Quality Assurance Methods In Proton Beam Therapy

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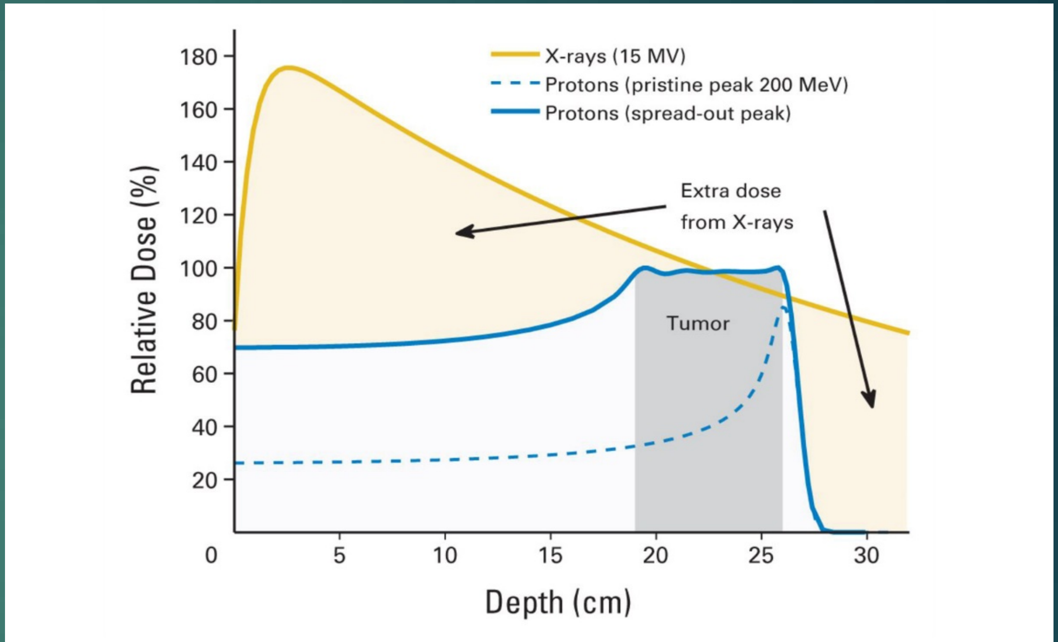
Introduction

- Proton Beam Therapy Background
- Beam characteristics
- What is Quality Assurance?
- QA at UCLH
- Commercially available QA machines and examples of clinical QA procedures
- Methods for measuring beam characteristics

Proton Beam Therapy Background

- An advanced form of radiotherapy that uses proton beams to target cancerous tumours.
- The advantage compared to traditional radiotherapy arises from Bragg curve behaviour of protons.
- Maximum proton energy is deposited at peak of curve.

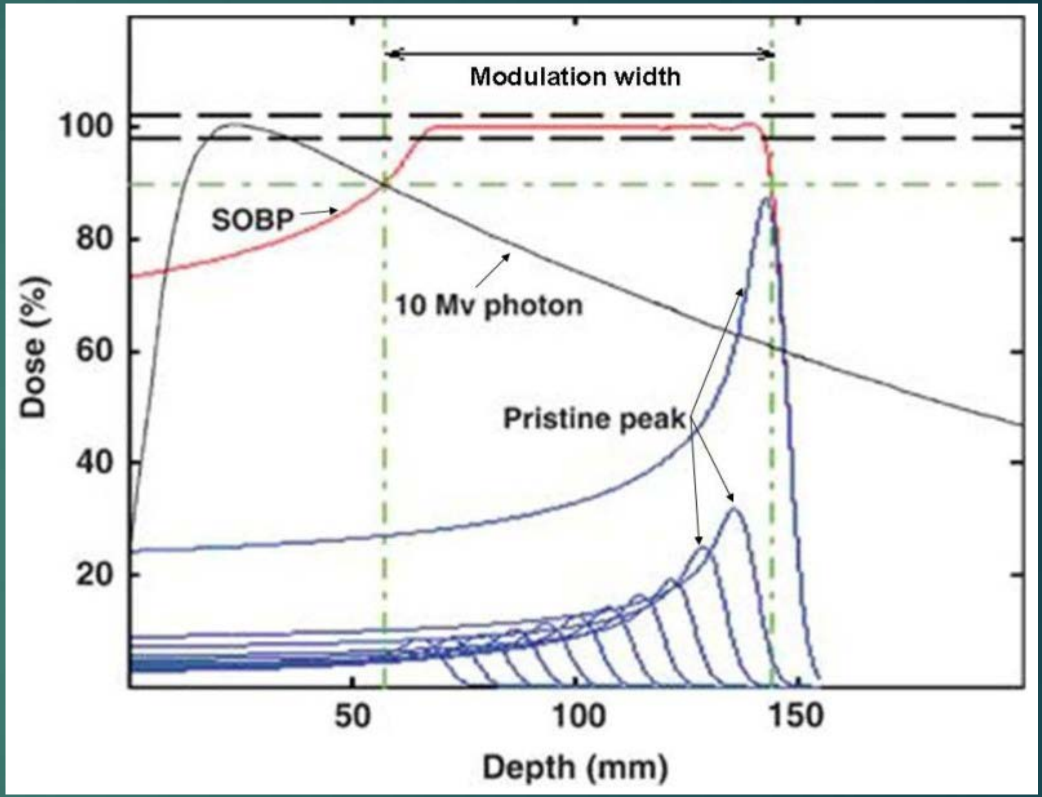


Taken from T Mitin, AL Zietman, *Promise and pitfalls of heavy-particle therapy*, J Clin Oncol, 2014 Sep 10, 32(26):2855-63.

Taken from Paganetti, H, *Proton Therapy Physics,* 2012, CRC Press.

Proton Beam Therapy Background

- A series of pristine Bragg peaks can be combined to treat an extended target volume.
- Result is a spread- out Bragg peak (SOBP).
- Homogenous dose distribution across SOBP.
- Range modulators are used to vary the proton energy.
- Typical proton energy range 70 – 250 MeV.



Taken from Trikalinos TA, Terasawa T, Ip S, et al. Particle Beam Radiation Therapies for Cancer [Internet]. Rockville (MD): Agency for Healthcare Research and Quality (US); 2009 Nov. (Comparative Effectiveness Technical Briefs, No. 1.)

Taken from Paganetti, H, *Proton Therapy Physics*, 2012, CRC Press.

Method of Beam Production

Cyclotrons

- Nearly continuous beam at constant energy.
- Protons at the maximum energy are extracted.
- Beam degraded to lower energy.
- Collimators, slits and magnets are required to restore the beam quality.

Synchrotrons

- Spills of protons of variable energy are produced.
- The injected protons are accelerated and then extracted at the desired energy.
- Each proton spill lasts for several seconds.
- Excess protons are decelerated.

Taken from Paganetti, H, *Proton Therapy Physics*, 2012, CRC Press.

Methods of Beam Production

- Advantages and disadvantages to both methods.
  - Synchrotrons are much larger than cyclotrons (about 6-8m in diameter) leading to spacial issues.
  - Beam quality has to be degraded for cyclotrons.
  - No degradation required for synchrotrons.
- Following acceleration the beams are transported to treatment rooms.
- The beams are focussed by magnets during the transportation phase to maintain beam quality.

Taken from Paganetti, H, *Proton Therapy Physics,* 2012, CRC Press.

Beam Parameters and Characteristics

- Beam energy – corresponds to beam range in the body.
- Beam energy and angular spread – related to distal fall off and energy straggling in tissue.
- Spot size – area covered by beam in PBS.
- Average beam intensity – relates to the dose patient receives.

Taken from Paganetti, H, *Proton Therapy Physics,* 2012, CRC Press.

What is Quality Assurance?

- Quality assurance (QA) is necessary to ensure the proton beam system is operating as intended.
- A QA system will find the problems and defects in a system before patient treatment begins.
- QA for X-ray radiotherapy is well established.
- PBT facilities have different QA systems in place with different checks making up the process.
- QA can be split into daily, monthly and annual QA depending on the failure criticality of that particular check.
- This project focusses on daily QA comprising of the most critical tests.

Properties of QA Systems

- An aspect of PBT QA systems is measuring beam properties.
- The QA should therefore be a detector or series of detectors that measure these properties.
- The QA checks should be comprehensive and measurements should be to the required precision.
- The QA system should be integrated and be able to carry out measurements consecutively.
- Needs to ensure the system runs from start to finish as planned.
- Uses patient specific information to carry out tests.

Taken from Paganetti, H, *Proton Therapy Physics,* 2012, CRC Press.

QA at UCLH

- UCLH PBT centre set to open in 2020.
- Christie Hospital in Manchester treated first patient in December 2018.
- Discussion with Alison Warry, Principal Radiotherapy Physicist, Proton Beam Therapy at UCLH.
  - What features they want from a daily QA system.
  - Criticisms of commercially available QA systems.

Taken from NHS Proton Beam Therapy Website
https://www.england.nhs.uk/commissioning/spec-services/highly-spec-services/pbt/

UCLH daily QA

Beam QA

- Range consistency
- Spot position
- Spot shape
- Variation with gantry angle

* Each parameter should be checked with 2/3 beam energies.

Machine QA

- Safety interlocks
- Communication between components
- Imaging system
- Patient support system

Commercially available machines: Sun Nuclear QA3

- Designed to measure photon and electron beams but can be modified to measure proton beam characteristics.
- Method for modification described by X Ding Et al, *A Novel QA system for proton therapy, J Appl Clin Med Phys. 2013 Mar; 14(2): 115–126.*
- *Can be used for PBS and US.*
- *Components:*
  - *13 parallel plate ionization chambers – 5 are used.*
  - *In house acrylic phantom*
  - *Blank acrylic compensator*

Sun Nuclear Daily QA 3

Acrylic Phantom

Diode – used to measure spot size.

Central Axis Chamber – positioned middle of SOBP. Collected charge used for output test.

Electron energy ion chamber:

- Bottom left and top right positioned at centre of SOBP.
- Top left and bottom right positioned in distal fall off range.
- Charge ratio implies range variation.

Image taken from Sun Nuclear Website https://www.sunnuclear.com/solutions/machineqa/dailyqa3-rfdaily

Sun Nuclear Daily QA Summary

Measurement	Component	Details	Tolerance
Output	CAX	Charge collected related to MU dose.	<3%
Beam range	E chambers	Ratio of charges to find fall off	<1.0mm
Symmetry	E chambers	Compare charge in each chamber.	<3%

- QA system takes less than 20 minutes.
- Can be incorporated into a larger QA system for further checks:
    - Couch alignment
    - Laser alignment
    - Image registration

Criticism and Improvement on Sun Nuclear QA3

- There are complexities associated with PBS.
  - Need to account for spot size and position variations.
  - Due to beam optics
- *Daily QA in proton therapy using a single commercially available detector,* JI Lambert Et al describes an improved method.
- Spot size and position can be measured by directing spot at innermost diode of triplet and measuring charge in diodes.
- Similar tolerances.
- Longer QA time of about 30 minutes.
- Mayo Clinic uses this and is discussed in *Technical Note: An efficient daily QA procedure for proton pencil beam scanning, J Younkin et al 2018, Phys. 45 1040.*

Commercially available machines: IBA Zebra

- 2D ionization chamber made up of 180 parallel plate chambers.
- Developed for X-ray therapy but can be adapted for PBT.
- Discussion taken from *Quality assurance of proton beams using a multilayer ionization chamber system,* September 2013, Medical Physics 40(9):092102.
- Primarily used to measure the dose distribution in tissue:
  - Range - depth of 90% of the dose
  - SOBP length - proximal 95% and distal 90%
  - Distal dose fall off – between distal 80% and 20%
- Can be used for scanned and scattered beams.

IBA Zebra

Specifications:

- 180 parallel plate ionization chambers
- Each plate has a resolution of 2mm
- Spacing of 1mm

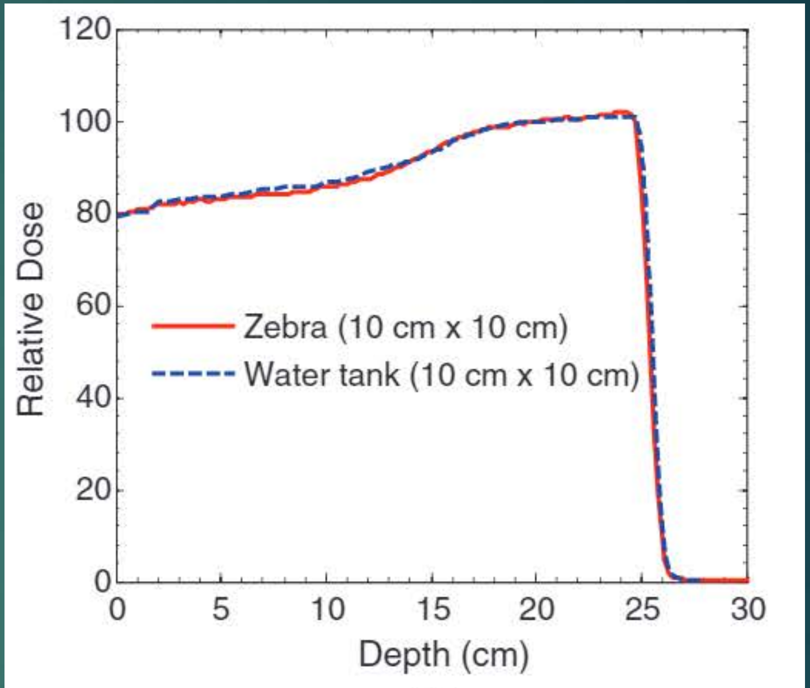
Method:

- Chambers irradiated for 60s.
- Carried out for radiation fields up to a maximum 18 cm x 18 cm.
- Depth dose distribution compared to measured values:
    - For scattered beams compared with a scanned water tank.
    - For scanned beams compared with data from a Bragg peak chamber from commissioning.

Image taken from IBA website

IBA Zebra Results

- Zebra found to be responsive to field sizes greater than 12.5 cm x 12.5 cm.
- Scattered proton beam:
  - Agreement in SOBP to 1.5%.
  - Range values agreed with a maximum deviation of 1.2mm.
  - SOBP length scales agreed to max deviation of 6mm.
- Scanned proton beams:
  - Range agreement with max deviation at 1.3mm.
- Zebra can be used for range measurements.
- This method is time efficient taking 3 minutes to set up and 20 minutes to carry out.



Graph showing normalised PDD distribution for a particular radiation field size. Taken from *Quality assurance of proton beams using a multilayer ionization chamber system*, September 2013, Medical Physics 40(9):092102.

Commercially available machines: IBA Matrixx

- Universal detector array.
- IBA's fastest and most accurate detector for QA.
- Initially designed for conventional and IMRT
- Composition:
  - 1020 parallel plate ionization chambers in a 32 x 32 array.
  - Highly sensitive: 1.4nC/Gy
- Example method taken from *Use of a two-dimensional ionization chamber array for proton therapy beam quality assurance,* B Arjomandy Et al, Med Phys. 2008 Sep;35(9):3889-94.

IBA Matrixx

- Method looks at suitability of using parallel plate ion chamber array for PBT.
- Measurements carried out:
  - Beam flatness
  - Beam Symmetry
- Compared results to those obtained with film dosimetry and ion chamber in water.
- Result:
  - Excellent agreement between Matrixx measurement and comparison with other methods.
  - Matrixx can be used to measure dosimetric properties.

IBA Matrixx

- Taken from *Quality assurance of carbon ion and proton beams: A feasibility study for using the 2D MatriXX detector,* M Donetti Et al, Phys Med. 2016 Jun;32(6):831-7. doi: 10.1016/j.ejmp.2016.05.058. Epub 2016 May 28.
- Paper further confirms that Matrixx can be used to replace films for measurements.
- Advantages: Quicker and almost instant results, good agreement with film results.
- There is also possibility to measure dose output but method not explored in detail.
- Conclusion: A good device when combined with others.

Beam Energy

- Beam energy is directly related to the range of the beam in tissue. There are several ways to measure the beam energy.
- Ionization chambers:
  - Multilayer ionization chamber
  - Thimble chamber
- Calorimeters – e.g graphite.
- PIN diode stacks

Spot Size and Symmetry

- Spot size and symmetry QA can be required for PBS.
- Spot size:
  - Ionization chambers – Gaussian produced in chamber and can obtain width [1].
  - Plastic scintillator fibre - photon output from a scintillating screen. Better than ionization chambers due to faster response and higher spatial resolution [2].
- Symmetry:
  - Using ionization chambers – method discussed using Sun Nuclear QA3 [3].

Scintillation Screens and Ionization Chambers

- Both can be used to check:
  - Range
  - Spot position
  - Shape
- Scintillation screens have a greater resolution but are more time consuming.

Criticisms of commercially available QA systems

- These commercial machines are fragile – cannot withstand knocks and bangs.
- Expensive to then replace, for example IBA machines cost £100,000’s and might have to be replaced twice a year.
- Multiple detectors needed to carry out a thorough QA analysis.
- Often difficult to use.
- Estimate from IBA of about 30 minutes per room for QA: often there are multiple rooms wanting access to beam accelerator so there is time competition.

Ideal UCLH QA System

- Ideal QA for UCLH:
  - Time efficient – 20 minutes.
  - Cost effective - £10,000 to buy.
  - Robust – in a container.
  - A single detector capable of multiple consecutive measurements.

Taken from UCLH website: https://www.uclh.nhs.uk/News/Pages/UCLHpartnerswithUScompany.aspx

Thank You