Developing a network of single-room proton therapy facilities

John Pettingell
Chief Physicist & Head of Radiotherapy
# Our Centres

<table>
<thead>
<tr>
<th>Location</th>
<th>Centre open</th>
<th>Proton go-live</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newport</td>
<td>March 2017</td>
<td>April 2018</td>
</tr>
<tr>
<td>Newcastle</td>
<td>June/July 2018</td>
<td>Q2 2019</td>
</tr>
<tr>
<td>Reading</td>
<td>July/Aug 2018</td>
<td>Q4 2019</td>
</tr>
<tr>
<td>Liverpool</td>
<td>Q2 2019</td>
<td>Q3 2020</td>
</tr>
</tbody>
</table>

**Plus** another 4 centres in UK
Our Centres

IBA Proteus One
- proton pencil beam scanning
- cone-beam CT
- oblique Xray
- 6D robotic table

Elekta Versa HD Linac
- VMAT, FFF
- cone-beam CT
- 6D ‘Hexapod’ table

Philips Big-Bore CT

Philips MR-RT

Elekta Mosaiq
Philips Pinnacle  

Centralised
Our Network

London Datacentre
- Elekta Mosaiq Server(s)
  - EMR, imaging
  - (secure data)
- Philips Pinnacle Server(s)
  - Contouring, planning
  - (backup / archive)
- IBA QA database etc.

Newport
- IBA Proteus One PBT
- Elekta Versa HD
- Philips Big-Bore CT
- Philips MRI
- Chemotherapy

Northumberland
- IBA Proteus One PBT
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Reading
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Other UK centres
- Liverpool
- London
- Dublin?

 Overseas centres
- Abu Dhabi
- Dublin?

1Gbps leased line
- www Remote access to: Pinnacle TPS Mosaiq EMR

Northumberland
- Dosimetrist
- Physicist
- Oncologist
  - PC, Mac
  - iPad

Overseas centres
- one way link for training and support

Northumberland
- backbone
- 100Mbps
- leased line
- backbone

Reading
- IBA Proteus One PBT
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Our Network
Proteus®ONE: IBA’s single room proton therapy solution

- Synchrocyclotron with superconducting coil: “S2C2”
- 230MeV pulsed proton beam, high dose per pulse
- 220° gantry
- proton pencil beam scanning
- 20x24cm field size
- cone-beam CT & oblique Xray
- ‘open feel’ treatment room
- Philips ambient experience
- Tried and tested radiation shielding vault design
- Engineer support in Control room with treatment staff
## Our Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>2015</td>
<td>Feb</td>
<td>Proton Partners International began – raise funding, recruit team</td>
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<td>2016</td>
<td>Apr</td>
<td>begin building in Newport</td>
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<td>2018</td>
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<td>commence acceptance tests and clinical commissioning</td>
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<td>2018</td>
<td>Mar</td>
<td>regulator approval to commence proton therapy treatment (inc paediatrics)</td>
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<tr>
<td>2018</td>
<td>Apr 10&lt;sup&gt;th&lt;/sup&gt;</td>
<td>first proton therapy treatment</td>
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<tr>
<td>2018</td>
<td>June</td>
<td>complete phase 2 of clinical commissioning (complex treatments)</td>
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Our Timeline

4 April 2017
https://www.youtube.com/watch?v=Xlak-lggej4

20 May 2017
https://youtu.be/jX6tINd0AlU
2015  Feb  Proton Partners International began – raise funding, recruit team
2016  Apr  begin building in Newport
2017  Mar  open Newport centre, regulator approval to commence radiotherapy treatment
2017  Apr  proton gantry delivered to Newport
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2018  Feb  commence acceptance tests and clinical commissioning
2018  Mar  regulator approval to commence proton therapy treatment (inc paediatrics)
2018  Apr 10th  first proton therapy treatment
2018  June  complete phase 2 of clinical commissioning (complex treatments)
Commissioning prior to ‘machine-time’

Philips Pinnacle TPS

• first clinical users – excellent support from Philips
• proton pencil beam scanning clinical release Jan 2017 – a year of testing prior to machine commissioning
  • modelled beam with Nice data > delivered fields on Proteus One in Nice
  • tested export to RCC Mosaiq
• beam modelling can be done by user, multiple beam models allowed
  • can have just one beam model and geometrically model the range-shifter, or
  • can have separate beam model(s) for range-shifter
• Relative Biological Effectiveness (RBE)
  • Cobalt-Gray-Equivalent (CGE) dose = “Gy(RBE)" = 1.1 x physical proton absorbed dose
  • how does Pinnacle deal with this?
    • no correction factor – input absolute dose in Gy(RBE), doses calculated/displayed in Gy(RBE)
  • BUT Mosaiq does have a correction factor! Make sure this is set to 1
  • make correction only when physically measure absorbed dose on machine
Commissioning prior to ‘machine-time’

CT ‘stoichiometric’ calibration

- Assisted by Philips
- HU to proton Stopping Power Ratio conversion calibration > potentially large range uncertainty
- electron density phantoms for CT calibration designed for radiotherapy not proton therapy
- Characterise/model CT scanner using CT scan of phantom and knowledge of densities and elemental compositions of phantom inserts. Use published data for real human tissues to calculate SPRs and to calculate HUs using CT scanner ‘model’, and hence determine HU to SPR calibration for real human tissues.

Schneider et al, The calibration of CT Hounsfield units for Radiotherapy Treatment Planning, PMB 41 (1996), 111-124

Yang et al, Theoretical variance analysis of single- and dual-energy computed tomography methods for calculating proton stopping power ratios of biological tissues, PMB 55 (2010), 1343-1362

Bourque et al, A stochiometric calibration method for dual energy computed tomography, PMB 59 (2014), 2059-2088
## Acceptance & Commissioning process (8 weeks)

<table>
<thead>
<tr>
<th>Machine time (RCC physicists double shifts)</th>
<th>Additional (Philips physicists &amp; RCC)</th>
</tr>
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<tbody>
<tr>
<td>Beam Acceptance Tests &amp; beam data for Treatment Planning System</td>
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<tr>
<td>Safety Acceptance Tests</td>
<td>Beam data modelling in TPS (no range-shifter), initial beam model used to create verification fields</td>
</tr>
<tr>
<td>Imaging Acceptance Tests &amp; clinical setup of CBCT</td>
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<tr>
<td>Calibrate QA devices</td>
<td></td>
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<tr>
<td>Verification fields delivered/measured</td>
<td></td>
</tr>
<tr>
<td>Absolute dose (TRS398) measurements (energy layers) for TPS</td>
<td></td>
</tr>
<tr>
<td>Measure WEP for immob devices etc.</td>
<td>Refine beam data model in TPS</td>
</tr>
<tr>
<td>Setup daily QA, patient QA</td>
<td>Recalculate verification fields and compare to measurements</td>
</tr>
<tr>
<td>Absolute dose (TRS398) in dose cubes created in TPS using PPC05 &amp; Roos chambers</td>
<td>Range-shifter beam data modelling on TPS</td>
</tr>
<tr>
<td><strong>External dose audit (Essen)</strong></td>
<td></td>
</tr>
<tr>
<td>Clinical Applications training, workflows, end-to-end testing</td>
<td></td>
</tr>
<tr>
<td>First treatment (small volume, no range-shifter)</td>
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</table>
Commissioning measurements for Pinnacle TPS

- Integral depth dose curves (Bragg peaks)
  - measured every 5 MeV from 70MeV to 230MeV, with and without range-shifter (64 IDDs)

- In air fluence
  - x & y profiles of central spots, measured every 5 MeV from 70MeV to 230MeV at
    - +20, +10, 0, -10, -20cm from isocentre

- Absolute dose
  - dose at two depths for a 10x10 single energy layer, every 5 MeV, with & without range-shifter

- Machine Characteristics
  SAD x (cm), SAD y (cm); max field size at iso (cm); max and min spot MU limits;
  max number of layers; max and min energy limits; max and min snout extension (cm);
  range-shifter physical thickness; range-shifter WET
Commissioning measurements for Pinnacle TPS

Integral depth dose curves (Bragg peaks)
- measured every 5 MeV from 70MeV to 230MeV
- with and without range-shifter

Measured with IBA Stingray chamber (12.5cm diameter)
Commissioning measurements for TPS

Pinnacle fit of 160MeV Bragg Peak
Commissioning measurements for Pinnacle TPS

**Absolute dose**

Dose at single depth (2cm) for a 10x10 single energy layer, measured every 5 MeV

Measured with and without range shifter
Matching two Proteus Ones?

Our PPC05 chamber and 2cm plastic water slab went to Beaumont in Detroit.

IBA carried out measurements, then sent it to Nice to make same measurements.

(Unfortunately IBA Detroit measured with range-shifter in, and no time for Nice measurements)

BUT seemingly good match between ourselves and Beaumont with range-shifter in
Commissioning measurements for Pinnacle TPS

- In air fluence
  - measured with Lynx scintillator
  - x & y profiles of central spots, measured every 5 MeV from 70MeV to 230MeV at +20, +10, 0, -10, -20cm from isocentre
Commissioning measurements for Pinnacle TPS

- In air fluence
  - x & y profiles of central spots, measured every 5 MeV from 70MeV to 230MeV at +20, +10, 0, -10, -20cm

226 MeV

100 MeV

70 MeV
Commissioning measurements for Pinnacle TPS

- In air fluence
  - x & y profiles of central spots, measured every 5 MeV from 70MeV to 230MeV at +20, +10, 0, -10, -20cm
Calibrate QA devices

**Zebra**
- For fastest commissioning and fastest daily consistency checks
- Unique multi-layer ionization chamber design:
  - Instant uniform scanning of entire Percentage Depth Dose
  - High spatial resolution: 180 independent plane parallel chambers
  - Water equivalent material for equivalent scattering properties
  - Easy to use interface to OmniPro-Incline software

**Lynx**
- Optimized for pencil beam scanning
- High resolution scintillator-based sensor
- Active surface of 30 x 30 cm², effective resolution of 0.5 mm
- Single shot and movie mode measurements
- Compatible with OmniPro-I'mRT, Dicom RT export supported

**DigiPhant™ PT**
- Replaces time consuming manual solutions
- Dedicated MatriXX PT with 1020 ion chambers
- Measuring 2D and 3D dose distribution in water
- Analysis of relative and absorbed dose
- Data storage and evaluation in OmniPro-I'mRT
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2018 Mar  regulator approval to commence proton therapy treatment (inc paediatrics)
2018 Apr 10th first proton therapy treatment
2018 June  complete phase 2 of clinical commissioning (complex treatments)
First patient treatment 10/04/18

- Prostate treatment
  - 60GyRBE in 20#
  - two lateral fields, ‘single-field uniform dose’
  - PBSTV = CTV + 5mm isotropic margin increased to 9mm in beam direction
- Rectal Spacer, “Bio-Protect” balloon,
  - push rectum away from prostate to reduce high doses
- Endo-rectal balloon
  - stabilise prostate and internal anatomy with respect to pelvic bones that beams pass through
- Bladder filling & immobilisation as for linac treatment
- Daily image guidance with 6D correction
First patient – “Bio-Protect” rectal spacer
First patient – “Bio-Protect” rectal spacer

Bio-Protect balloon

endo-rectal balloon
First patient – Single Field Uniform Dose (SFUD)
First patient – Single Field Uniform Dose (SFUD)
**First patient – proton vs linac VMAT**

![Dose Volume Histogram](image)

- **Red** = CTV + 5mm
- **Proton** = solid lines
- **Linac** = dotted lines
First patient – proton vs linac VMAT

Dose Volume Histogram

femoral heads

proton = solid lines
linac = dotted lines
First patient – proton vs linac VMAT

Dose Volume Histogram

rectum

proton = solid lines
linac = dotted lines
First patient – proton vs linac VMAT

Dose Volume Histogram

- proton = solid lines
- linac = dotted lines

bladder
First patient – proton vs linac VMAT

Dose Volume Histogram

proton = solid lines
linac = dotted lines

penile bulb
First patient treatment 10/04/18

Daily image guidance with 6D correction

- Setup patient to lasers
- oblique images
- cone-beam CT & 6D correction
  - automatic bone match, then check soft tissue & adjust if necessary
  - be particularly careful about bone that the beams pass through
- repeat oblique images, verify position correction
- treat first field
- rotate table 180°
- oblique images, verify correction & 6D correction if necessary
- treat second field
First patient treatment 10/04/18

Looking for good match with respect to pelvic bones through which beams pass.
First patient CT evaluation scan mid-treatment

planning CT

plan eval CT
First patient CT evaluation scan mid-treatment

planning CT

eval CT

• plan copied and re-calculated
• bone contours from original CT
First patient CT evaluation scan mid-treatment

Dose Volume Histogram

dark blue = CTV
light blue = PBSTV
original = solid lines
eval = dotted lines
First patient CT evaluation scan mid-treatment

Dose Volume Histogram

- dark blue = CTV
- light blue = PBSTV
- original = solid lines
- eval = dotted lines

rectum
First patient CT evaluation scan mid-treatment

- dark blue = CTV
- light blue = PBSTV
- original = solid lines
- eval = dotted lines
First patient CT evaluation scan mid-treatment

Dose Volume Histogram

dark blue = CTV
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penile bulb
Other things... Training, Mentorship, Peer Review, MDT

• Training, purchased from IBA, provided by University Pennsylvania
  • Comprehensive on-line training package prior to on-site visit
  • One to three weeks hands-on training at Roberts Proton Therapy centre, Pennsylvania
  • 13 clinical oncologists, 7 radiographers, 3 physicists, 1 dosimetrist

• Other training/visits:
  • Shreveport, Louisiana – first Proteus One gantry (plus CBCT)
  • Essen, Germany; Skandion, Sweden; Nice, France; William Beaumont, Detroit

• Proton specific MDT:
  • local oncologist team
  • collaborating with remote referring oncologists
  • radiologist, and other specialties if necessary
  • RCC clinical team

• Penn support
  • treatment plan review
  • Advice at MDT stage and throughout process if required
# Proton specific MDT first few weeks

All patients go through RCC proton specific MDT
8 patients so far:

<p>| | |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>prostates</strong></td>
<td>1 on-treatment&lt;br&gt;1 on hormones will be planned for proton &amp; linac&lt;br&gt;1 being planned for linac treatment at RCC</td>
</tr>
<tr>
<td><strong>H&amp;N</strong></td>
<td>suitable for proton, but too complex for RCC at this time</td>
</tr>
<tr>
<td><strong>bladder</strong></td>
<td>too complex: anatomical uncertainty and metal hip (degraded CT scan)</td>
</tr>
<tr>
<td><strong>bone chordoma</strong></td>
<td>suitable for proton, but volume too large for RCC at this time</td>
</tr>
<tr>
<td><strong>paediatric rhabdomyosarcoma</strong></td>
<td>suitable for proton, but volume too large for RCC at this time</td>
</tr>
<tr>
<td><strong>paediatric hodgkin lymphoma</strong></td>
<td>potentially suitable, more data required</td>
</tr>
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</table>

### Treatment Enquiries
- Jan = 27
- Feb = 38
- March = 70
- April = 72
Next steps

• Continue phase 2 of commissioning:
  • complete validation of range-shifter model
  • treating through the table and immobilisation devices
  • field-stitching – gradient matching
  • IMPT

• use NPL graphite calorimeter to measure proton absorbed dose
Acknowledgements

• Jamil Lambert – RCC senior physicist
• Jo Clorley – RCC senior physicist
• Laertes Papaspyrou – Philips clinical scientist
• Nigel Deshpande – Philips clinical scientist
• Russell Thomas & team at NPL
Partnership with the NHS *(the Welsh Experience)*

- Management of each patient in close liaison with Treating and Referring Oncologists
- RCC employees – radiographers, physicists, dosimetrists, administration
- Treating oncologists from local NHS Trusts have practicing privileges with RCC
- Partner organisations providing clinical services under SLA with RCC including:
  - Anaesthesia
  - Chemotherapy *(or see below…)*
- Aspects of pathway may be treated by referring centre or local NHS specialist service:
  - Neurosurgery
  - Chemotherapy
- Integral part of NHS pathway
  - Benefit of not removing the child/young adult from NHS/UK pathway
  - Supportive care in place to support this both in NHS pathway and through RCC
  - AHP links e.g. social worker
Our Group

Rutherford Cancer Centres
- Operate the Rutherford Cancer Centres,
- Employ the clinical staff & the centre staff
- Clinical commissioning and treatments

Rutherford Diagnostics
- Developing advanced diagnostics & genomics

Rutherford Estates
- Develop, maintain and own the Rutherford Cancer Centres and associated equipment

Rutherford Innovations
- Drive research, innovation, education & training in proton therapy and related areas
CT ‘stoichiometric’ calibration

1. Acquire CT scan of phantom with tissue equivalent materials
   • Obtain details of physical density and elemental composition of inserts from phantom manufacturer

2. Use HUs from CT scan to determine K coefficients for stoichiometric equation
   • Determine K coefficients for CT scanner  \( \mu = \rho N_g (Z,A) [K_{ph} Z^{3.62} + K_{coh} Z^{1.86} + K^{KN}] \)

3. Use K coefficients to calculate HUs for a full range of real human tissues
   • Use published data for physical density and elemental composition of human tissues

4. Calculate proton stopping power ratios for same real human tissues:
   \( SPR_{w} = \frac{\rho_e m_e c^2 \beta^2 / l_w (1-\beta^2)}{\rho_e w \ln(2 m_e c^2 \beta^2 / l_w (1-\beta^2))} \)

5. Use data from 3 & 4 to create HU to SPR calibration for TPS for real human tissues
   • Range uncertainty reduced to ~3.5%