Design, Development and Operation of a Primary Standard Graphite Calorimeter for Proton Beam Dosimetry

Russell Thomas
*Principal Research & Clinical Scientist*
*Medical Radiation Science Group*
*National Physical Laboratory*

IDOS 2019
Current situation for Proton Beams

- It has long been recognised and indeed stated in TRS 398 that the preferred method of calibration is to calibrate chambers in a similar or ideally the same beam to that which is being used therapeutically.
- To date, no primary standards laboratory has a proton or ion beam in which to conduct calibrations.
- Current standard methods typically involve the use of an ionization chamber calibrated in a $^{60}$Co beam – so a beam quality correction factor is needed to account for the difference between the chamber response in the proton/ion and the calibration beams.
- This approach gives rise to uncertainties (at 68% confidence level) on the reference dosimetry of 2.3% for proton beams and 3.4% for carbon ion beams when using a plane-parallel ionization chamber (ref TRS-398).
- Clinically we really need reference dosimetry uncertainty at the level of 1% (at the 95% confidence level).
First graphite calorimeter measurements
Ratio of Dose from prototype calorimeter to that calculated using TRS-398 derived chamber factors

### Table: Calibration beam quality

<table>
<thead>
<tr>
<th>Calibration beam quality</th>
<th>modulated</th>
<th>non-modulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co</td>
<td>0.996</td>
<td>1.019</td>
</tr>
<tr>
<td>$^{6}$e19</td>
<td>0.983</td>
<td>1.004</td>
</tr>
</tbody>
</table>
Aim of the introduction of the New UK Primary standard graphite calorimeter

- New IPEM code of practice is intended to facilitate calibration of proton beams both for scattered and scanned beam delivery modes.
- The initial aim is to deliver an uncertainty on reference dosimetry for protons of approximately 2% (at 95% CL) and ultimately to a similar level to that achieved in external MV photon beam radiotherapy.
- The method will utilise a primary standard graphite calorimeter that is robust and portable enough to be used in the end-user facility.
- In principle the Code should be applicable to other ion beams, but this will require more development work.
“New” Primary Standard Calorimeter

Vacuum vessel - graphite mantle

O ring seal

Annular PCB

Outer jacket

Inner jacket

Tubes containing wires, leading to vacuum system

Core

Inner jacket

Outer jacket

1cm
Calibration methods

There are two main approaches to reference dosimetry in scanned particle beams. These are:

– Calibration of the individual pencil beams and extrapolation from this to the composite fields utilised for treatment

– Calibration in composite fields defined to cover what is termed a Standard Test Volume (STV) of delivered dose.

The IPEM code will use the STV approach for scanned beams…

…but the calorimeter is also being used to measure the $k_Q$ factors for chambers in line with the update of TRS-398
Calibration will be performed in a Standard Test Volume (STV) of dose

For high energy scanned particle beams a 10 x 10 x 10 cm dose volume is defined. The “primary” STV is defined as being centred at 15 cm deep with “secondary” STVs defined to be centred at 10cm and 25cm deep.

- Laterally the 10 cm dimension is defined to the 50 % isodose.
- At the distal edge, the 10cm is defined to 98% isodose.
- At the proximal edge the 10cm is defined to the 95% isodose
Measurements in the passively scattered ocular beam line at Clatterbridge Cancer Centre NHS Hospital Liverpool (CCC)

• Three experimental setups are considered (from left to right):
  • Transfer standard PTW Roos chamber setup in water phantom
  • Proton primary-standard graphite calorimeter
  • Transfer standard PTW Roos chamber setup in graphite phantom

• The setups are placed on a moving platform that allows each setup to be positioned in the beam
Calibration procedure - CCC

Two modes of operation:

• Quasi-adiabatic – temperature of the calorimeter is allowed to rise due to heating from ionising radiation (a typical patient fraction of 2 Gy results in a temperature rise of 2.8 mK)

• Isothermal – temperature of the calorimeter is actively controlled through electrical heating and the amount of the radiation incident on the device is quantified through the measurement of the reduction in electrical power required to maintain constant temperature in the calorimeter
Example of a calorimeter run - CCC

Temperature of the core during quasi-adiabatic irradiation at CCC

Electrical power delivered to the core during isothermal irradiation at CCC
Example of a calorimeter run – IBA Machine at Rutherford Centre Newport

- The upper graph shows a single quasi-adiabatic run and the lower figure shows an isothermal run acquired at Newport.
- Both figures clearly show the individual layers of the box field being delivered.
- In the isothermal run, for the first few layers being delivered, it is clear how the beam is delivered as three separate deliveries per layer.
Example of a calorimeter run – Varian Machine at The Christie NHS Hospital, Manchester

- In this run, each layer is delivered only once - with the 1st (deepest) layer delivering a large percentage of the total dose.
Conclusions 1

• Measurements were successfully performed at three clinical proton facilities with very different beam characteristics. One passively-scattered and two scanned beams with significantly different beam deliveries (publications in preparation)

• The calorimeter data clearly shows the difference in the time structure of the beam deliveries

• The new procedure based on the calorimeter gives good results for each centre and suggests a consistent and repeatable difference to the current procedure based on a cobalt calibration following recommendations in TRS-398

• The new procedure based on the calorimeter gives a significant improvement in uncertainty

• There is a consistent difference between the dose from calorimeter and the dose derived from TRS-398 but lies within the larger uncertainties in reference dosimetry in TRS-398 for proton beams

• Another strand to this work is the comparison of the Proton Calorimeter with the UK primary standard photon calorimeter that has just been commissioned and entered into key comparison database through comparison with BIPM (publication in preparation)
Food for thought!

- Radiotherapy has developed enormously over the last one hundred years and that development appears to be accelerating with new modalities and techniques being introduced.

- We have a comfortable grounding of basing Absorbed dose measurements on Co-60. But as primary standards laboratories it is our duty to develop and improve standards for these new treatment modalities.

- Micro/Mini beams, Micro/Mini grids and Flash therapy are just some of the new challenges we face.

- We have spent years producing nicely conformal and even dose distributions. With these new treatment types it now appears that this may no longer be what is required!

- So, as we have moved on from primary standards based on Exposure and Air Kerma measurements to those for Absorbed Dose, we need to develop better ways of standardising “dose” and/or defining more relevant quantities.
Main references

Very much a team effort. Thank you!