Recent advances in dosimetry in reference conditions for proton and light-ion beams

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about 30 treatment facilities are established
90,000 patients are treated with all heavy-charged particles
another 20 light-ion centers are planned to be open in 5 years
Main clinical applications of light ion beams

- Treatment of large or deep seated tumours
- Treatment of ocular tumours
- Stereotactic radiosurgery (cross-fire technique)
Consistent and harmonized dosimetry guidelines

Accurate beam calibration

Ensure exact delivery of prescribed dose

Perform planning of high-precision conformal therapy

Provide interchange of clinical experience and treatment protocols between facilities

Provide standardization of dosimetry in radiobiology experiments
Absorbed dose determination in reference conditions for light ion beams

- Faraday Cup
- Calorimeter
- Thimble air-filled ionization chamber

Lack of national and international dosimetry standards
Protocols/Code of Practice
for proton and heavier ion beam dosimetry
$N_{D,w}$ - based formalism - IAEA TRS-398

$D_w(z_{\text{ref}})$ at any user quality $Q$
(photons, electrons, protons, heavier ions)

$$D_{w,Q} = M_Q N_{D,w,Q_o} k_{Q,Q_o}$$

corrected instrument reading at $Q$
calibration coefficient at $Q_o$
beam quality factor
Lack of standards

$\Rightarrow Q_o = {}^{60}\text{Co}$

\[ k_Q = \frac{(S_{w,\text{air}})^Q_Q}{(S_{w,\text{air}})^{60}\text{Co}} \times \frac{(W_{\text{air}})^Q_Q}{(W_{\text{air}})^{60}\text{Co}} \times \frac{p_Q}{p^{60}\text{Co}} \]

\[ p_Q = p_{\text{dis}}p_{\text{wall}}p_{\text{cav}}p_{\text{cel}} \]

\[ \approx 1 \text{ for protons} \]

\[ \approx 1 \text{ for heavier ions} \]

\[ \neq 1 \text{ for } {}^{60}\text{Co} \]
Stopping powers for proton beams

- Basic proton stopping powers from ICRU 49
- Calculation using MC code PETRA following Spencer-Attix cavity theory
- Transport included secondary electrons and nuclear inelastic process
Ratio of stopping powers water/air for heavy ions calculated using the computer codes developed by Salamon (for C, Ne, Ar and He) and by Hiraoka and Bichsel (for C). Data for protons and He from ICRU 49.

A constant value of $s_{w,air} = 1.13$ adopted in TRS 398 (ignores fragments).
mean excitation energy of liquid water

- I-water DRF
- I-water EXP
- I-water EST

ICRU 73 (2005) superseded

ICRU 37 (1984)
ICRU 49 (1993)
ICRU (2009) tentative
\[ ^{12}\text{C} \text{ 400 MeV/u on water} \]

**SHIELD-HIT**

Energy deposition (MeV/cm)

Depth (cm)

Variation with \( I_{\text{water}} \) is \(~1 \text{ mm for 2 eV}\)

- Energy deposition peak at 69 MeV/cm at a depth of 26.0 cm
- Energy deposition peak at 75 MeV/cm at a depth of 26.5 cm
- Energy deposition peak at 77 MeV/cm at a depth of 27.0 cm
- Energy deposition peak at 79.7 MeV/cm at a depth of 27.5 cm

5 mm displacement between curves
Transportable water calorimeters

**McGill**

- Copper tubing with cooling liquid
- Thermistor cables (to AC bridge)
- Heat exchanger
- Glass vessel and probes
- Copper plate
- Brass foil
- Proton gantry

**PTB**

- Water
- Magnetic stirrer
- PT100 probes
- Lucite
- Styrofoam
- 200 mm

<table>
<thead>
<tr>
<th>Protons</th>
<th>Calorimetry Gy/MU</th>
<th>Ionometry Gy/MU</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scattering</td>
<td>$9.087 \times 10^{-3}$</td>
<td>$9.118 \times 10^{-3}$</td>
<td>0.34</td>
</tr>
<tr>
<td>Scanning</td>
<td>$1.198 \times 10^{-3}$</td>
<td>$1.203 \times 10^{-3}$</td>
<td>0.42</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Calorimetry Gy/MU</th>
<th>Ionometry Gy/MU</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons 182 MeV</td>
<td>2.95±0.04</td>
<td>2.97±0.09</td>
<td>+0.7</td>
</tr>
<tr>
<td>$^12$C 430 MeV/u</td>
<td>2.77 ± 0.05</td>
<td>2.69 ± 0.08</td>
<td>-3.0</td>
</tr>
</tbody>
</table>

Sarfehnia et al., 2010

Brede et al., 2006
Graphite calorimetry
protons at CCO
carbon ions at NIRS

Palmans et al 2004

Sacama et al 2008
Values of $w/e$ for protons and carbon ions deduced from comparison of ionization chamber and calorimeter measurements.
Experimental and calculated ratios of proton perturbation factors in 75 MeV proton beam

Data from Palmans et al 2001, and Palmans and Verhaegen, Montreal workshop 2001
Monte Carlo calculated $p_{\text{wall}}$ and $p_{\text{cel}}$ for Farmer type chambers in proton beam

Details see in the poster by Palmans et al IAEA-CN182-230, this symposium.
Experimental $k_Q$ values
(Medin et al., 2006)

- Passive beam delivery
  NE 2571: $1.021 \pm 0.7\%$
  FC65-G: $1.021 \pm 0.7\%$

- Scanning beam
  NE 2571: $1.032 \pm 1.2\%$

These values can be compared with the tabulated theoretical values from IAEA TRS-398, which are $1.039 \pm 1.7\%$ for both chamber types

(details in the next presentation by J. Medin)
recombination

- initial (columnar)
- general (volume)

“intra-track”
one single track
dose or dose-rate independent

“inter-tracks”
multiple tracks
dose or dose-rate dependent
Recommendations for protons and heavier ions

Pulsed or pulse scanned proton beams

Scanned light ion beams

\[ k_s = a_o + a_1 \left( \frac{M_1}{M_2} \right) + a_2 \left( \frac{M_1}{M_2} \right)^2 \]

Two-voltage method

\[ k_s = a_o + a_1 \left( \frac{M_1}{M_2} \right) + a_2 \left( \frac{M_1}{M_2} \right)^2 \]

\[ 1/M = 1/M_\infty + b/V \]

general recombination
Reported discrepancies

Palmans et al 2006
Eye beam line
Over-estimate 2%

Recommendation of TRS 398 and given equation for pulsed proton beams are valid if pulse duration is short compared to the ion transit time in the ionization chamber,

Lorin et al 2008
Continuous scanning
Over-estimate 1%

If pulse duration is long compared to the ion transit time in the ionization chamber, then the conditions in the chamber during the pulse will be similar to those of a continuous high intensity beam.

Jaekel et al 2002
Raster scanning
Over-estimate 1%
Proton beams – ICRU 78

- **Cyclotrons** (small pulses, high repetition, high dose per pulse)

- **Synchrotrons** (Repetition < 0.5 Hz, Acceleration 0.5 – 1s)

Effective pulse duration is long compared to ion collection time of ionization chamber

\[
k_s = \frac{(V_N/V_L)^2 - 1}{(V_N/V_L)^2 - (M_N/M_L)}
\]
Example of proton scanned continuous beam

Cyclotron
• high dose per pulse (0.2 Gy)
• pulse length 400μs
• maximum transit time for the ionization chamber 152 μs (300 V) and 76 μs (600 V)

Lorin et al, 2008

Ion collection time of ionization chamber is shorter compared to pulse duration

Scanned continuous beam

\[ k_s = \frac{\left(\frac{V_N}{V_L}\right)^2 - 1}{\left(\frac{V_N}{V_L}\right)^2 - \left(M_N / M_L\right)} \]

The user should verify the validity of recombination corrections against independent method (Faraday cup, calorimeter, alanine)
The user of a scanned light-ion beam delivery system can perform the measurements of the saturation effects at different voltages by placing the ionization chamber at a calibration depth.

If the data are well described by a linear fit, then the conditions of pulsed scanned beam are met.

If the data are well described by a quadratic fit, then the conditions for continuous radiation are met.

Jaekel et al 2002
Issues to be resolved in upcoming ICRU report on light-ion beams

- TRS 398 may be adopted for light-ion beam dosimetry with beam-line specific adjustments

- The currently recommended values of $s_{w,air}$ (and $W_{air}$) for absolute dosimetry should be re-considered

- Uncertainties in stopping powers, including those of the I-values for different tissues (5-10%), must be taken into account to re-estimate what “precision” is really achievable in clinical practice
Future improvements in proton and heavier ion beams dosimetry would be focused on:

- ion chamber specific factors and perturbation effects
- calculation of beam quality correction factors, for new ionization chambers and experimental verification of calculated values
- calculation of stopping power ratios
- determination of w-values
Standard uncertainties in $D_w$ (TRS 398, ICRU 78)

\[ u(N_{D,w}^{SSDL}) = 0.6 \quad k_Q \text{ calc} \]

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>$k_Q$</th>
</tr>
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<tbody>
<tr>
<td>Co-60 gamma-rays</td>
<td>0.9</td>
</tr>
<tr>
<td>High-energy photons</td>
<td>1.5</td>
</tr>
<tr>
<td>High-energy electrons</td>
<td>1.4-2.1</td>
</tr>
<tr>
<td>Proton beams</td>
<td>2.0-2.3</td>
</tr>
<tr>
<td>Heavier ions</td>
<td>3.0-3.4</td>
</tr>
</tbody>
</table>
### Uncertainties of reference dosimetry (adapted from Karger et al 2010)

<table>
<thead>
<tr>
<th>Reference dosimetry method</th>
<th>Standard uncertainty (k=1), %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Protons</td>
</tr>
<tr>
<td>Ionization chamber</td>
<td>2.0 – 2.3</td>
</tr>
<tr>
<td>Water calorimetry</td>
<td></td>
</tr>
<tr>
<td>Graphite calorimetry</td>
<td></td>
</tr>
<tr>
<td>Faraday Cup dosimetry</td>
<td>1.5</td>
</tr>
<tr>
<td>Activation-based dosimetry</td>
<td>3.1</td>
</tr>
</tbody>
</table>
Implementation of ICRU Report 78, IAEA TRS 398, or ICRU Report xx can provide a level of accuracy comparable to that in calibration of photon and electron beams, thus harmonizing clinical dosimetry at proton and heavier ion beam facilities.
Proton or light ion beam therapy centers in 2010

Thank you for your attention!