Traceability and absorbed dose standards for small fields, IMRT and helical tomotherapy

Simon Duane, Hugo Palmans, Peter Sharpe – NPL, UK
Stefaan Vynckier – UCL, Brussels, Belgium

LNE-LNHB / BIPM workshop, May 2007, Paris
• Helical tomotherapy
  – what makes traceability difficult

• Alanine/EPR
  – a solution

• Results
  – alanine
    – ion chamber

• Further questions
Tomotherapy beam profiles

Open field at isocentre:

length: 40 cm
width: 5 cm, 2.5 cm or 1 cm

Tomotherapy beam collimation

- 51 gantry angles
- 64 MLC leaves
- Continuous couch translation
- ... ~ $10^5$ beamlets

Binary MLC (beam’s eye view - displaced)
Dosimetry issues

Max field size is 40 x 5 cm, and field is non-uniform

• Cannot get a 10 cm square, flat field

• None of our dosimetry protocols is directly applicable
  – how to link dose measurements to our familiar absorbed dose standards?
  – we need to restore traceability

• How can the hospital physicist check the doses claimed by the Treatment Planning System?
advantages
• Pellets are just about sensitive enough for measurements in small therapy-level fields
• Close to water-equivalent (density, atomic no.)
• Response has negligible energy-dependence
• Response is isotropic

drawbacks
• Delayed readout
  – allow 1 day for EPR signal to stabilise
  – results are not available immediately
• Needs an expensive spectrometer for good uncertainty
  – use NPL mailed service!
Alanine sensitivity

Depends on

• the dosimeter pellet size (mass)
  – In this work, the pellets are ~ 5mm diameter and 2.3 mm thick small enough for measurements in tomotherapy beams.

• the EPR spectrometer: standard deviation on dose for one pellet in this work: 0.06 Gy

Desktop spectrometer may be used, but
  less sensitive ⇒ poorer reproducibility ⇒ worse uncertainty in dose e.g. 0.3 Gy.
The response of alanine to Co-60 radiation is ~0.6% larger than the response to linac beams.

NPL data:

NPL linac TPRs:
4MV: 0.584, 0.621
6MV: 0.646, 0.670

Uncertainties are 2 sigma
Outline protocol

• Alanine/EPR sensitivity calibrated at NPL
  – traceable to the same absorbed dose primary standard as our usual NE2611 calibration

• Alanine measurement of absorbed dose in tomotherapy beams
  – Beam size and non-uniformity not a problem
  – Gives machine output

• NE2611 (and field chamber) measurement in same tomo beams
  – Gives cross-calibration

• Measure something like $\text{TPR}_{20/10}$ to monitor changes in beam

User can check one chamber against another after NPL has gone
UK Code of Practice (IPSM, 1990)

Starting with a calibrated secondary standard $N_{D,w}^{NE2611}(Q)$:

- Beam quality parameter $Q$ is
  - $TPR_{20/10}$ in a 10 x 10 cm beam

- Cross-calibration of field instrument in user beam
  - Interpolate in $Q$ and use a 10 cm square, flat beam, at a depth of 5 cm

- Machine output measurement (Gy per monitor unit)
  - the definition of MU is left to the user …

Our use of alanine has to address all these points
Initial measurements at UCL, Brussels

- Alanine pellets inserted directly in the commissioning phantoms (both homogeneous, solid water), using holes intended for an Exradin A1SL chamber

rectangular phantom (static beam)  cheese phantom (rotating beam)

Alanine measurements allow an audit of A1SL ion chamber dosimetry for a Tomotherapy delivery
Commissioning check – summary

• UCL chambers calibrated at Gent Primary Std lab
  ($^{60}$Co absorbed dose)

• UCL apply corrections as recommended by TomoTherapy Inc.
  (i.e. $k_Q$, $k_{ion}$, $k_{pol}$)

• Agreement to better than 2% in planned target volume

$$k_Q = 0.9965$$
$$k_{ion} = 1.010$$
$$k_{pol} = 1.000$$

(That’s ok.)
Exradin A1SL ion chamber

- Small volume 0.056 cm³

- Recommended polarising potential –300V
  - Surely too high.
### Summary of data (UCL)

Alanine data are averaged over 2-5 adjacent pellets.

<table>
<thead>
<tr>
<th>Machine/beam</th>
<th>UCL dosimeter</th>
<th>UCL / NPL alanine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomo / static 5 cm thick, 1.5 cm deep</td>
<td>A1SL</td>
<td>1.000</td>
</tr>
<tr>
<td>Tomo / static 5 cm thick, 5 cm deep</td>
<td>A1SL</td>
<td>1.002</td>
</tr>
<tr>
<td>SL25 / 6MV 10x10 cm, 5 cm deep</td>
<td>NE2571</td>
<td>1.002</td>
</tr>
<tr>
<td>SL25 / 6MV 10x10 cm, 5 cm deep</td>
<td>NE2571</td>
<td>1.001</td>
</tr>
<tr>
<td>Tomo / helical, 2.5 cm thick, in target</td>
<td>A1SL</td>
<td>1.015</td>
</tr>
<tr>
<td>Tomo / helical, 2.5 cm thick, in target</td>
<td>A1SL</td>
<td>1.012</td>
</tr>
<tr>
<td>Tomo / helical, 1.1 cm thick, in target</td>
<td>A1SL</td>
<td>1.002</td>
</tr>
<tr>
<td>Tomo / helical, 1.1 cm thick, in target</td>
<td>A1SL</td>
<td>1.005</td>
</tr>
<tr>
<td>Tomo / helical, 5 cm thick, in target</td>
<td>A1SL</td>
<td>1.009</td>
</tr>
<tr>
<td>Tomo / helical, 5 cm thick, in target</td>
<td>A1SL</td>
<td>1.011</td>
</tr>
</tbody>
</table>

NB measurements in conventional beams to check consistency in traceability (Gent vs NPL)

Overall, agreement to within 1.5%, with UCL dose greater than NPL dose.
Subsequent measurements (phantom funded by OSL)

• New phantom designed and made at NPL
  – Rexolite (polystyrene)
  – 10 cm diameter x 20 cm length, hole bored on central axis
  – Takes existing 15mm diameter adaptors for
    • NE2611, NE2571 ion chambers
    • alanine in delrin holder (4 pellets)
• also
  – alanine in new Perspex holder (14 pellets)
  – new adaptor for Exradin A1SL chamber
Measurement Protocol

- Hospital makes CT scans of NPL-tomo phantom
- Hospital prepares four helical treatment plans, all with cylindrical target volume, 8 cm diameter x 10 cm long, centred on phantom
  - Phantom concentric with machine
    - 5cm, 2.5cm, 1.1cm thick beam (3 plans)
  - Phantom offset horizontally from isocentre by 13 cm
    - 2.5cm thick beam (1 plan)
  
  All plans have helical pitch 0.3, rotation time varies with beam thickness
- Irradiations performed in 3Gy fractions
  - Two sets of 14 alanine pellets per plan, 9Gy per set
  - Hospital’s secondary standard chamber in each plan (one fraction per reading)
- alanine readout by NPL determines secondary standard calibration
  - Use of alanine contributes 0.1% (type A, reproducibility) plus 0.3% (type B, for Co-60 / MV difference) to calibration uncertainty
  - Combined uncertainty 1.6% \((k=2)\) (c.f. 1.5% for a calibration at NPL)
<table>
<thead>
<tr>
<th>Treatment plan</th>
<th>NE2611/235 (x10^7 Gy/C)</th>
<th>A1SL/52238 (x10^7 Gy/C)</th>
<th>Uncertainty (k = 2, 95% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helical, on-axis, 5cm</td>
<td>10.15</td>
<td>55.95</td>
<td>1.6%</td>
</tr>
<tr>
<td>Helical, on-axis, 2.5cm</td>
<td>10.16</td>
<td>55.95</td>
<td>1.6%</td>
</tr>
<tr>
<td>Helical, on-axis, 1cm</td>
<td>10.12</td>
<td>55.92</td>
<td>1.6%</td>
</tr>
<tr>
<td>Helical, off-axis, 2.5cm</td>
<td>10.18</td>
<td>55.48</td>
<td>3%</td>
</tr>
<tr>
<td>Static, 5 x 10 cm</td>
<td>10.15</td>
<td>56.16</td>
<td>1.6%</td>
</tr>
<tr>
<td>NPL beam (TPR=0.621)</td>
<td>10.15 (in 2005)</td>
<td>-</td>
<td>1.5%</td>
</tr>
<tr>
<td>NPL beam (TPR=0.646)</td>
<td>-</td>
<td>56.35 (in 2006)</td>
<td>1.5%</td>
</tr>
<tr>
<td>NPL beam (TPR=0.670)</td>
<td>10.11 (in 2005)</td>
<td>56.46 (in 2006)</td>
<td>1.5%</td>
</tr>
<tr>
<td>Treatment plan</td>
<td>Dosimeter</td>
<td>Mean dose / TPS dose and sample std dev</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-------------</td>
<td>----------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Helical, on-axis, 5cm</td>
<td>60/2017-18</td>
<td>1.010 ± 0.006 (14)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60/2019-20</td>
<td>1.008 ± 0.004 (14)</td>
<td></td>
</tr>
<tr>
<td>Helical, on-axis, 2.5cm</td>
<td>60/2025-26</td>
<td>0.999 ± 0.004 (14)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60/2021-22</td>
<td>0.992 ± 0.005 (14)</td>
<td></td>
</tr>
<tr>
<td>Helical, on-axis, 1cm</td>
<td>60/2023-24</td>
<td>1.010 ± 0.005 (14)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60/2027-28</td>
<td>1.013 ± 0.004 (10)</td>
<td></td>
</tr>
<tr>
<td>Helical, off-axis, 2.5cm</td>
<td>60/2029-30</td>
<td>0.983 ± 0.017 (14)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60/2031-32</td>
<td>0.983 ± 0.017 (14)</td>
<td></td>
</tr>
<tr>
<td>Static, 5 x 10 cm</td>
<td>60/2037</td>
<td>1.009 ± 0.003 (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60/2038</td>
<td>1.007 ± 0.005 (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60/2039</td>
<td>1.007 ± 0.007 (4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>60/2040</td>
<td>1.013 ± 0.002 (4)</td>
<td></td>
</tr>
</tbody>
</table>
Individual pellet doses (Cromwell)

Measured dose / TPS dose

1.0 ± 2%
Measured dose / TPS dose

1.0 ± 2%
Tomotherapy suggest to use helical pitch = 0.3
  - Couch advances 0.3 x W per gantry rotation, for beam width W
  - “may need smaller value for off-axis treatments”
• Pitch 0.3 used here
  - 4.4% peak-to-peak measured
  - < 1% peak-to-peak according to TPS
Calculation resolution issue?
TPS needs care in use?!

Phantom set up 14 cm off-axis
Planned target volume centred on phantom
Thread effect (VUB, Brussels)

2.5 cm beam, phantom set up 13 cm off-axis

Comparable to Cromwell

~4% peak-to-peak
Thread non-effect (RISO, Deventer)

2.5 cm beam, on-axis

2.5 cm beam, off-axis

RISO used pitch = 0.287 instead of 0.300

std dev of pellet doses is 0.5% in each case
Recombination investigation

- NE2611, NE2571 and A1SL ion chambers
  - four dose rates (static tomo beam, various depths and distances)
  - many polarising voltages
  - initial and volume recombination separated
  - charge multiplication seen
    - A1SL above –100V (-300V is recommended)
    - NE2571 at –400V (-250V is recommended)
    - not seen in NE2611
Dose per pulse and beam modulation

Static beam

rotating beam

Helical beam

helical 1cm beam on NE2357/23047

NPL
Ion recombination – summary of results

- NE2611 chamber
  - Saturation measurements in tomo beams at Cromwell give \( k_{\text{ion}} = 1.009 \)
  - consistent with expectations: \( k_{\text{ion}} = 1 + a + b D_p \)
  - though dose per pulse \( D_p \) may not be what you expect.

- A1SL chamber
  - Saturation measurements in tomo beams at Cromwell give \( k_{\text{ion}} = 1.001 \) to \( 1.002 \)
  - depending on position in phantom, consistent with theory
  - Much less than the \( k_{\text{ion}} = 1.01 \) recommended by TomoTherapy Inc
Charge multiplication in the A1SL

- A1SL measurements in Co-60
- using $V = -400, -300, -200, -150, -100$

For this chamber, $V = -300$ and $V/2 = -150$ are clearly in the range where charge multiplication is happening. The correction for ion recombination is more complicated…
Conclusions

Hospital physicists in Europe are less ready than those in North America to take the manufacturer’s dosimetry at face value (to use the system as a “black box”)

- The manufacturer’s dosimetry in their TomoTherapy machines is ok:
  - NPL alanine dosimetry agrees with TPS within 2% at Cromwell
  - Alanine and ion chamber dosimetry agree within 1.5% at UCL
  - Tomo 1 and Tomo 2 at RISO agree (after a 1% adjustment of Tomo 2)

- 1.01 correction for ion recombination in A1SL chamber is too large
  - NPL measurements indicate 1.001 to 1.002 (depending on position in phantom)
  - Correction for an NE2611 is 1.009 (for these measurements)

- pitch = 0.287 is much better than pitch = 0.300 (thread effect)
• NPL offers alanine measurements in the NPL-tomo phantom as a routine service to any TomoTherapy user, with
  – on-site measurements by NPL for UK users
  – Postal service (phantom and dosimeters) for non-UK users

• TomoTherapy Inc propose a similar use of NPL alanine to check their commissioning of new machines.
Acknowledgements

Thanks to

• TomoTherapy users for permission to use their results
  – Vincent Althof et al. (RISO, Deventer)
  – Dirk Verellen et al. (VUB, Brussels)
  – David Nicholas (Cromwell, London)

• OSL for funding
  – Design and manufacture of NPL-tomo phantom
  – NPL measurements at Cromwell Hospital

• UK Government DTI funded the rest of NPL’s work, as part of a dosimetry in small fields and for IMRT.
General questions

• In this work we only specified the dose distribution, and let the TPS determine the treatment (i.e. decide how to set up the MLC).
  – Proper reference conditions are not so ambiguous!
  – Could we define clinically relevant “reference” conditions?

• Is the resulting chamber calibration applicable to other treatments?
  – Arguably a helical beam is at least more relevant than a static beam.

• Do we need a primary standard more suited to IMRT?
Thank you!