Radiation Dosimetry of Proton Beams

Narayan Sahoo
Department of Radiation Physics
University of Texas MD Anderson Cancer Center
Proton Therapy Center
Houston, USA

THE UNIVERSITY OF TEXAS MD Anderson Cancer Center
Making Cancer History

What I plan to talk

- Detectors used for to determine absorbed dose
- Dosimetry under reference condition
- Dosimetry under non-reference condition
- Detector size effects
- Patient treatment field dose verification
- Future developments
- Summary

Detectors for absorbed dose measurements

Same detectors used for photon and electron beam dosimetry are used for protons

Reference or absolute dose measurement

Calorimeter
Ion Chamber
Faraday Cup- Fluence based calibration

Detectors for absorbed dose measurements

Relative dosimetry

Ion chambers
Films
Solid State Detectors: TLD, Diodes, Diamond detectors, OSLD, Scintillation plates
Liquid Scintillators
Gel dosimeters

Problems for protons: LET dependence

Reviewed in Karger *et al*, PMB, 55 (2010) R193-R234

Dosimetry under reference conditions

- Reference condition to minimize uncertainties
- Dose standard should be traceable to primary standard (PSDL or SSDL)
- No primary standard exists for proton beams
- Calorimetry based standards are being developed

Calorimeter based standards

If a material of known specific heat (C) is irradiated in adiabatic condition, the absorbed energy is converted to heat and the temperature of the material will increase by ΔT, then

$$\text{Dose} = 4.186 * C * \Delta T$$

Calorimeter based standards

Simple in theory, difficult in practice

Limitations

- Difficulty in measuring small temperature change 2 Gy, $\Delta T = 0.5$ mK,
- For less than 0.5% uncertainties, $\Delta T = 0.25\ \mu K$
- Uncertainties in thermistor calibration
- Corrections for deviation from adiabatic condition
- Existence of thermal defect- part of energy does not appear as heat
- Non-tissue equivalence of the core material
- Proton beam related limitations-high dose gradient and dynamics of the dose delivery

Ion chamber based reference dosimetry

- Most widely used in practice
- TRS – 398 protocol from IAEA is the latest protocol
- Similar to TG-51 for photons and electrons
- ICRU-59 protocol is still used at some centers, similar to TG-21
- Updated in ICRU-78 (2008), it has adopted TRS-398

Ion chamber based reference dosimetry

- Measure charge generated in ion chamber (IC)
- Convert charge to dose through IC dose to water calibration coefficient from ADCL

$$D_{w,Q} = M_{corr} \cdot N_{D,W} \cdot K_Q$$

$N_{D,w}$ is Co-60 Water calibration factor for the IC
K_Q is for the specific chamber and calibrated beam

Annual calibration with ADCL calibrated chamber
Daily/weekly/monthly checks with a IC cross-calibrated with an ADCL calibrated IC

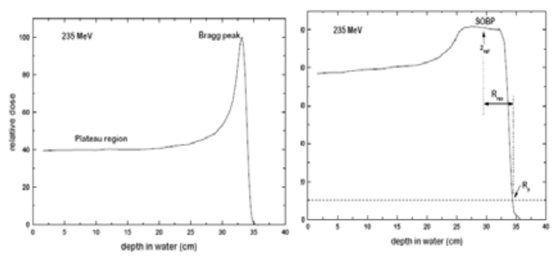
Reference condition for IAEA TRS-398 calibration

TABLE 10.II. REFERENCE CONDITIONS FOR THE DETERMINATION OF ABSORBED DOSE IN PROTON BEAMS

Influence quantity	Reference value or reference characteristics
Phantom material	water
Chamber type	for $R_{res} \geq 0.5$ g cm^{-2}, cylindrical and plane-parallel.
	for $R_{res} < 0.5$ g cm^{-2}, plane-parallel.
Measurement depth z_{ref}	middle of the SOBP [a]
Reference point of chamber	for plane-parallel chambers, on the inner surface of the window at its centre. For cylindrical chambers, on the central axis at the centre of the cavity volume
Position of reference point of chamber	for plane-parallel and cylindrical chambers, at the measurement depth z_{ref}.
SSD	clinical treatment distance
Field size at the phantom surface	10 cm x 10 cm, or that used for normalization of the output factors whichever is larger. For small field applications (i.e. eye treatments), 10 cm x 10 cm or the largest field clinically available

[a] The reference depth can be chosen in the "plateau region", at a depth of 3 g cm^{-2}, for clinical applications with a mono-energetic proton beam (e.g. for plateau irradiations).

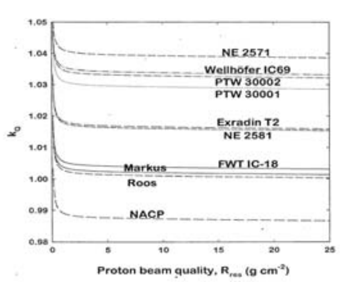
Beam Quality Specification



$R_{res} = R_p - z$

From IAEA TRS 398

K_Q values for some ion chambers



Calculated values of k_Q for various cylindrical and plan-parallel ionization chambers commonly used for reference dosimetry, as a function of proton beam quality Q (R_{res}).

From IAEA TRS 398

Fluence based reference dosimetry

$$D_w(z) = \phi \cdot \frac{S_w(z)}{\rho_w}.$$

From: Karger *et al*, PMB, 55 (2010) R193-R234

Needs determination of the incident particle fluence (ϕ) and knowledge of the collision stopping power in water

S_w is known within 2%

Fluence can be measured by Faraday Cup or Sample Activation

Reference: Grussel *et al*, Phys. Med. Biol. 40, 1831-1840 (1995)

Uncertainties in reference dosimetry

- Water calorimetry: 0.6 %
- Graphite calorimetry: 1.4%
- Ion chamber: 2.3%
- Faraday cup: 2.3%
- Activation based dosimetry: 3.5%

From: Karger et al, PMB, 55 (2010) R193-R234

At PTCH, ADCL calibrated ion chamber for reference dosimetry

At PSI, Faraday cup is used to determine the number of protons per MU, but ion chamber is used to determine the dose under reference condition

Dosimetry under non-reference (NR) conditions

For scattered broad beam,

(Dose/MU)NR = (Dose/MU)R . ROF. SOBPF. RSF. PDD. ISF. PSF. CSF. FSF.OAF

N. Sahoo *et al*, Med. Phys., 35 (2008) 5088-5097

For proton pencil beam spots (PPBS)

(Dose) NR = Sum of each spot dose at the point of interest

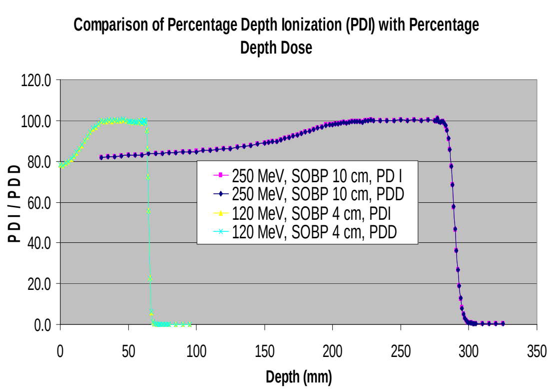
Central axis depth dose curves and lateral profiles are needed to determine dose under NR conditions

For PPBS, integral depth dose (IDD) is used in currently available commercial TPS for beam modeling

- either measured with a large diameter chamber like PTW BPC or simulated for a large area chamber

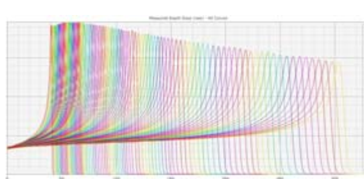
IAEA 398 10.6.1
Central Axis (CA) depth dose distributions

- Usually a water tank scanning system is used to measure depth dose distribution
- The use of plane-parallel chambers is recommended
- The depth-ionization distribution must be converted to a depth-dose distribution
- Perturbation factors are assumed to have a value of unity
- Multi layer ionization chambers are useful for quick checks



IDD for PPBS-Monte Carlo simulation

- Monte Carlo simulated data (Uwe Titt, Ph.D.) are used as input data for the our Eclipse TPS
  - Validated with BPC measurement
  - Integrated depth doses are in MeV/cm^3 and need to be converted to Gy/MUmm^2



Lateral fluence and dose profiles

Small Ionization chambers like PTW Pinpoint

Ion chamber arrays – limited spatial resolution

Diode arrays - may need frequent calibration

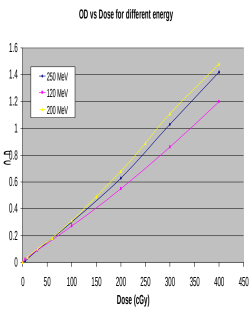
Film

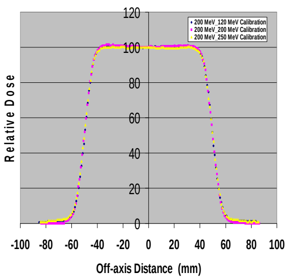
OSLD

OSLD and EBT Film would be useful for mail-in phantom dose verification

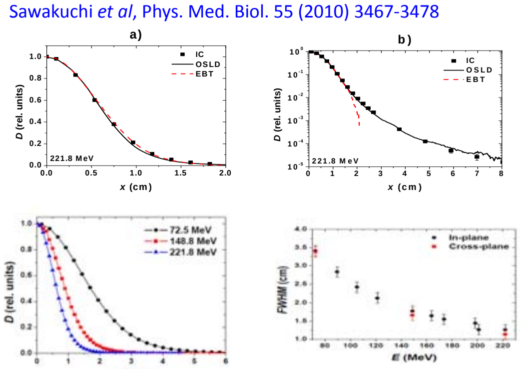
Scintillation plate / screen with CCD camera

Profile with EDR-2
Film Calibration at the center of SOBP





In air profiles. MT Gillin *et al*, Medical Phys. 37 (2010), 154-163, Sawakuchi *et al*, Phys. Med. Biol. 55 (2010) 3467-3478



Detector size effect on spot profiles

- An analytical deconvolution method shows that the detector size has a rather small effect.
- This may be a consequence of the small second gradient of the lateral profile function in most of the region beyond the peak of the Gaussian like functions.

N. Sahoo *et al*, Medical Phys. 37 (2010) 3293 (abstract)

Effect of detector size on IDD

BPC has limited size (r=4.08 cm)
BPC measured IDD may need correction for missing long tail contribution (Halo dose)

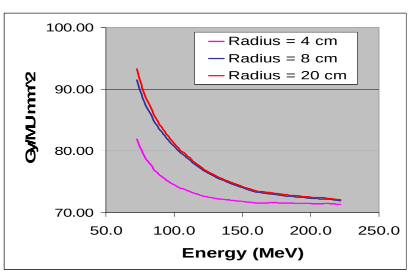
Correction factor (CF) = Calculated IDD / BPC measured IDD

$$IDD(d) = D_o \int_0^{2\pi} \int_{-\infty}^{\infty} f(r,\theta)\, r\, dr\, d\theta$$

The CF for BPC measured IDD ranged from 1.01 to 1.11, being higher for the lower energy PPBS, which have longer tails in the profiles.
Anand *et al*, Med. Phys. 39 (2012), 891-900.
Values agrees with Monte –Carlo Data

PISD or IDD Gy/MUmm^2 at 2.0 cm

- Gy/MU at 2.0 cm, converted Gy/MUmm^2



MT Gillin *et al*, Medical Phys. 37 (2010), 154-163

PSI method to determine halo dose

Pedroni *et al*, Phys. Med. Biol. **50** (2005) 541–561

$$D(x,y,w) = T(w)\times\left(\left(1-f_{NI}(w)\right)\times G_2^{P}(x,y,\sigma_P(w)) + f_{NI}(w)\times G_2^{NI}(x,y,\sigma_{NI}(w))\right)$$

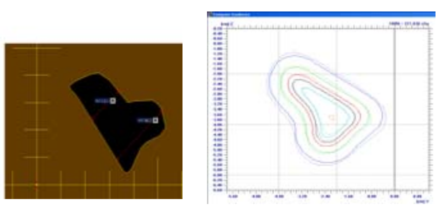
f_{NI} (w) and $\sigma_{NI}(w)$ were determined by matching calculated and measured dose at the center of concentric square fields created by the superposition of pencil beams represented by the empirical dose function.

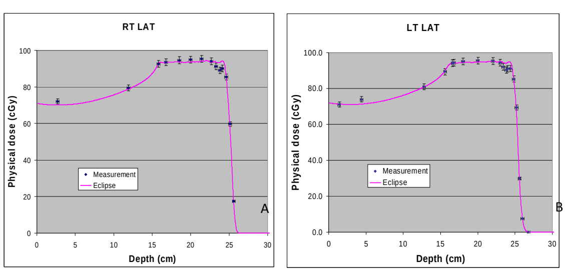
Halo dose contribution was found to be as much as 14% for 214 MeV beam at 20 cm depth.

Patient treatment field dose verification

1. Point dose measurement with ion chamber
2. Depth dose measurement with ion chamber or MLIC
3. Planar dose distribution measurement with ion chamber chamber array or film or other 2-D detectors

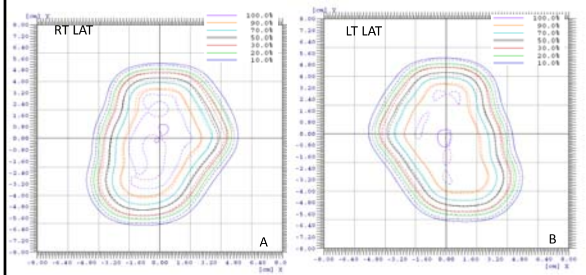
2-D dose distribution curves for a scattered beam treatment field





Depth dose curves for prostate treatment fields- scanning proton beam

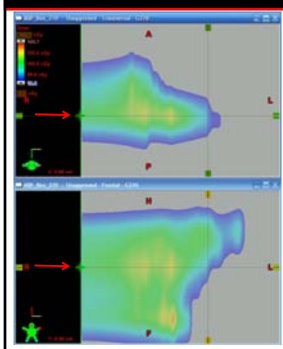
X. R. Zhu *et al*, Int. J. Radiat. Oncol. Biol. Phys. 81 (2011) 552-559

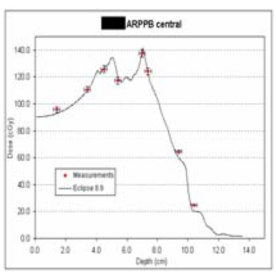


2-D dose distribution for prostate treatment fields- scanning proton beam

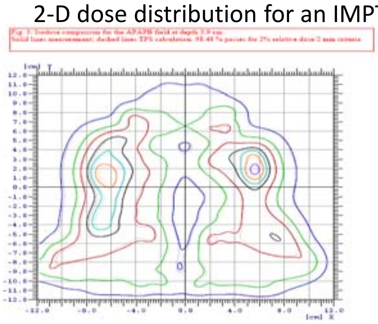
X. R. Zhu *et al*, Int. J. Radiat. Oncol. Biol. Phys. 81 (2011) 552-559

MFO - Field 1 Depth Dose





2-D dose distribution for an IMPT field



2-D dose verification is also done with CCD camera systems

Pedroni *et al*, Phys. Med. Biol. **50** (2005) 541–561

Future developments-3D Dosimetry

PRESAGE® cuvettes
T Gorjiara *et al*, Journal of Physics: Conference Series 444 (2013) 012058

Gel dosimeters
Zeidan *et al*, Med. Phys. 37 (2010) 2145-52

Liquid scintillator with CCD camera
Beddar *et al*, Med. Phys. 36 (2009) 1736-1743

Summary

- Ion Chambers or ion chamber arrays are the detectors of choice
- Other dosimetry systems like EBT film, TLD, OSLD are useful in many situations, especially for small fields and for mail-in phantom dose verification
- Choice depends on the measured quantity and required precision
- All dosimeters need proper characterization
- 3-D dosimetry and dose verification in inhomogeneous phantoms need to be explored
- Dosimetry quality assurance is important, but requires substantial time and manpower

Acknowledgements

All the physicists from our department who have contributed to our proton therapy dosimetry and QA efforts

Radiation Oncologists for their support

Hitachi engineers for their support

Proton Physics Fellows: past and present

Physics Assistants

Postdoctoral Fellows who were / are involved in proton therapy related projects

All Physics Residents: past and present

UTGSBS Medical Physics Graduate students who were / are involved in proton therapy related projects,

Proton Therapy Center-Houston

Thank you very much for listening