Ion Beam Dosimetry

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Radiotherapy

External Radiotherapy
  - Conventional / 2DRT
  - 3DCRT
  - IMRT/VMAT (RapidArc)
  - SRS/SRT (Intracranial tumour)
  - SBRT/Ablative RT (Extracranial Tumour)
  - Hadron/Particle Therapy (Proton/Carbon)

Relatively large tumour
1.8-2.5 Gy/Frs in 20-35 Frs

Relatively small tumour
12-80 Gy in single Fr
5-20 Gy/Fr in 3-s

Use as sole modality Or + EXRT; 1-10 Frs

Brachytherapy
  - Intracavitary
  - Intraluminal
  - Interstitial
  - Intraoperative RT

10/02/2023

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Radiation Delivery System: MeV X-rays
Rational for Proton beam therapy

1. Depth Dose Characteristics

- Dosimetric advantage
- Better target conformity
- Reduction of OAR & integral dose
- Possibility of dose escalation
- Better tumour control
- Reduced acute and late toxicity
- Improve quality of life
- Lower risk of induced disorders (e.g. Secondary cancers or child growth abnormalities etc)
Proton therapy: How it works
• Requirements are specific to beam delivery techniques
  • Double scattering (DS)
  • Uniform scanning (US)
  • Pencil beam scanning (PBS)
• PBS at Apollo Proton Cancer Centre
• Identify vital beam parameters which influence dosimetric properties
  • ICRU 78 identified parameters for broad beam pertaining to DS, US & PBS
• AAPM TG-224; 2019
• AAPM TG-185; 2020
## Topical Review

**Dosimetry for ion beam radiotherapy**

Christian P Karger1,5, Oliver Jakel1,2, Hugo Palmas3 and Tatsuki Kanai7

### Table 1. Detectors for absorbed dose applied in ion beam radiotherapy.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Application in ion RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeter</td>
<td>Direct dose measurement</td>
<td>High effort, knowledge of chemical heat defect and thermal heat conduction required</td>
<td>Potential primary standard in the future, $k_q$ measurements</td>
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<tr>
<td>Ionization chamber</td>
<td>High accuracy and reproducibility, small LET and energy dependence, easy to handle, many chamber types for different applications</td>
<td>Corrections for deviation from calibration conditions required, incomplete knowledge of corrections (chamber dependent)</td>
<td>Reference dosimetry, commissioning, dosimetric QA, dose verification, beam monitoring</td>
</tr>
<tr>
<td>Films</td>
<td>High spatial resolution, 2D measurement</td>
<td>LET and energy dependence, dose cannot be obtained from optical density in mixed fields, off-line analysis required</td>
<td>Measurement of lateral dose profiles, beam widths, field geometry and homogeneity, documentation of beam ports</td>
</tr>
<tr>
<td>Radiographic films</td>
<td>Stability after development</td>
<td>Nonlinear response, daylight sensitivity, stable developing conditions required</td>
<td>Mostly experimental investigations, Lateral profile measurements</td>
</tr>
<tr>
<td>Radioluminescent films</td>
<td>Linear response, no daylight sensitivity, self-developing, less LET- and energy dependent</td>
<td>Complex evaluation protocols, long term self-development, mechanical sensitivity</td>
<td>Lateral and energy dependence, off-line evaluation, 2D distributions, field homogeneity, beam width, dose verification</td>
</tr>
<tr>
<td>Silicon diode and diamond</td>
<td>High spatial resolution, high signal, electronic read-out</td>
<td>LET, dose rate and energy dependence</td>
<td>Mostly experimental investigations, Lateral profile measurements</td>
</tr>
<tr>
<td>TLD</td>
<td>High spatial resolution</td>
<td>LET and energy dependence, off-line evaluation</td>
<td>Point measurements, in vivo dosimetry</td>
</tr>
<tr>
<td>OSL detector</td>
<td>High spatial resolution, linear response, repeated electronic read-out</td>
<td>LET and energy dependence</td>
<td>Point measurements, profiles</td>
</tr>
<tr>
<td>Alanine detector</td>
<td>Nearly water-equivalent, linear response</td>
<td>LET and energy dependence, off-line evaluation with electron spin resonance</td>
<td>Point measurements</td>
</tr>
<tr>
<td>Scintillating screen</td>
<td>High 2D spatial resolution, linear intensity-independent response, electronic read-out</td>
<td>LET and energy dependence, large device</td>
<td>1D/2D distributions, field homogeneity, beam width, dose verification</td>
</tr>
<tr>
<td>Amorphous silicon detector</td>
<td>High 2D spatial resolution, linear response, electronic read-out</td>
<td>LET and energy dependence, potential radiation damage, expensive</td>
<td>1D/2D distributions, field homogeneity, beam analysis</td>
</tr>
</tbody>
</table>
Commissioning

Machine QA

Patient QA

Blue Phantom²

Lynx

Giraffe

MatriXX

Stingray

Zebra

Sphinx

DigiPhant

FC 65 P IC
PPC 05
CC13 IC
CC01 IC
SFD

10/02/2023 AOCRP6_Dayananda
IDD/Pristine Bragg Peak:

- Scanning water Phantom & PPC
- Recommended detector
  - Small chamber in large field
  - Large diameter PPC in pencil beam
  - Intercept all primary protons and secondary products in the beam
IDD/Pristine Bragg Peak:

- Range (g/cm²):
  - Distal R90%
  - Proximal R90%
- Pristine Bragg peak width:
  - Distal 80%-proximal 80%
- Distal Fall off
  - Distal (R80-R20)
Normalized IDDs: 226 – 70 MeV @ 5 MeV interval

Energy vs Range (R90) in g/cm2
Pull back accuracy

IDD measurement using water Phantom & PPC

- Highly accurate
- Require Extensive time
- Mainly use for commissioning, annual QA & after major intervention
<table>
<thead>
<tr>
<th>Technical Comparison</th>
<th>Zebra</th>
<th>Giraffe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Broad beam</td>
<td>Single spot</td>
</tr>
<tr>
<td>Electrode Diameter</td>
<td>2.5 cm signal pad</td>
<td>12 cm signal pad</td>
</tr>
<tr>
<td>Number of chambers</td>
<td>180 chambers</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>2 mm</td>
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<tr>
<td>Typical Sensitivity</td>
<td>~14.76 nC/Gy</td>
<td>~247 nC/Gy</td>
</tr>
<tr>
<td>Charge Resolution</td>
<td>100 fC/count</td>
<td>200 fC/count</td>
</tr>
<tr>
<td>Bias Voltage</td>
<td>- 85V</td>
<td>-150 V</td>
</tr>
<tr>
<td>Energy Range</td>
<td>Up to 33cm WET</td>
<td></td>
</tr>
<tr>
<td>Scattering</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>Uniform Scanning</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>PBS</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

**Zebra Vs Giraffe**

- StingRay x 180

**IDS: Multi-layer ionization chambers (MLIC)**

**JACMP 16 (6) 2016**
IDD : Zebra

- Calibration wrt to
  - water phantom measured IDD for maximum proton energy using PPC05
  - IDD measurement with Zebra for 4 arbitrarily chosen energy

- Range
- SOBP
  - Distal R80-ProximalR80
Accuracy of Zebra for range measurement:

- Max Range deviation between Zebra & StingRay: 1.1 mm
- In agreement with published data

Advantage of MLIC

- RFA set-up & dismantle time 1.5 hr
- Zebra 30 min
- 15 min / PDD in RFA
- 40 Sec / PDD in Zebra
- Zebra is a fast and accurate device for QA of IDD
• Small filed in nature
• Smallest field size : 1 spot 
(Spot sigma 3 mm)
• Maximum field size : 35X40 cm²
• Dosimetry
  • Relative
  • Absolute
• Spot position
• Spot size (FWHM/Spot sigma as 67%)
• Lateral penumbra (80%-20%)
• Recommend high resolution detector
  • Small volume ionization chamber (≈0.1 cc)
  • Silicon Diodes
  • Gafchromic EBT Film
  • Time and labour intensive
  • Energy dependence specially for diodes & EBT film

• 2D linear detector Array
  • IMatrixx
  • Limited spatial resolution
Scintillation detector (Lynx)

- 2-D high-resolution scintillation based system
- Consists of a
  - scintillating screen of gadolinium-based plastic material (0.4 mm thickness), coupled with
  - CCD camera, in a compact light-tight box.
- Detector active surface area of 30 × 30 cm²
- Effective spatial resolution of 0.5 mm.
- Iris setting 0-100. Recommended >20
- Acquires data in 10-bit format
Scintillation detector (Lynx)

- Principal: Scintillating screen converts the energy lost by the incoming radiation into photons (green light, 540 nm wavelength) which are reflected by a mirror and collected by the photodiodes of the CCD camera.

- Raw data from CCD is corrected for:
  - Image deformation
  - Background
    - thermal &
    - communication noises of the camera
  - Non-uniform pixels intensity response
  - Median filter to reduce intensity variation between each pixel and neighbour
Characterization of Lynx for PBS

- Signal linearity with MU is better 3% even in the lowest dose
- Iris 90 is 7 times sensitive than iris 50

115 MeV Proton beam

280 MeV/u carbon ion

Lynx

Gafchromic EBT2

Phy Med Bio 58; 2013
Physica Medica 2017
Characterization of Lynx for PBS

- Coefficient of variation of the mean signal in the investigated ROIs centred around the nine spots was less than 2%
- Indicating a good image uniformity
- No evident of image geometrical distortion
- Spot position accuracy within ±1mm
Characterization of Lynx

- Spot profile independent of iris setting & MU
- No observable difference in spot profile between Lynx & EBT2
- Spot size difference (FWHM): <0.5 mm
Lynx is therefore suitable to replace EBT3 films, allowing real-time less time-consuming **beam commissioning**, **Validation** and **periodic constancy tests** for Proton. Not suitable for 3D dosimetry measurements, unless quenching is modelled.
Relative spot positioning error

Spot positional accuracy in mm

Relative positional deviation of the four corner spots wrt normalized central spot for G90, d=0 cm

< 0.6 mm
Average Spot sigma at different air gap

![Graph showing Spot sigma at different energy levels for various air gaps.](image)
Spot symmetry

Spot symmetry at G90 < +-10%

Energy in MeV

Spot symmetry in X and Y

Spot symmetry at G90 < +-10%
Lateral Penumbra
Absolute dosimetry

• Different code of practice
  • AAPM) report 16 (Lyman et al 1986)
  • European Clinical Heavy Particle Dosimetry Group (ECHED) code (Vynckier et al 1991, 1994)
    • International commission on radiation unit (ICRU) report 59 (ICRU 1998).
  • All these codes recommend the use of thimble ionization chamber calibrated in a $^{60}$Co beam in terms of air kerma (or exposure) (Lyman et al 1986, Vynckier et al 1991, 1994) or absorbed dose to water (ICRU 1998).
• IAEA TRS-398 (IAEA 2000, 2003) is the latest and most widely used
  • based on standards of absorbed dose to water.
• Recommended calibrated chambers
  • Thimble ionization chamber
  • Parallel plate chamber
Output: cGy/MU calibration

IAEA TRS 398

Calibrated ionization chamber

Water Phantom measurement

Reference depth: 3 cm
  - variable depth
  - TPS requirement

Water Phantom

Calibrated PP05 Parallel plate chamber

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

IAEA, TRS 398
Fig 1. Variation of Ks with proton energy for CC13, FC65P and PPC05 IC

Dayananda et al PTCOG 2019, Manchester
Polarity correction

Fig 2: Variation of Ks with proton energy for FC65P, CC13 and PPC05

Dayananda et al PTCOG 2019, Manchester
Absolute Dosimetry

- Chamber perturbation correction factor
- Combines many corrections into one factor based on beam quality ($R_{\text{res}}$)

### Table V. Calculated Values of $k_0$ for Proton Beams

For various cylindrical and plane-parallel ionization chambers as a function of beam quality $R_{\text{res}}$.

<table>
<thead>
<tr>
<th>Ionization Chamber Type</th>
<th>0.25</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>4.5</th>
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<th>7.5</th>
<th>10</th>
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<tr>
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<td>1.000</td>
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</tbody>
</table>
Output measurement

Fig: Variation of cGy/MU measured on different dates using PPC05

Set 1_28/10/2018  Set 2_13-11-2018

Characterization and Performance Evaluation of the First-Proton Therapy Facility in India

Departments of Medical Physics and Radiation Oncology, Apollo Proton Cancer Centre, Chennai, Tamil Nadu, India
Imaging QA:
Alignment of X-ray iso with laser & Proton Iso

Geometrical QA
Alignment of X-ray iso with lasers & Proton Isocenter

Image quality
Uniformity
Linearity of CT number
Spatial resolution

Imaging Dose

10/02/2023
What does it mean practically?

Different Proton centres
- Check different parameters
- Use different QA device (commercial/In-house)
- Time Spend varies widely

<table>
<thead>
<tr>
<th>QA Test</th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
<td>Daily</td>
<td>20 min</td>
<td>60 min</td>
<td>≈ 30 min</td>
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<tr>
<td>Monthly</td>
<td>2 hours</td>
<td>5 hours</td>
<td>≈ 3 hours</td>
</tr>
<tr>
<td>Yearly</td>
<td>1 day</td>
<td>3 days</td>
<td>≈ 2 days</td>
</tr>
</tbody>
</table>

Yearly Working Days

Courtesy Mr Simon, JBA dosimetry
<table>
<thead>
<tr>
<th>Devices Summary</th>
<th>Energy</th>
<th>Spots Positions</th>
<th>Spots Sizes</th>
<th>Spots Symmetry</th>
<th>Output</th>
<th>Imaging System</th>
<th>Beam vs X-ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zebra or MLFC</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Lynx or films</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>~</td>
<td>~</td>
<td>~</td>
</tr>
<tr>
<td>MatriXX or equivalent</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>~</td>
<td>✗</td>
<td>~</td>
<td>~</td>
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<tr>
<td>PPC05 + water equivalent</td>
<td>~</td>
<td>✗</td>
<td>✗</td>
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<td>✗</td>
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<tr>
<td>Stringray + Blue Phantom</td>
<td>✓</td>
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<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
</tbody>
</table>

**Today’s current practices:**

- Zebra or MLFC
- Lynx or films
- MatriXX or equivalent
- PPC05 + water equivalent
- Stringray + Blue Phantom

OR
<table>
<thead>
<tr>
<th>DEVICES</th>
<th>SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Spots Position</td>
</tr>
<tr>
<td>Zebra or MLFC</td>
<td>✔</td>
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<td>Lynx or films</td>
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<tr>
<td>MatriXX or equivalent</td>
<td>✔</td>
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<tr>
<td>PPC05 + water equivalent</td>
<td>✔</td>
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<tr>
<td>Stringray + Blue Phantom</td>
<td>✔</td>
</tr>
<tr>
<td>...</td>
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</table>

**OBJECTIVE**

- ✔
- ✔
- ✔
- ✔
- ✔
- ✔
- ✔

Courtesy Mr Simon, IBA dosimetry
How to improve the efficiency

• What can we eliminate?
  • Entire steps or part
  • conditions within a step of a type of measurement

• What can we automate?

• What can we combine?

• PTCOG Subcommittee report on Particle Therapy Efficiency: Aspects of Quality Assurance, May 2016

• Proposed to develop and adopt good tools & methods to integrate the measurements
• 4 wedges blocks of RW3 of varying thickness for range verification
• Corresponding energy of 120, 150, 180 and 230 MeV.
• Fiducials inserted in to the RW3 blocks
• Opening to hold a PPC 05 (0.5 cc) parallel plate IC for absolute dose measurement
• A small radiopaque ball mounted on the centre of the imaging system
Integrated efficient daily QA tool for PBS

- CCD camera (Lynx) integrated to Sphinx wedge phantom using carbon fibre frame
- Segregated regions for testing different aspects of proton beams
- Software:
  - Lynx software for data acquisition and
  - myQA for data analysis
- PPC 05 parallel plate chamber
- Dose 1 Electrometer
INTEGRATED EFFICIENT DAILY QA IN ONE SHOT

- Energy
- Spots Size
- Spots Position
- Spots Symmetry
- Absolute dose
- X-ray vs Proton
- Lasers
- Uniformity
- Imaging system
- Couch translation
- …

+ AAPM TG Compliant
Daily Machine QA

- Energy
- Spots Size
- Spots Position
- Spots Symmetry
- Absolute dose
- X-ray vs Proton
- Lasers
- Uniformity
- Imaging system
- Couch translation
Do we really need a QA for each treatment plan?

1. High degree of complexity involved in IMPT plans
Do we really need a QA for each treatment plan?

1. High degree of complexity involved in IMPT plans

   Multiple proton beams staked over one another (SOBP)
   Thousands of spots distributed in a complex pattern in each layer
   Spot positions, spot spacing and weights
   Intricacy of this spot intensity map becomes complex (SFO – MFO)
## PSQA – Work flow

<table>
<thead>
<tr>
<th>Treatment Planning room</th>
<th>Treatment room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose distribution in patient</td>
<td>Dose distribution in phantom</td>
</tr>
<tr>
<td>Plan delivery &amp; measurement</td>
<td></td>
</tr>
</tbody>
</table>

10/02/2023
IMPT: Measure at as many depths as possible
MatriXX PT for patient specific QA

- Specially designed to handle PBS high dose rate
- 1020 ICs covering area of 24.4x24.4 cm²
- Distance between ICs = 7.6 mm
- ICs size: 4mm diameter over 2 mm of active gap (instead of 5 mm for standard MatriXX)
- Sigma of 3mm: Typical collection efficiency for various bias voltage (Jaffe’s protocol)
  - 100V -- 93.9%
  - 250V -- 98.9%
  - 500V -- 99.8%
- 500V polarizing voltage
Patient specific QA using DigiMatriXX PT for

• Create patient verification plan by calculating patient dose on phantom (MatriXX PT or DigiPhant)
• Export each layer of SOBP from TPS and import to software
• Measure 2-3 layers for each patient plan
• Deliver patient dose for all fields MatriXX PT.
• Verify delivered dose vs planned dose in myQA Patient software.
• 3D plan verification
Pre-treatment PSQA of PBT
APCC Proposal – to simplify the PSQA
Original Article

Critical Appraisal of Paediatric Embryonal Cancers Treated with Image-guided Intensity-modulated Proton Therapy

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The Value of On-Site Proton Audits

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## Summery: Water tank measurement with ICs

### Chamber type
- Small volume chamber
- Parallel plate chamber
- Large diameter PPC
- Farmer chamber
- + computerized Water tank

### Measurement type
- Beam profile measurement
- Absolute dose calibration
- Beam range and modulation measurement
- Relative dose output
- Patient specific QA output

Generally use during commissioning, quarterly and annual QA
Summery : Linx

Measurement types
• Alignment check
• Alignment check with gantry mount
• Spot alignment
• Spot distribution characteristics

Applications
• Commissioning
• Validation
• Daily QA
• Monthly QA
• Annual QA
Summery: Sphinx phantom with Linx

Measurement type
• Energy
• Spots Size
• Spots Position
• Spots Symmetry
• Absolute dose
• X-ray vs Proton
• Lasers
• Uniformity
• Imaging system
• Couch translation

Application
• Daily QA
• Monthly QA
• Annual QA
Zebra MLIC

Measurement type
• Range
• Modulation
• Pristine Bragg Peak
• SOBP

Application
• Commissioning
• Validation
• Monthly QA
• Annual QA
MatriXX-PT / DigiMatrixxPT

Measurement type
• Output
• Beam profile analysis
• Planar dose distribution
• Comparison of measurements to other measurement to calculated dose distribution

Application
• Patient specific QA
• Monthly QA
Conclusion

• Proton therapy provides superior sparing of OAR and reduce integral dose to normal tissue significantly due to its physical Bragg’s peak characteristic.
• PBS technique is highly flexible & have the potential of treating very complex cases using IMPT.
• Dosimetry of pencil beam proton requires different type of dosimetric equipment different than photon.
• Accurate measurement of PBS beam data requires good knowledge of proton characteristic, dosimetric equipment toll.
• Proton beam characteristic parameters are quite reproducible.
The Team
Thank You