Dosimetry aspects of proton radiotherapy

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Content

- Introduction
- Reference dosimetry for proton beams
  Methods, detectors, protocols
- Dosimetry in non-reference conditions for proton beams
  Methods, detectors
- Recommendations

About 25 treatment facilities are established
another 20 proton and light-ion centers are planned to be open in 5 years

Typical layout of charged-particle beam radiotherapy facility
Main clinical applications for proton beams

- Treatment of large or deep seated tumours
- Treatment of ocular tumours
- Stereotactic radiosurgery (cross-fire technique)

Consistent and harmonized dosimetry guidelines

- Accurate beam calibration
- Ensure exact delivery of prescribed dose
- Perform planning of high-precision conformal therapy
- Provide interchange of clinical experience and treatment protocols between facilities
- Provide standardization of dosimetry in radiobiology experiments

Dosimetry tasks in proton radiotherapy

- Acceptance testing and commissioning of treatment beam lines
- Commissioning of treatment planning system
- Periodic checks
- Verification of dose delivery

Reference dosimetry

- Basic output calibration of a clinical beam, is a direct determination of dose or dose rate in water under specific reference conditions, that is referred to as: Reference dosimetry.
- Reference dosimetry techniques for clinical proton beams:
  - Calorimetry
  - Faraday Cup
  - Ionization chamber dosimetry
Absorbed dose determination in reference conditions for charged-particle beams

Lack of national and international dosimetry standards

Faraday Cup

Calorimeter

Absorbed dose determination in reference conditions for charged-particle beams

TG 20 Protocol for charged-particle therapy beam dosimetry

Reference instruments
- Faraday cup
- calorimeter

Ion chamber dosimetry
- A-150 walled with Nx calibration
- No beam quality specifier
- \( S/\rho \) for plateau and peak only

AAPM TG 20
ECHED

ECHED Suppl.
ICRU 59
IAEA TRS 398

TG 20 Protocol for charged-particle therapy beam dosimetry

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FC-based calibration of the ionization chamber

\[ D_w = \left( \frac{N}{A} \right) \left( \frac{S}{\rho} \right)_w \times 1.602 \times 10^{-10} \]

N: number of protons per MU collected in the FC
A: effective area of the beam
\( (S/\rho)_w \): stopping power for water at the incident proton energy

FC-based calibration at HCL
FC-based calibration of the ionization chamber at LLUMC

\[
D_x(Q, FC) = \frac{N}{A} \times (S/p) \times 1.602 \times 10^{-10}
\]

\[
N_{D_x, FC} = \frac{D_x(Q, FC)}{M_{corr}}
\]

Calorimetry-based calibration of the ionization chamber

- Calorimetry is the most fundamental of the three reference dosimetry techniques, since it relies on basic definition of either electrical energy or temperature.
  - In principle, calorimetric dosimetry is simple.
  - In practice, calorimetric dosimetry is very complex because of the need for measuring extremely small temperature differences.

Main characteristics of calorimetry dosimetry:

- Energy imparted to matter by radiation causes an increase in temperature \( \Delta T \).
- Dose absorbed in the sensitive volume is proportional to \( \Delta T \).
- \( \Delta T \) is measured with thermocouples or thermistors.
- Calorimetric dosimetry is the most precise of all absolute dosimetry techniques.
Calorimetry-based calibration of the ionization chamber

- Two types of absorbed dose calorimeter are used in charged particle beams:
  
  In graphite calorimeters the average temperature rise is measured in a graphite body that is thermally insulated from surrounding bodies (jackets) by evacuated vacuum gaps.

Calorimetry-based calibration of the ionization chamber

In sealed water calorimeters low thermal diffusivity of water enables the temperature rise to be measured directly at a point in continuous water.
### Water calorimeter measurements in 250 MeV proton beam at LLUMC

- **Water Calorimeter**

### Ionization chamber measurements (dummy calorimeter) in 250 MeV proton beam

- **Dummy calorimeter with IC**

### Experimental calorimetry to ionometry ratios for clinical proton beams

<table>
<thead>
<tr>
<th>Energy, MeV</th>
<th>$D_{\text{water}} / D_{\text{ion}}$</th>
<th>CoP</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.99±0.01</td>
<td>TG 20</td>
</tr>
<tr>
<td>180</td>
<td>0.978±0.005</td>
<td>ECHED</td>
</tr>
<tr>
<td>85</td>
<td>0.974±0.008</td>
<td>ECHED</td>
</tr>
<tr>
<td>33-186</td>
<td>0.985±0.007</td>
<td>ECHED</td>
</tr>
</tbody>
</table>

### Absorbed dose determination in reference conditions for charged-particle beams

- **Faraday Cup**
- **Calorimeter**

Lack of national and international dosimetry standards

- **Thimble air-filled ionization chamber**

- **AAPM TG 20 ECHED**
- **ECHED Suppl. ICRU 59 IAEA TRS 398**
A dosimetry protocol provides the formalism and the data to relate a calibration of an ionization chamber at a standards laboratory to the measurement of absorbed dose to water under reference conditions in the clinical beam.

Two types of dosimetry protocol are currently in use:
- Protocols based on air kerma in air calibration coefficients.
- Protocols based on absorbed dose to water calibration coefficients.

Both cylindrical and plane-parallel chambers are recommended for reference dosimetry. Plane-parallel chambers yield higher \( \Delta D_w \) in absolute \( D_w \), though are better suited for relative dosimetry. Cylindrical chambers recommended for \( \text{SOBP width} \geq 2 \text{ cm} \).

For \( \text{SOBP widths} < 2 \text{ cm} \), plane-parallel chambers must be used.

Versatile electrometer with cable and connectors fitting to the electrometer and all chambers, thermometer, barometer.
Water phantoms for reference dosimetry

Water is the only standard and most universal phantom material for proton dosimetry measurements.

Reference geometry for proton beam calibration (passive beam modulation)

Basic formalisms used in ion chamber dosimetry of clinical proton beams

Air kerma – based

Absorbed dose to water – based

Air filled ionization chamber is considered as a Bragg-Gray cavity

Contributions to ionization by charged particles other than protons is neglected

A robust system of $D_w$ standards

Ionization method

Calorimetric method

Graphite

Chemical method

Calorimetric method

Water
Steps in the determination of $D_w$ at the reference point using $N_{w,N_{D,w\text{-air}}}$ formalism and $N_{D,w\text{-formalism}}$

1. $K_{w,Q_0} = \frac{K_{w,Q_0}}{M_{Q_0}}$  
   $D_{w,Q_0}$

2. $N_{k,Q_0} = \frac{N_{k,Q_0}}{M_{Q_0}}$  
   $N_{D,w,Q_0} = \frac{D_{w,Q_0}}{M_{Q_0}}$

3. $N_{D,w,Q_0} = \frac{D_{w,Q_0}}{M_{Q_0}} = \frac{N_{D,w,Q_0}}{k_{w,Q_0}} = \frac{k_{w,Q_0}}{k_{w,Q_0}}$

4. $D_{w,Q_0} = N_{D,w,Q_0}$

5. $D_{w,Q} = \frac{D_{w,Q_0}}{k_{w,Q_0}}$

6. $D_{w,Q} = M_{Q} N_{D,w,Q_0} k_{Q_0,Q_0}$

$I_{\text{air}} = \frac{I_{\text{air}}}{I_{\text{air}}} = \frac{I_{\text{air}}}{I_{\text{air}}}$

$Lack of standards for proton dosimetry \Rightarrow Q_0 = ^{60}\text{Co}$

$kQ = \left(\frac{S_{w,\text{air}}}{S_{w,\text{air}}}\right)_{Q} \left(\frac{W_{\text{air}}}{W_{\text{air}}}\right)_{Q} \frac{P_Q}{P_{Q_{\text{air}}}}$

\[ P_Q = P_{\text{ind}} P_{\text{mul}} P_{\text{ind}} P_{\text{col}} \]

\[ \approx 1 \text{ for protons} \]

\[ \neq 1 \text{ for } ^{60}\text{Co} \]

Tabulated values of proton beam quality correction factors for various ionization chambers are given in TRS 398

$I_{\text{air}} = \frac{I_{\text{air}}}{I_{\text{air}}}$

$N_{D,w\text{-based formalism - IAEA TRS-398}}$

$D_w(z_{\text{ref}}) \text{ at any user quality } Q$

(photons, electrons, protons, heavier particles)

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

Corrected instrument reading at $Q$  

Calibration coefficient at $Q_0$

Beam quality factor

$Lack of standards for proton dosimetry \Rightarrow Q_0 = ^{60}\text{Co}$

$kQ = \left(\frac{S_{w,\text{air}}}{S_{w,\text{air}}}\right)_{Q} \left(\frac{W_{\text{air}}}{W_{\text{air}}}\right)_{Q} \frac{P_Q}{P_{Q_{\text{air}}}}$

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$I_{\text{air}} = \frac{I_{\text{air}}}{I_{\text{air}}}$

$Stopping powers for for proton beams$

TRS 398

- Basic proton stopping powers from ICRU 49
- Calculation using MC code PETRA following Spencer-Attix cavity theory
- Transport included secondary electrons and nuclear inelastic process
Comparison of stopping power ratios, $s_{w,\text{air}}$, for proton dosimetry: ICRU-59 versus IAEA TRS-398

Comparison of $W_{\text{air}}/e$ for proton beam dosimetry: ICRU-59 versus IAEA TRS-398

Standard uncertainties in $D_w$

- Co-60 gamma-rays: 0.9
- High-energy photons: 1.5
- High-energy electrons: 1.4-2.1
- Low energy X-rays: 2.2-4.0
- Medium energy X-rays: 1.9-3.4
- Proton beams: 2.0-2.3
- Heavy ions: 3.0

Comparison results from measurements in a 155 MeV clinical proton beam
Main features of current CoPs for dosimetry of clinical proton beams

<table>
<thead>
<tr>
<th>ICRU 59</th>
<th>TRS 398</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle type</td>
<td>Protons</td>
</tr>
<tr>
<td>Phantom material</td>
<td>water</td>
</tr>
<tr>
<td>Reference dosimeter</td>
<td>IC thimble</td>
</tr>
<tr>
<td>Calibration quality</td>
<td>Co-60 beam</td>
</tr>
<tr>
<td>IC calibration Factor</td>
<td>$N_X$, $N_k$, $N_{wa}$</td>
</tr>
</tbody>
</table>


- Recommendations and guidelines of IAEA TRS 398
- $w_{air}$ and $(S/\rho)_{w,air}$ are established as in TRS 398
- Additional recommendations for scanned beams

$(w_{air}/e)_p$ as determined from calorimetry measurements in clinical proton beams

- Delacroix et al., 1997
- Palmans et al., 2004
- Palmans et al., 1996
- Hashemian et al., 2003
- Siebers et al., 1995
- Schulz et al., 1992
- Brede et al., 2006
- Medin et al., 2006

34.2 J°C⁻¹
• TRS-398 needs to be extended by explicit recommendations for the beam monitor calibration and dose verification in charged-particle beams.

• These recommendations should then distinguish systems using static and dynamic beams.

• This would ultimately lead to a dosimetry system, where the dose applied to a patient is traceable to the dosimetry standards of the national PSDL.
Guidelines for absorbed dose determination in reference conditions for charge-particle beams

- Large and small fields: high-energy proton and ion beams
- Small fields: low energy proton beams
- Narrow beams for stereotactic radiosurgery: Cross-fire technique

Dosimetry in non-reference conditions

Relative dose measurements require no detector calibration other than verification of linearity of response within assumed dynamic range of measurement conditions

- Routine daily clinical physics activity
- Beam line commissioning
- Collecting data for TPS
- Periodic QA
  - Beam characteristics
    - Depth dose
    - Lateral profiles
    - Output factors

Detectors for measurements in non-reference conditions in clinical proton beams

For ionometric and film measurements a polystyrene or water equivalent plastic phantom is convenient.

Plastic phantoms

For ionometric and film measurements a polystyrene or water equivalent plastic phantom is convenient.
Plastic phantoms for ionization chambers

A second block should be machined to place the entrance window of a parallel plate chamber at the level of one surface of the block. This arrangement allows measurements with the parallel plate chamber with no material between the window and the radiation beam.

Plastic phantoms for ionization chambers

One block should be drilled to accommodate an ionization chamber with the center of the hole, 1 cm from one surface.

Diodes for characterization of small proton beams

• Because of their small size silicon diodes are convenient for profile measurements and characterization of small proton beams.

• Note: The response of diodes must always be checked against ionometric measurements before use.
Characterization of small proton beams

126 MeV protons, collimator 30 mm, no modulation

Magic Cube: multi-wire ionization chamber

Alanine ESR dosimetry

Onori et al, 2000
**Alanine ESR dosimetry**

- **Pellets**
- **Films**

Onori et al, 2000

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**Two dimensional dosimetry with fluorescent screen and CCD camera**

Boon et al, 2000

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**Two dimensional dosimetry with fluorescent screen and CCD camera**

Rosenthal et al, 2004

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**2D TLD film for characterization of proton beams**

Olko et al, 2004
Imaging plate for depth dose measurements in proton beams

IP utilizes a photostimulable phosphor of BaFBr:Eu²⁺ and latent images are created by proton beam
Latent images are scanned by stimulating laser beam and are read as PSL

Radiochromic film for characterization of clinical proton beams

Radiochromic film is self-developing, requiring neither developer nor fixer

Principle:
Radiochromic film contains a special dye that is polymerized and develops a blue color upon exposure to radiation.
Radiochromic film dosimetry of proton beams

155 MeV, modulation 3 cm, normalized at 11 cm water equivalent depth, cm

Relative dose

Parallel plate ionization chamber
MD-55 film, 70 Gy

3D Gel dosimetry for characterization of proton beams

Heufelder et al., 2003

Current status of charged-particle dosimetry:

Implementation of IAEA TRS 398 and new ICRU Report

harmonize clinical dosimetry at charged-particle beam facilities

provide a level of accuracy comparable to that in calibration of photon and electron beams

Current status of charged-particle dosimetry:

Protons and ions:
- passive range modulation
- TRS 398 (center of SOBP)

Protons and ions:
- active range modulation
- TRS 398 (plateau region)

Protons and ions:
- radiosurgery (narrow beams)
- Special methods (MC)
**Take home message**

<table>
<thead>
<tr>
<th>Reference dosimetry</th>
<th>Dosimetry in non-reference conditions</th>
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<tbody>
<tr>
<td>• TRS 398</td>
<td>Depth dose</td>
</tr>
<tr>
<td>• ICRU xx 2007</td>
<td>• small volume ion chamber</td>
</tr>
<tr>
<td>• Ionization chamber</td>
<td>• other detectors can be used when</td>
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<tr>
<td>• Water phantom</td>
<td>the response was verified versus</td>
</tr>
<tr>
<td></td>
<td>ion chamber</td>
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<tr>
<td></td>
<td>• Water or Plastic phantoms</td>
</tr>
<tr>
<td></td>
<td>Lateral profiles</td>
</tr>
<tr>
<td></td>
<td>• Diode, diamond, CCD, TLD, film etc.</td>
</tr>
<tr>
<td></td>
<td>• Water or Plastic phantoms</td>
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</tbody>
</table>

**THANK YOU**