Active Scanning Beam 3
Checking Delivery/Dosimetry

C Algranati, J Salk, A Coray, A Lomax, E Pedroni, T Boeringer, S Lin, E Hug

Center for Proton Radiation Therapy
Contents

• Absolute Dose Measurements for Protons
  • Dosimetry Protocols
  • Monitor Calibration
• Machine Specific Checks and Dosimetry
• Patient Specific Dosimetry
• Summary
Absolute dose measurements

1954: LBL, Berkley, USA
1957: GWI, Uppsala, Sweden
1961: HCL, Cambridge, Boston, USA
1967: JINR, Dubna, Russia
1969: ITEP, Moscow, Russia
1975: PINP, St. Petersburg, Russia
1983: PMRC, Tsubaka, Japan
1986: AAPM Report 16 (TG 20)

Protocol for heavy charged particle therapy beam dosimetry
Absolute dose measurements

ICRU report 59 (1998):
- First *international* standard for clinical proton dosimetry
- Thimble ionisation chamber dosimetry protocol
- $^{60}$Co calibration in terms of air kerma or absorbed dose to water calibration coefficients
- Applies to protons only

IAEA TRS 398 (2000):
- Ionisation chamber dosimetry protocol
- Based on absorbed dose to water calibration coefficients
- Code of practice for photon, electron, protons, and ions


*Differences in absolute dose of up to 2.6% for clinical proton beams*

ICRU 78 (2007)
Ionisation chamber dosimetry according to TRS 398

Ionisation chambers

- Both cylindrical and plane parallel chambers are recommended
- Plane-parallel chambers yield higher uncertainty in absolute $D_w$, although better suited for relative dosimetry
- Cylindrical ionisation chambers recommended for SOBP lengths $\geq 2\text{cm}$
- Plane-parallel chambers **must** be used for SOBP lengths $< 2\text{ cm}$
- Many commercial systems available (usually not explicitly specified as proton chamber)
Ionisation chamber dosimetry according to TRS 398

Basic formalism used in ionisation chamber dosimetry

\[ D_{w,Q} = M_Q \times N_{D,w,Q_0} \times k_{Q,Q_0} \]

- **\( M_Q \)**: Instrument reading at users beam quality \( Q \), corrected for all influence quantities other than beam quality, e.g.:
  - \( k_{\text{elec}} \): calibration factor for electrometer
  - \( k_{pT} \): temperature and air pressure
  - \( k_S \): recombination losses

- **\( N_{D,w,Q_0} \)**: Absorbed dose to water calibration coefficient for calibration beam quality \( Q_0 \) ( = Co-60 )

- **\( k_{Q,Q_0} \)**: Beam quality factor to correct for effects of differences between calibration beam quality \( Q_0 \) and user beam quality \( Q \)

This applies to any user beam quality (photons, electrons, protons, ions)
Ionisation chamber dosimetry according to TRS 398

Basic formalism used in ionisation chamber dosimetry for proton beams

$$k_{Q,Q_o} = \frac{s_{w,air}^Q}{s_{w,air}^{Q_o}} \frac{W_{air}^Q}{W_{air}^{Q_o}} \frac{P_Q}{P_{Q_o}}$$

$$P_Q = P_{cav} P_{dis} P_{wall} P_{cel}$$

$$p_Q \approx 1$$ for protons

$$p_Q \neq 1$$ for $^{60}$Co

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Reference dosimetry for scanned proton beams at PSI

Faraday cup measurement:
- Determines number of incident particles in pencil beam
- Monitor calibration in terms of protons per MU

<table>
<thead>
<tr>
<th>Energy</th>
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<td>138 MeV</td>
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<td>160 MeV</td>
<td>7333</td>
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<tr>
<td>177 MeV</td>
<td>7921</td>
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Pencil beam dose model:
- Predicts absolute dose per incident proton
- \( D(x,y,z) = T(z) \times G(x, z, \sigma_x(z)) \times G(y, z, \sigma_y(z)) \)
- Integral depth dose \( T(z) \): based on first principles (Bethe-Bloch stopping power formula)
- Corrections for nuclear interactions (proton flux attenuation)
- total nuclear cross sections of protons in hydrogen and oxygen

Scheib S. “Spot-Scanning mit Protonen: Experimentelle Resultate und Therapieplanung” 1993, Diss. ETH Zürich Nr.10451
Reference dosimetry for scanned proton beams at PSI

**Faraday cup measurement**
Number of protons/MU

**Pencil beam dose model**
Predicts number of protons (or MU) needed to fill a 10x10x10 cm³ box with homogeneous dose of 1.0 Gy

**Apply scan to phantom**
Measure actual dose with certified thimble ionisation chamber following code of practice IAEA TR 398

**Compare predicted and measured dose**
Correction factors for MU calculations
Reference dosimetry for scanned proton beams at PSI

Proton Monitor Calibration
Ratio of Protons/MU, measured using Faraday Cup and Ionization Chamber

± 2%

Date

Ratio FC / IC
0.95 0.96 0.97 0.98 0.99 1.00 1.01 1.02 1.03 1.04 1.05

ICRU 59
IAEA, TRS398

138 MeV
160 MeV
177 MeV
Reference dosimetry for scanned proton beams at PSI

METAS

Develop primary standard for (scanned) proton beams based on water calorimetry with an uncertainty $\leq 1\%$ (D. Twerenbold)
Reference dosimetry for scanned proton beams at PSI

Range Shifter

Fast Degrader

MU chamber

always “sees” constant proton energy during beam delivery
MU calibration stays constant during beam delivery

patient

“sees” varying proton energies during beam delivery
MU calibration changes during beam delivery

patient
Reference dosimetry for scanned proton beams at PSI

Energy dependent monitor calibration

![Proton Monitor Calibration vs Energy](image1)

![K(E) vs E](image2)

PSI

HIT, Heidelberg

Courtesy, A. Coray, PSI

Oliver Jäkel et al., A calibration procedure for beam monitors in a scanned beam of heavy charged particles, Med. Phys. 31 (5), May 2004
Machine specific dosimetry

Daily check (pre-treatment QA)

• Prepare and check the scanning system before starting the daily patient treatments
• Takes place in the mornings
• Successful completion is a requirement for the patient irradiation
• Tasks can be finished in about 30 minutes
• Procedure consists of the following tests activities:
  • Devices setup (Lasers, offsets of monitor chambers, air pressure etc.)
  • Dosimetry check
  • Beam energy and position checks
  • Sweeper magnet and strip monitor test
  • Range shifter check
  • Safety interlock tests
Machine specific dosimetry

Daily check phantom

- PMMA phantom
- Rotatable
  → Alignment to various gantry angles
- Embedded ionisation chambers
  → Two cylindrical Exradin chambers for absolute dose measurements
  → One large parallel plate chamber (Ø 8 cm) for range measurement (range shifter scan)
- Scintillating foil (Lanex)
  → Visual check of pencil beam
- 5 x 5 mini-strip chamber
  → Phasespace measurement
Machine specific dosimetry

Daily monitor calibration test

- Measurement of the absolute dose in the center and at the distal falloff of a scanned cubic box of 6x6x6 cm³ size.
- The dose is measured using a 0.5 cm³ Exradin IC and a 0.05 cm³ Exradin IC.
- Tolerance in dose: ±3% in the center of the box.
Machine specific dosimetry

Daily range measurement

- Range shifter scan: insertion of range shifter plates
- Ionisation current measured with large parallel plate chamber
  - Ø 8 cm
  - Collection volume 30 cm$^3$
- Plotted against absorber material
- This results in the well known Bragg peak curve
Machine specific dosimetry

Daily range measurement (example for 177 MeV proton beam)

Compare nominal range with measured one
Check that the shape of the measured range curve coincides with the expected curve
Tolerance in range: ±2 mm
Machine specific dosimetry

Dose Deviations:
- 0.7 % ± 0.4%
- 0.5 % ± 0.5%
- 0.8 % ± 0.6%

Range Deviations:
- 1.1 mm ± 0.3 mm
- 0.6 mm ± 0.4 mm
- 0.4 mm ± 0.4 mm

Fig. 1: Results of the daily QA checks of absolute dose (a) and beam range (b). The measured doses for 138 MeV, 160 MeV and 177 MeV protons differ from the expected values by 0.7%, 0.5% and 0.8%, respectively, with standard deviations (SD) of 0.4%, 0.5% and 0.6%. The measured ranges differ from the nominal ranges by 1.1 mm, 0.6 mm and 0.4 mm with a SD of 0.3 mm, 0.4 mm and 0.4 mm.
Machine specific dosimetry

Beam position and width measurements

- Check of parallelism and width of the pencil beam along the longitudinal beam axis (S-axis)
- 5 by 5 ministrip chamber
- similar to strip monitor mounted in the gantry nozzle
- The strip spacing: 4.5 mm (4 mm strip, 0.5 mm gap)
- Active area: 23 mm x 23 mm.
- The air gap between sensor and HV-plate is 4 mm and the voltage used is 400 V.
Machine specific dosimetry

Beam position and width measurement: S-Axis Scan

Tolerance in T and U direction: ±2 mm
Patient specific dose verification (IMPT)

Patient

Treatment plan

Fields

Spot weights

Phantom
Patient specific dose verification (IMPT)

Patient

Treatment plan

Field 1

Recalculated 3D dose distribution

Field 2

Field 3

Field 4

Phantom

Fields

Spot weights
Patient specific dose verification (IMPT)

- Dedicated water phantom
- Two ionisation chamber arrays
  → 13 chambers each (0.1 ccm)
  → Spacing: 1 cm
  → Two orthogonal dose profiles
  → Measures absolute dose in Gy
- Rotatable
  → Alignment to gantry angle
- Adjustable water column
  → Measurements at various depths
- Readout interface to planning system
  → Online analysis of measured profiles against calculation
Patient specific dose verification

- Field verification for the first field of first patient treated with the COMET cyclotron
- Cervical cordoma case
- Correction of -1.0 mm in T-direction (table motion) and 2.0 % in dose
- Standard deviation: 0.015 Gy
Patient specific dose verification

- Histograms of best fit parameters (based on 53 field measurements)
  - No systematic positioning errors observed
  - Small residual error of 0.8% in total dose (still within our tolerance limits).
Patient specific dose verification

2D ionisation chamber arrays

2D-Array seven29 xdr, PTW Freiburg

“xdr“ = extended dose rate
CCD Dosimetry System

- Build at PSI (derived from M. Schippers at KVI)
- High spatial resolution: 0.5mm
- High reproducibility: 0.2%
- Fast data acquisition
- Suitable tool for relative dosimetry (patient specific & beam spot analysis)
CCD Dosimetry System

**Scintillation foil & CCD camera**


- Wedge-like dose distribution
- Varying monitor units linearly with coordinate
- Linear light yield (dose response)

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**Fig. 4.** ‘‘Wedge’’-like dose distribution measured with the CCD+screen system at a depth of 1 mm polystyrene. The dose distribution is produced by varying the monitor units (i.e., number of protons per pencil beam) linearly with the T coordinate.
CCD Dosimetry System for beam analysis

- Sweeper magnet scan [cm]: -9.0, -4.5, 0.0, 4.5, 9.0
- Distances from nozzle [cm]: 7.0, 14.5, 22.0, 29.5, 37.0
- Apply a Gaussfit
- Phase space (in air) – for each energy and angle
CCD Dosimetry System for field verification

- Calculated dose distribution
- Measured dose distribution
- Dose difference
- \( \gamma \)-evaluation
  - \( \Delta D = 3\% \)
  - \( \Delta d = 3\text{mm} \)
- \( \gamma \)-volume-histogram
  - 1.0
Quenching Effects

- Under-response of scintillator in bragg peak region (high LET)
- Effect must be considered when dose measurements involve different parts of the bragg peak
  - Inclusion of quenching in dose calculation by (empirical) correction factor:
    \[ C = 1 / (1 + 0.008 \text{dE/dx}) \]
- Development of scintillating powder mixture without quenching
CCD Dosimetry System

“Magic mixture” of two scintillating powders
Correct quenching effects at the Bragg peak

\[ \text{Gd}_2\text{O}_2\text{S}:\text{Tb} \]
\[ (\text{Zn,Cd})\text{S}:\text{Ag} \]
Radiochromic Films

- High spatial resolution
- Self-developing
  - no developer/fixer needed
  - ideal for filmless radiotherapy departments
- Easy to handle at room light
  - no dark room or light proof packaging
- No electronics required during measurement
- Simultaneous measurements in various depths by stacking
- Needs postprocessing for quantitative analysis
- Sensitive to ultraviolet light, temperature
- Post-radiation colorization
- Under-response in bragg peak region (Quenching)

Protons

PMMA

EBT Film

before Scan

after Scan
Radiochromic Films

GafChromic EBT Film

- Usable dose range 0 – 8 Gy
- Near linear response in dose range < 2 Gy
Radiochromic Films

Comparison of pre-calculated and actual beam entries for different combinations of gantry- and table angles

⇒ end to end test of the treatment delivery system
Radiochromic Films

End-to-end steering file check
Summary and Conclusions

• For absolute dosimetry use the standard protocols (IAEA TRS-398)
• Current protocols do not provide explicit recommendations for scanned beams
  • Beam monitor calibration
  • Dose verification
• Machine specific QA includes extensive checks on a daily basis
• Patient specific dosimetry is an essential part of the treatment
• Highly effective QA tools are needed
• QA protocol is needed to give advice to novice proton users
Thank you
Dosimetry and QA for proton radiotherapy

2. Machine Specific Checks and Dosimetry
3. Patient Specific Dosimetry
4. Summary
Absolute dosimetry

- Measurement
- Treatment planning:
  - Dose calculation based on depth dose curve derived from Bethe-Bloch formulation
  - Beam flux attenuation
  - Nuclear interaction effects
- Dose calculation in homogenous phantom (10x10x10 cm box)
- Thimble measurements

Absolute dose measurements
The Scheib-Pedroni 1-d model

Absolute dose measurements

33% at point of interaction
33% Distributed linearly to approximation
33% Lost (photons/neutrons)

a) Deposited dose
b) Proton fluence
c) Local deposited dose as result of NI
d) Dose deposited by ‘long range’ secondaries
e) Dose from primary protons

Scheib 1993 (PhD thesis)
Monitor unit results for PSI

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1 MU ~ 7000 Protons ~ 1 fC (proton charge)
In clinical practice

Based on field specific IC measurements, measured dose 1-9% too low c.f. calculation…

Problem of lateral distribution of secondary particles?

The Scheib-Pedroni 1-d model

Measurements predicted dose 1-9%
The Pedroni extended model

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

$\sigma^P(w)$ - Beam with of primary beam at depth $w$
$G^P$ – Gaussian distribution of primary beam
$\sigma^{NI}(w)$ - Beam with of secondary particle distribution at depth $w$
$G^{NI}$ – Gaussian distribution of secondary particle distribution
$f_{NI}(w)$ - Fraction of total integral dose at depth $w$ resulting from secondary particles
The Pedroni extended model

Measure dose at centre of various frame sizes (A-D)
The Pedroni extended model

From these distributions, possible to derive $\sigma_{NI}$ and $f_{NI}$

Pedroni et al, PMB, 50 (2005) 541-561

Absolute dose measurements

Relative dose vs. depth in water (cm) for frames A+B+C+D.
The Pedroni extended model

Global dose corrections over 390 measured fields

10x10x10 cm field

3x3x10 cm field

Without NI halo

With NI halo

Dose (Gy)

Depth in water (cm)

Dose correction (%)

Number of fields

Global dose correction required due to NI effects over 390 measured fields

Pedroni et al, PMB, 50 (2005) 541-561

Absolute dose measurements
Dose Deviations:
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- 0.8 % ± 0.6%

Range Deviations:
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Secondary particle effects in complex fields

Challenges 1: Dosimetry

- Without NI corrections
- With NI corrections

Bolsi et al., SASRO, 2005

Dose (Gy)

Position (cm)

T-axis profiles

U-axis profiles

Dose (Gy)

Position (cm)
IC Measurements in water for complex IMPT field

Challenges 1: Dosimetry
Secondary particle effects in complex fields

With NI halo
IC measurements
Under-response of scintillator in bragg peak region (high LET)

Effect must be considered when dose measurements involve different parts of the bragg peak

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CCD Dosimetry System for field verification

calculated

measured
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