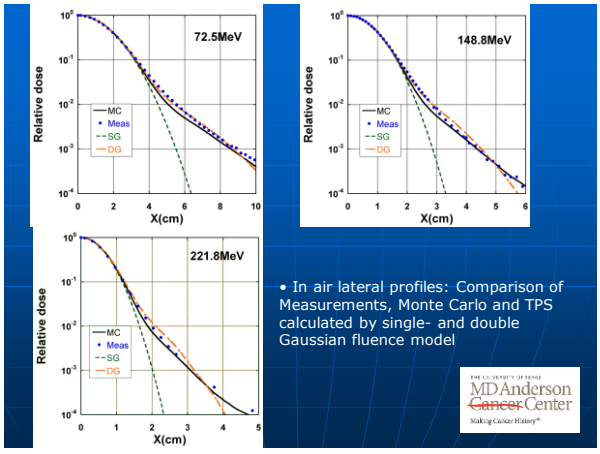
- Parameters were initially determined fitting input data to analytical formula
- Adjusted based on field size factors



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

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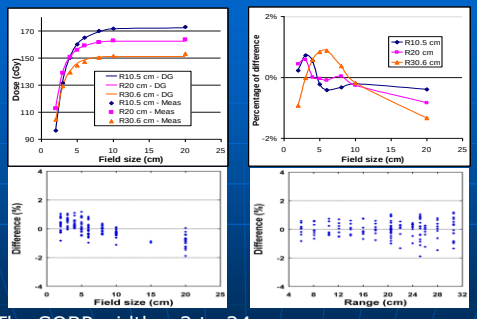
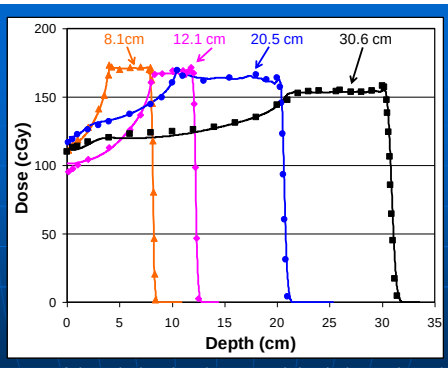
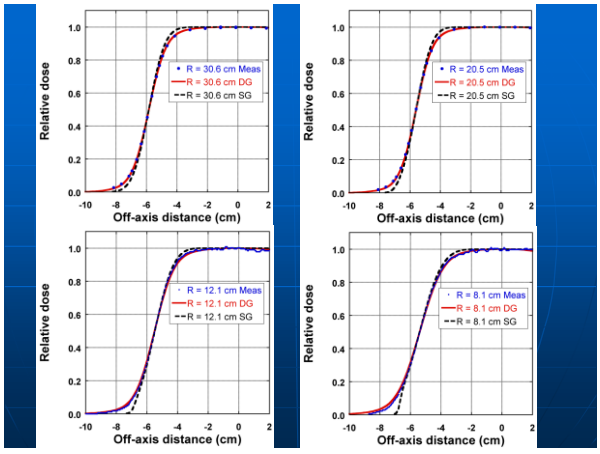
Dose at the center of SOBP

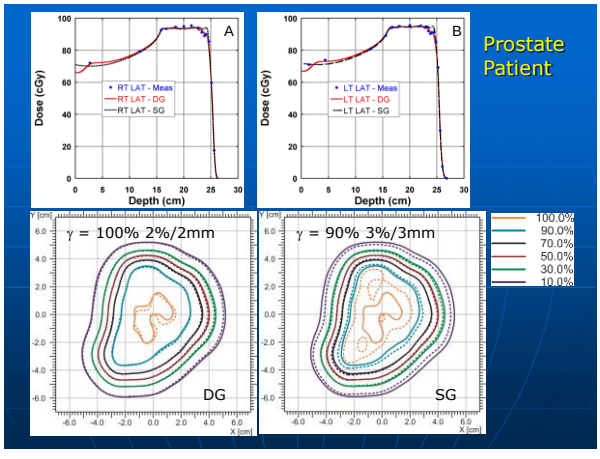


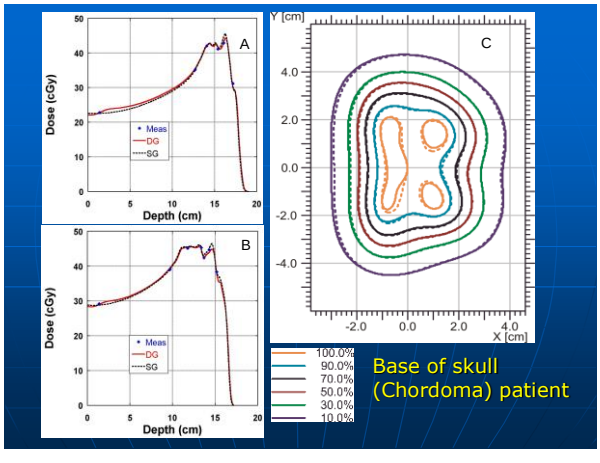
The SOBP widths: 2 to 24 cm.
Avg ± Stdev = 0.0% ±0.6% (range, -1.9% to 1.2%)



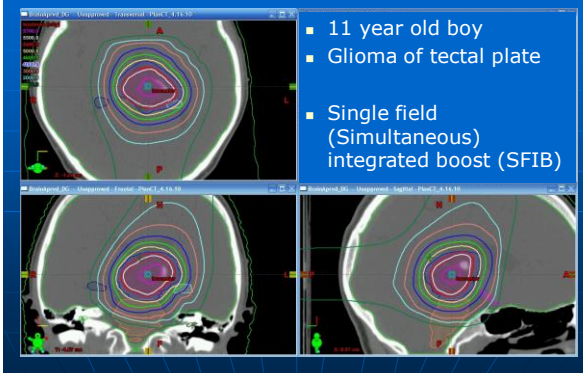
Comparison of the calculated and measured depth doses along the central axis of proton fields with the field size of 10 cm × 10 cm, different proton ranges and an SOBP width of 10 or 4 cm.


Relative dose
Off-axis distance (cm)
R = 30.6 cm Meas
R = 30.6 cm DG
R = 30.6 cm SG
R = 20.5 cm Meas
R = 20.5 cm DG
R = 20.5 cm SG
R = 12.1 cm Meas
R = 12.1 cm DG
R = 12.1 cm SG
R = 8.1 cm Meas
R = 8.1 cm DG
R = 8.1 cm SG

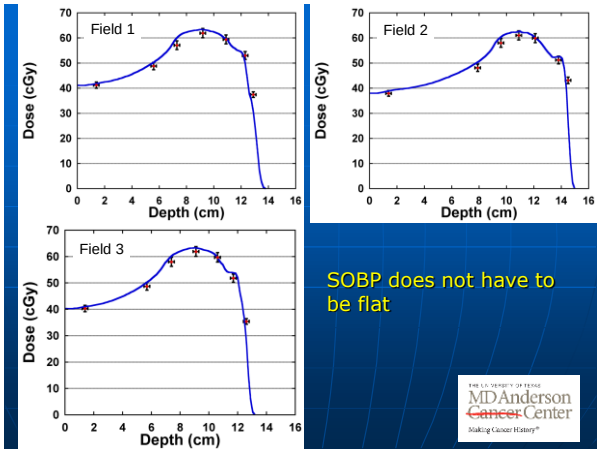

A
B
Dose (cGy)
Depth (cm)
RT LAT - Meas
RT LAT - DG
RT LAT - SG
LT LAT - Meas
LT LAT - DG
LT LAT - SG
Prostate Patient
γ = 100% 2%/2mm
γ = 90% 3%/3mm
DG
SG
100.0%
90.0%
70.0%
50.0%
30.0%
10.0%


A
B
C
Dose (cGy)
Depth (cm)
Meas
DG
SG
Y [cm]
X [cm]
100.0%
90.0%
70.0%
50.0%
30.0%
10.0%
Base of skull (Chordoma) patient

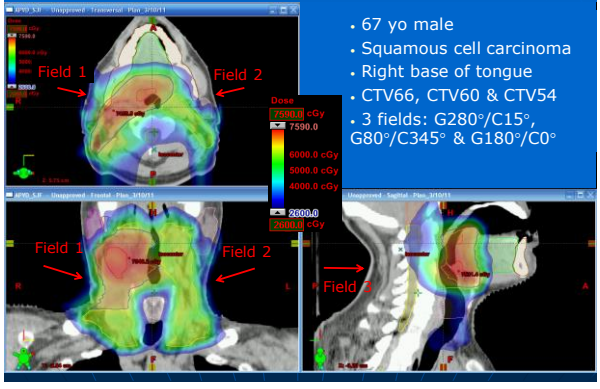
Brain - SFIB



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

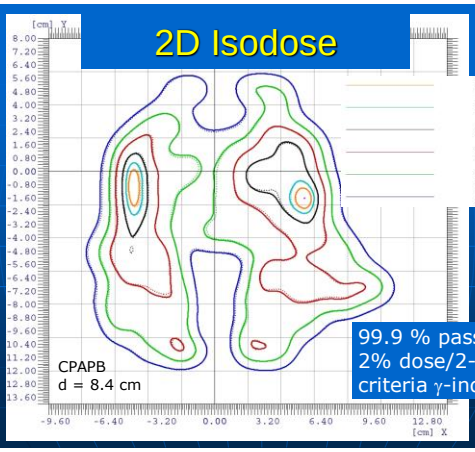


Head & Neck – MFO/IMPT



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

2D Isodose



It is not perfect

- Commissioning will not exhaustively test all clinical scenarios
- Patient specific 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±0.6%

Mackin *et al*. (to be submitted)

Summary

- The current dose models for IMPT available in clinical practice are pencil beam algorithms.
- Accurately modeling the low dose envelope due to nuclear reaction is one of the most important elements during commissioning
- Pencil beam models are not perfect – better dose calculation models or techniques such Monte Carlo simulation are desirable
- Patient specific QA should include dose measurements to continue validating the dose model.

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Many others

Thank you!

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