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Radiation Dosimetry for Proton Therapy

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Topics covered

- 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

All the detectors used for photon and electron beam dosimetry can used for protons. A large area ionization chamber is used to measure integral depth dose of proton pencil beam spots.

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, possibility of radiation damage for solid state detectors

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, ΔT = 0.5 mK,
- For less than 0.5% uncertainties, ΔT = 0.25 μK
- 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

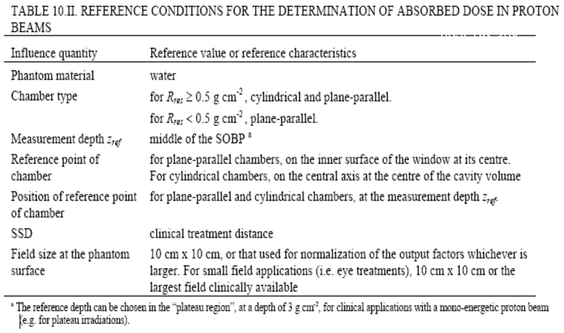
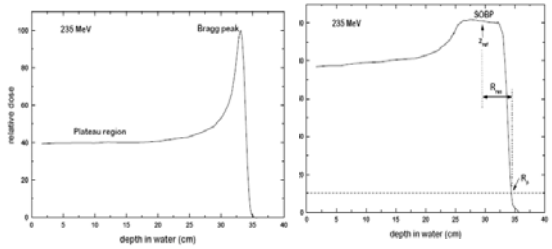


TABLE 10.II. REFERENCE CONDITIONS FOR THE DETERMINATION OF ABSORBED DOSE IN PROTON BEAMS

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).

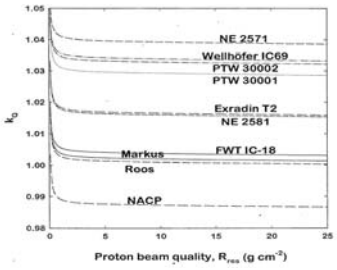
Beam Quality Specification



$R_{res} = R_p - z$

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

Some measurement tools

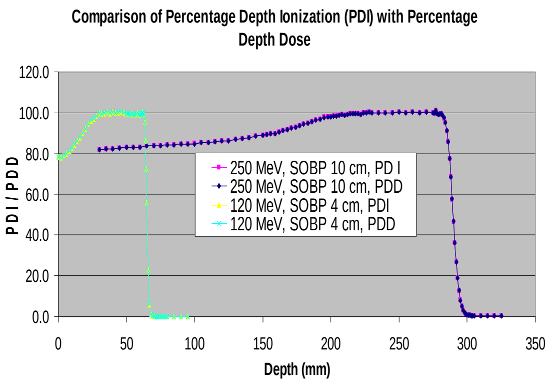
- Water tank scanning system
- Ion chambers of different sizes and shapes
- Large area ion chambers for IDD measurement
- Multilayer ion chamber arrays for fast depth dose measurements
- 2-D ion chamber arrays
- Scintillation screen and films for high resolution dosimetry
- Available from commercial vendors

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

Depth dose measurements with ionization chambers

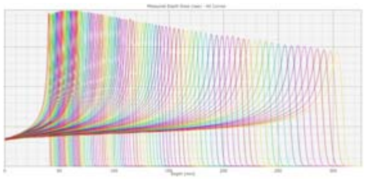
- Values for the stopping power ratio as a function of R_{res} can be calculated from:
- $S_{w/air} = a + b R_{res} + c / R_{res}$
- $a = 1.137$, $b = 4.3 \times 10^{-5}$, $c = 1.84 \times 10^{-3}$
- If the field size is < the 2d of the plane-parallel chamber, then a smaller detector like mini-chamber, diode or diamond is recommended with appropriate conversion factors for stopping power ratios
- Each detector should be tested by comparing with PP chamber



IDD for PPBS-Monte Carlo simulation

Monte Carlo simulated data are useful as input data for the 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

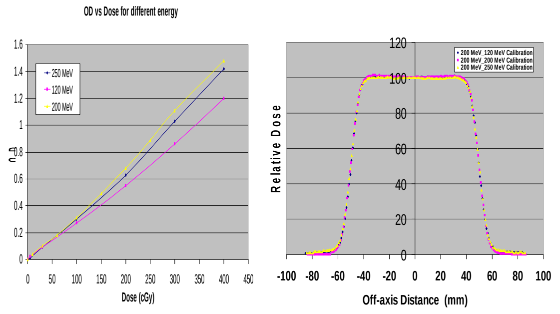
Small Ionization chambers like PTW Pinpoint

Ion chamber arrays – limited spatial resolution
Diode arrays - may need frequent calibration
Film

Scintillation plate / screen with CCD camera
OSLD strips

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

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)

Low dose envelope or halo dose

Pencil beam spot profiles has long low dose tails

- Large angle scattering in the beam line components and irradiation media
- Dose deposition at large distance from the central axis by the secondary particles created by nuclear interaction in the irradiation media

Sawakuchi et al., Phys. Med. Biol. 55(2010) 711-721.

This low dose envelope is difficult:

- to measure,
- to model by a single Gaussian function.

One or more Gaussian functions are used to account for the halo component.

PSI method to determine halo dose

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

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

f_{NI} (w) and $\sigma_{\mathrm{NI}}(w)$ 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.

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

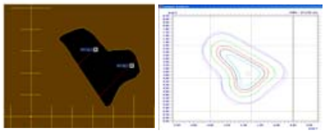
MT Gillin *et al*, Medical Phys. 37 (2010), 154-163

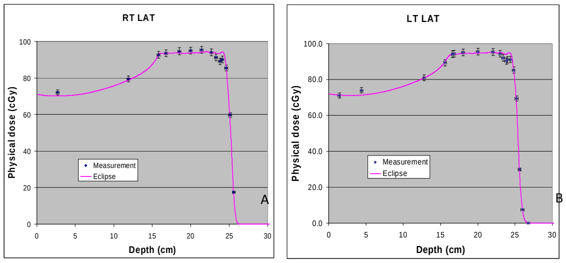
Patient treatment field dose verification

Goal: QA program ensures *that the planned dose would be delivered within established tolerance*.

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

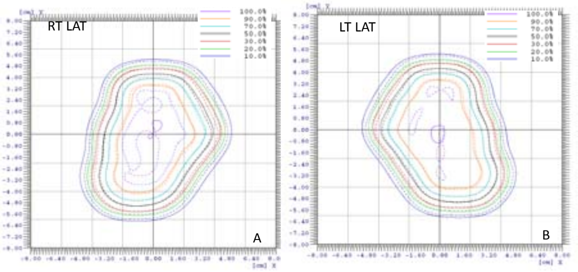
2-D dose distribution curves for a scattered beam treatment field





Depth dose curves for prostate treatment fields- scanning proton beam

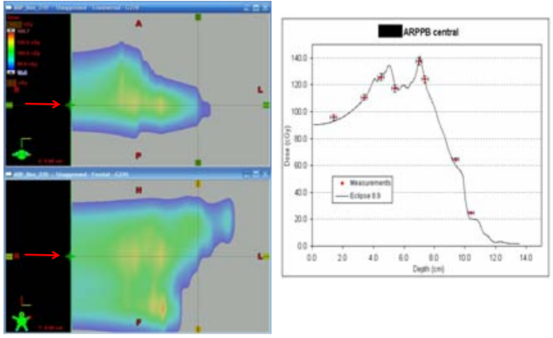
X. R. Zhu *et al*, Int. J. Radiat. Oncol. Biol. Phys. 81 (2011) 552-559



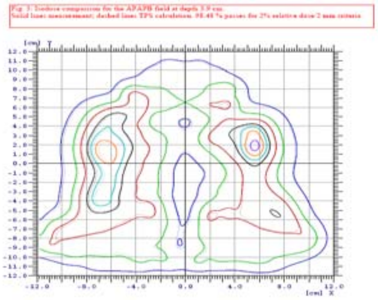
2-D dose distribution for prostate treatment fields- scanning proton beam

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

MFO - Field 1 Depth Dose

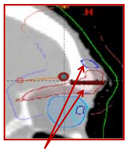


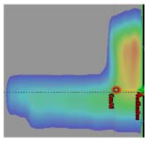
2-D dose distribution for an IMPT field

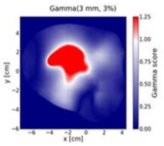


2-D dose verification done with a 2-D ion chamber array

Comparison of 2-D dose distribution of a complex IMPT field measured with scintillation plate and CCD camera
Pedroni *et al*, Phys. Med. Biol. **50** (2005) 541–561


Target


Field dose



Depth of calculation (cm)	Depth of measurement (cm)	% of pixels passing the 3%/3mm Dose/distance agreement criteria
2	2	87.2
1.95	2	100

Multiple ion chambers used for dose verification of scanned heavy ion beam at GSI, Darmstadt, Christian P. Karger et al, Med. Phys. 26, 2125 (1999)

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

Future developments-3D Dosimetry

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

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

PRESAGE® cuvettes irradiated to different doses

Summary

- Ion Chambers or ion chamber arrays are the detectors of choice
- Other dosimetry systems like EBT film, TLD, diode, OSLD, Scintillator plates are useful in many situations and for fast dose measurements
- 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

Proton Therapy Center-Houston

Thank you very much for listening