Nuclear data impact on proton radiation therapy calculations

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Nuclear data impact on proton radiation therapy calculations

- Impact of nuclear interactions on dose
- Neutron dose in proton beam therapy
- PET imaging for quality assurance
- Monte Carlo benchmarking
Nuclear data impact on proton radiation therapy calculations

- Impact of nuclear interactions on dose
Energy deposition of protons

- **Electronic (energy loss)**
  - Ionization
  - Excitation

- **Nuclear (energy loss, fluence reduction)**
  - Multiple Coulomb scattering, small $\theta$
  - Elastic nuclear collision, large $\theta$
  - Nuclear interaction
Electromagnetic energy loss of protons

- Distal distribution

Peak broadening due to range straggling
Electromagnetic energy loss of protons

- Lateral distribution

Multiple Coulomb scattering

![Graph showing electromagnetic energy loss of protons](image)
Energy-range relationship of protons (driven by electronic energy loss)

ICRU 49

Analytical fit: $R_0 = 0.0022 \cdot E_0^{1.77}$
Pencil Beam Algorithms

- Measured or calculated pencil kernel
- Water-equivalent pathlength
Nuclear interactions of protons

Elastic nuclear collision (large $\theta$)  Nuclear interaction

Nuclear interactions lead to secondary particles and thus to

- local dose deposition (secondary protons)
- non-local dose deposition (secondary neutrons)
Monte Carlo dose calculation

Para-spinal tumor
176 x 147 x 126 slices
voxels: 0.932 x 0.932 x 2.5-3.75 mm³
3 fields: ~15.0 Gy each
Nuclear interactions in absolute dosimetry

Volume for absolute dosimetry

\[ \text{Output - Factor} \approx \frac{D_{\text{cal}}}{i_{ic}} \left[ \frac{\text{cGy}}{\text{MU}} \right] \]

\[ i_{ic} = \frac{e \cdot \varepsilon_{ic}}{W_{\text{air}}} \times \int \int \left( \frac{dE}{dx} \right)_{\text{air}} p \cdot d\xi dF \]
## Contributions to Output Factor

<table>
<thead>
<tr>
<th></th>
<th>R=7.5 M=7</th>
<th>R=10 M=4</th>
<th>R=15.5 M=15</th>
<th>R=22 M=4</th>
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</thead>
<tbody>
<tr>
<td><strong>Beam energy [MeV]</strong></td>
<td>153.02</td>
<td>169.23</td>
<td>180.99</td>
<td>215.45</td>
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<tr>
<td>Primary P</td>
<td>70.5 %</td>
<td>71.7%</td>
<td>69.8 %</td>
<td>71.3 %</td>
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<tr>
<td>Secondary P</td>
<td>1.1 %</td>
<td>1.3 %</td>
<td>1.3 %</td>
<td>1.6 %</td>
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<tr>
<td>Electrons</td>
<td>27.5 %</td>
<td>27.0 %</td>
<td>27.2 %</td>
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<tr>
<td>Helium</td>
<td>0.9 %</td>
<td>0.1 %</td>
<td>1.6 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>Others</td>
<td>&lt; 0.1 %</td>
<td>&lt; 0.1%</td>
<td>&lt; 0.1 %</td>
<td>&lt; 0.1 %</td>
</tr>
</tbody>
</table>
Nuclear data impact on proton radiation therapy calculations

- Neutron dose in proton beam therapy
Neutron interactions in matter (tissue)

Neutrons are not directly ionizing

- Neutrons (uncharged) do not interact electromagnetically
- Nuclear interactions occur only if the neutron comes close to the nucleus

- Attenuation coefficient is small; neutrons can penetrate large amounts of matter
- Low non-local (!) dose deposition
Main potential sources of neutrons

Typically lower

Aperture, Compensator

Jaws (X and Y) (& Range Verifier)

Snout

First Scatterers

Second Scatterers

IC2 and IC3

Magnet 1

Magnet 2

Range Modulator Wheels

IC1

Typically lower
Neutron yield depends on the facility


Neutron yield depends on beam energy
Neutron yield depends on aperture size


~20% of the beam treats
~80% of the beam produces neutr.

~60% of the beam treats
~40% of the beam produces neutr.
Scattered dose as a function of lateral distance

![Graph showing scattered dose as a function of lateral distance. The graph includes data from IMRT (Klein06), Yan02, Wroe07, and Mesoloras06. The x-axis represents the lateral distance to the field edge in centimeters, and the y-axis represents the scattered dose in milliSv/Gy.](image)
Is the dose as a function of distance really what we need to know?

“Epidemiologic studies … should be based on accurate, individual dose estimates, preferably to the organ of interest …”

[BEIR VII]
Pediatric patients

- have a long life expectancy
- show different dosimetric characteristics
- have a higher risk for second malignancies

"Do we have to worry when treating pediatric patients?"

BEIR, Health risks from exposure to low levels of ionizing radiation, BEIR VII, Phase 2. National Research Council, National Academy of Science, 2006
Previous Study  


Adult phantom (VIP-Man)  
Visible Human Project by the National Library of Medicine

- 63 segmented organs/tissues
- Number of voxels: 147×86×470
- Resolution: 4×4×4mm³

G. Xu et al., Health Phys. 78 (2000) 476
Whole-body computational phantoms
### Pediatric phantoms


#### Table 2. Elemental compositions (% by mass) and tissue densities (g cm⁻³) of individuals at the ICRP reference ages.

<table>
<thead>
<tr>
<th>Phantom age (years)</th>
<th>Element</th>
<th>Newborn</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>15 (male)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Group 1 (cranium/mandible)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>5.551</td>
<td>5.272</td>
<td>5.173</td>
<td>5.340</td>
<td>5.434</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>4.259</td>
<td>4.280</td>
<td>4.230</td>
<td>4.019</td>
<td>3.831</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>51.209</td>
<td>49.850</td>
<td>46.759</td>
<td>44.757</td>
<td>43.526</td>
</tr>
<tr>
<td></td>
<td>Ca</td>
<td>12.892</td>
<td>13.852</td>
<td>15.619</td>
<td>15.801</td>
<td>15.773</td>
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<tr>
<td></td>
<td>Na</td>
<td>0.031</td>
<td>0.025</td>
<td>0.104</td>
<td>0.103</td>
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<tr>
<td></td>
<td>Mg</td>
<td>0.260</td>
<td>0.268</td>
<td>0.187</td>
<td>0.181</td>
<td>0.176</td>
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<tr>
<td></td>
<td>P</td>
<td>6.303</td>
<td>6.969</td>
<td>7.435</td>
<td>7.544</td>
<td>7.346</td>
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<tr>
<td></td>
<td>S</td>
<td>0.287</td>
<td>0.287</td>
<td>0.283</td>
<td>0.276</td>
<td>0.271</td>
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<tr>
<td></td>
<td>Cl</td>
<td>0.018</td>
<td>0.012</td>
<td>0.007</td>
<td>0.006</td>
<td>0.006</td>
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<tr>
<td></td>
<td>K</td>
<td>0.027</td>
<td>0.019</td>
<td>0.011</td>
<td>0.009</td>
<td>0.006</td>
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<tr>
<td></td>
<td>Fe</td>
<td>0.013</td>
<td>0.012</td>
<td>0.011</td>
<td>0.012</td>
<td>0.011</td>
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<tr>
<td></td>
<td>Density</td>
<td>1.458</td>
<td>1.456</td>
<td>1.526</td>
<td>1.519</td>
<td>1.525</td>
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<tr>
<td></td>
<td></td>
<td>Group 2 (vertebrae—cervical, thoracic, lumbar)</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>H</td>
<td>8.760</td>
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<td>7.957</td>
<td>7.901</td>
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<td>C</td>
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<td>17.855</td>
<td>21.884</td>
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<td>0.116</td>
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<td>P</td>
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<td>0.598</td>
<td>0.485</td>
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<tr>
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<td>Cl</td>
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<td>0.006</td>
<td>0.004</td>
<td>0.004</td>
<td>0.003</td>
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<tr>
<td></td>
<td>Fe</td>
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<td>0.019</td>
<td>0.024</td>
<td>0.033</td>
<td>0.036</td>
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<tr>
<td></td>
<td>Density</td>
<td>1.157</td>
<td>1.184</td>
<td>1.219</td>
<td>1.232</td>
<td>1.230</td>
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</tbody>
</table>

#### Phantom number of voxels and voxel dim (mm)

<table>
<thead>
<tr>
<th>Phantom</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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<tr>
<td>9 month old</td>
<td>289</td>
<td>180</td>
<td>241</td>
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<td>0.9</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>4 year old</td>
<td>351</td>
<td>207</td>
<td>211</td>
<td>0.9</td>
<td>0.9</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 year old</td>
<td>322</td>
<td>171</td>
<td>220</td>
<td>1.1</td>
<td>1.1</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 year old</td>
<td>398</td>
<td>242</td>
<td>252</td>
<td>0.9</td>
<td>0.9</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 year old</td>
<td>349</td>
<td>193</td>
<td>252</td>
<td>1.2</td>
<td>1.2</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adult</td>
<td>147</td>
<td>86</td>
<td>470</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Example: Female Organ Index

<table>
<thead>
<tr>
<th>Organ Index</th>
<th>Organ/Tissue</th>
<th>Organ Index</th>
<th>Organ/Tissue</th>
<th>Organ Index</th>
<th>Organ/Tissue</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>eyes</td>
<td>17</td>
<td>spleen</td>
<td>33</td>
<td>scapulae</td>
</tr>
<tr>
<td>2</td>
<td>tonsil</td>
<td>18</td>
<td>gall bladder wall</td>
<td>34</td>
<td>sternum</td>
</tr>
<tr>
<td>3</td>
<td>salivary glands</td>
<td>19</td>
<td>spinal cord</td>
<td>35</td>
<td>upper humerus</td>
</tr>
<tr>
<td>4</td>
<td>tongue</td>
<td>20</td>
<td>aorta</td>
<td>36</td>
<td>ribs</td>
</tr>
<tr>
<td>5</td>
<td>pharynx</td>
<td>21</td>
<td>adrenals</td>
<td>37</td>
<td>T-vertebrae</td>
</tr>
<tr>
<td>6</td>
<td>larynx</td>
<td>22</td>
<td>pancreas</td>
<td>38</td>
<td>lower humerus</td>
</tr>
<tr>
<td>7</td>
<td>trachea</td>
<td>23</td>
<td>kidneys</td>
<td>39</td>
<td>L-vertebrae</td>
</tr>
<tr>
<td>8</td>
<td>thyroid</td>
<td>24</td>
<td>small intestine wall</td>
<td>40</td>
<td>radii, ulnae</td>
</tr>
<tr>
<td>9</td>
<td>thymus</td>
<td>25</td>
<td>colon wall</td>
<td>41</td>
<td>os coxae</td>
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<tr>
<td>10</td>
<td>bronchi</td>
<td>26</td>
<td>ovaries</td>
<td>42</td>
<td>sacrum</td>
</tr>
<tr>
<td>11</td>
<td>breast</td>
<td>27</td>
<td>uterus</td>
<td>43</td>
<td>hand</td>
</tr>
<tr>
<td>12</td>
<td>lungs</td>
<td>28</td>
<td>bladder wall</td>
<td>44</td>
<td>upper femur</td>
</tr>
<tr>
<td>13</td>
<td>esophagus</td>
<td>29</td>
<td>rectosigmoid wall</td>
<td>45</td>
<td>lower femur</td>
</tr>
<tr>
<td>14</td>
<td>heart</td>
<td>30</td>
<td>mandible</td>
<td>46</td>
<td>tibiae, patellae</td>
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<tr>
<td>15</td>
<td>liver</td>
<td>31</td>
<td>C-vertebrae</td>
<td>47</td>
<td>fibula</td>
</tr>
<tr>
<td>16</td>
<td>stomach wall</td>
<td>32</td>
<td>clavicles</td>
<td>48</td>
<td>ankle, feet</td>
</tr>
</tbody>
</table>
Simulation of the radiation field entering the patient

Output:
Neutron phase space (→ external)
Proton phase space (→ internal)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>12</td>
<td>169.2</td>
<td>10</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td></td>
<td>178.3</td>
<td>15</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>~9.1</td>
<td>164.0</td>
<td>9.2</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>~6.4</td>
<td>180.1</td>
<td>11.8</td>
<td>9.5</td>
<td></td>
</tr>
</tbody>
</table>
Simulation the patient/phantom as ‘virtual patients’
Equivalent dose: \[ H = w_R D \] - PROTONS -

Protons:
Kinetic energy dependence for proton \( w_R \):
\[
\begin{align*}
    w_R &= 1.1, \quad E_p/\text{MeV} > 1 \\
    w_R &= 2.5, \quad 0.5 \leq E_p/\text{MeV} < 1 \\
    w_R &= 5, \quad E_p/\text{MeV} < 0.5
\end{align*}
\]
Equivalent dose: \[ H = w_R D \] - NEUTRONS -

From: *Annals of the ICRP; ICRP Publication 92; Relative Biological Effectiveness (RBE), QualityFactor (Q), and Radiation Weighting Factor (w_R)*
Neutron RBE as a function of dose

![Graph showing Neutrons and X rays](image)

**Table 9.1—Summary of estimated RBE<sub>M</sub> values for fission neutrons versus gamma rays**

<table>
<thead>
<tr>
<th>End point</th>
<th>Range of values&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cytogenetic studies, human lymphocytes in culture</td>
<td>34—53</td>
</tr>
<tr>
<td>Transformation</td>
<td>3—80&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Genetic endpoints in mammalian systems</td>
<td>5—70&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Genetic endpoints in plant systems</td>
<td>2—100</td>
</tr>
<tr>
<td>Life shortening, mouse</td>
<td>10—46</td>
</tr>
<tr>
<td>Tumor induction</td>
<td>16—59</td>
</tr>
</tbody>
</table>

NCRP Report No. 104, The Relative Biological Effectiveness of Radiations of Different Quality
Computation of organ equivalent doses

\[ H = D_{pp1} \times 1.1 + D_{pp2} \times 2.5 + D_{pp3} \times 5 + D_{ep} \times 1.1 + (D_{pnw} + D_{enw} + D_{other}) \times w_R \]
Organ equivalent dose as a function of organ index (4-year-old phantom)

(a) Small Range and Mod

(b) Large Range and Mod

(c) Patient Fields
Total equivalent dose for the lungs

9-mo old (circles)
4-yr old (squares)
8-yr old (triangles)
11-yr old (circles)
14-yr old (squares)
adult (triangles)
External equivalent dose for the lungs

9-mo old (circles)  
4-yr old (squares)  
8-yr old (triangles)  
11-yr old (circles)  
14-yr old (squares)  
adult (triangles).
Internal equivalent dose for the lungs

9-mo old (circles)
4-yr old (squares)
8-yr old (triangles)
11-yr old (circles)
14-yr old (squares)
adult (triangles).
Total equivalent dose (dashed histograms)
Internal equivalent dose (solid histograms)
(8-year-old phantom)

(a) field 1
(b) field 2
(c) field 3
Internal versus external neutrons as a function of aperture opening

![Graph showing the relationship between aperture opening and internal/external neutrons.]

Internal versus external neutrons as a function of phantom age (large apertures)

![Graph showing the relationship between patient age and internal/external neutrons.]

MGH 1913
Organ equivalent dose
thyroid (circles)
lung (squares)
liver (triangles)
Organ equivalent dose as a function of distance (adult phantom)
Fit $H = (366.2 \times \text{distance}^{-1.861})$

(Wroe et al. 2007)
Neutron dose as a function of lateral distance

![Graph showing neutron dose as a function of lateral distance](image)

- IMRT (Klein06)
- Wroe07
- Yan02
- Mesoloras06
CONCLUSION (Part I)

- Neutron dose is mainly caused by neutrons from the treatment head.
- The neutron dose increases with increasing R/M.
- The neutron dose increases with decreasing aperture.
- Younger patients are subject to higher neutron doses.
- Typically, neutron doses from proton therapy are lower than scattered photon doses in IMRT.
BEIR, Health risks from exposure to low levels of ionizing radiation, BEIR VII, Phase 2. National Research Council, National Academy of Science, 2006

BEIR (Biological Effects of Ionizing Radiation) report:

Recommendation of dose-response relationships to allow risk assessment
as a function of dose
as a function of patient’s age
as a function of organ
Excess Relative Risk for Thyroid Cancer

Note: male phantom

4-year-old: $ERR \approx 1.3\%$
adult: $ERR \approx 0.02\%$
Excess Relative Risk for Thyroid Cancer

internal neutrons only

ERR\textsubscript{p} per treatment Gy (%)

- 4-year-old
- 8-year-old

field number

0.0 0.2 0.4 0.6

0 1 2 3 4 5 6 7

ERR\textsubscript{p} per treatment Gy (%)
Excess Relative Risk for Thyroid Cancer

External neutrons only

ERR per treatment (Gy (%))

4-year-old
8-year-old

Field number

0 1 2 3 4 5 6 7
Excess Relative Risk for Thyroid Cancer

Implies that beam scanning would reduce the risk by about 1 order of magnitude!
Excess Relative Risk for Thyroid Cancer

Assuming a 70 Gy treatment of a 4-yr old (worst case field):

\[ \text{ERR} \leq 1.2 \]

\[ (0.026 \text{ Sv/Gy} \times 70 \text{ Gy} / 1.5_{DDREF}) \]

Baseline lifetime incidence for Thyroid:

- male 0.23 %
- female 0.55 %

Numbers would increase by up to a factor of 2.2
Excess Relative Risk for Lung Cancer (depends on time since exposure)

ERR per treatment Gy (%)

- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

$t (yr)$

- 5
- 15
- 25
- 35
- 45

4-yr
9-mo
8-yr
11-yr
14-yr

small R/M fields
Excess Relative Risk for Lung Cancer

**ERR** per treatment Gy (%)

- **Patient 1**
- **Patient 2**

**e.g.**
- after 5 years: \( \text{ERR} \approx 0.8\% / 1.3\% \)
- after 15 years: \( \text{ERR} \approx 0.3\% / 0.6\% \)
Excess Relative Risk for Lung Cancer

e.g. 10-cm range field: 4-year-old: $ERR \approx 3.8\%$

adult: $ERR \approx 0.01\%$

5 years post treatment
Excess Relative Risk for Lung Cancer

ERR per treatment Gy (%) vs. field number

Field dependency

Age dependency

5 years post treatment
5-yr Excess Relative Risk for Lung Cancer

Assuming a 70 Gy treatment of a 4-yr old (worst case field):

\[ \text{ERR} \leq 3.6 \]
\[ (0.078 \text{ Sv/Gy} \times 70 \text{ Gy} / 1.5_{DDREF}) \]
5-year risk increase: factor of 4.6

Assuming a 70 Gy treatment of a 8-yr old (worst case field):

\[ \text{ERR} \leq 1.1 \]
\[ (0.023 \text{ Sv/Gy} \times 70 \text{ Gy} / 1.5_{DDREF}) \]
5-year risk increase: factor of 2.1
CONCLUSION (Part II)

- Neutrons generated during passive scattered proton beam therapy cause a non-negligible risk for the development of second malignancies.

- The risk seems to be negligible for adult patients.

- Neutron exposure has to be considered when treating pediatric patients.

- IMRT is not an option.
Nuclear data impact on proton radiation therapy calculations

- PET imaging for quality assurance
The principle of PET monitoring

In-vivo, non-invasive detection of $\beta^+$-activation induced by irradiation

Mainly $^{11}$C ($T_{1/2} = 20.3$ min) and $^{15}$O ($T_{1/2} = 121.8$ s)
Para-spinal tumor
176 x 147 x 126 slices
voxels: 0.932 x 0.932 x 2.5-3.75 mm³
3 fields: \(~15.0\) Gy each
PET/CT scanning of MGH proton patients

Time delay between end of treatment and PET/CT scan: 15 min

Scan time: 30 min

Siemens Biograph 16
PET imaging for proton therapy QA
Quantitative Analysis

[Graph showing activity and dose distribution across different depths and modalities.
- CT PET/CT
- CT TP
- Meas PET
- MC PET
- TP Dose
- MC Dose]
Used additional cross-sections values (lines) interpolated from experimental and evaluated data for proton induced reactions on O, N, P, Ca yielding $^{14}$O, $^{13}$N, $^{11}$C, $^{30}$P, $^{38}$K positron emitters.
Nuclear data impact on proton radiation therapy calculations

- Monte Carlo benchmarking
Benchmarking nuclear data

• Patient dose calculation
  ➡️ Predict secondary dose (1-3% effect)
    - Needed: Secondary proton yield in tissue -

• Neutron dose assessment
  ➡️ Predict cancer risk (20% uncertainty?)
    - Needed: Neutron yield in heavy materials and tissue -

• PET imaging
  ➡️ Assess beam range (1-2 mm effect)
    - Needed: Beta-emitter yield in tissue -
Benchmarking nuclear data

- Compare Monte Carlo simulations with experiments (directly, if possible, or indirectly)
How accurate do we know the cross sections?

Calculations typically use models, experimental data or hybrid approaches.
Electromagnetic interaction uncertainties

- Depth [mm]: 0 100 200 300
- Relative Dose: 0.0, 0.2, 0.4, 0.6, 0.8, 1.0
- Depth [mm]: 0 50 100 150 200
- Relative Dose: 0.30, 0.32, 0.34, 0.36, 0.38, 0.40, 0.42, 0.44

- Up to 10%
- Up to 4 mm
Nuclear interaction uncertainties

Depth [mm] 0 100 200 300
Relative Dose 0.0 0.2 0.4 0.6 0.8 1.0

Depth [mm] 0 50 100 150 200
Relative Dose 0.30 0.32 0.34 0.36 0.38 0.40 0.42 0.44

Depth [mm] 300 310 320 330 340
Relative Dose 0.0 0.2 0.4 0.6 0.8

up to 10% up to 4 mm

Nuclear interaction uncertainties
Benchmarking requires treatment head simulation
Beam characterization at nozzle entrance:

1. Beam size and spread (measured)
2. Beam angular spread (manufacturer info)
3. Beam energy (control system)
4. Beam energy spread (indirectly measured)

Multi-Layer Faraday Cup (MLFC)

Clean benchmark for nuclear models:
- separated nuclear buildup region
- device has 100% acceptance for charged secondaries
- technique measures charge, not dose (no problems of dosimeter linearity and response to particle types) (secondary electrons have no effect (will bind the ion left behind))

\[
\begin{array}{c}
\text{p}^+ \\
\text{Cu} \quad \text{Cu} \quad \text{Cu} \\
\text{A} \quad \text{B} \quad \text{C} \\
\text{p}^+ \quad \text{n}
\end{array}
\]

e.g., \((p, pn)\) charge: 0 (+p; -recoil) 1 (+p)
Multi-Layer Faraday Cup (MLFC) can be used for high and low-\( Z \)!

e.g., (p,pn) charge: 0 (+p; -recoil) 1 (+p)
MLFC – Charge Distribution

Nuclear interactions only
MLFC - Reference Physics

- Standard EM
- Binary cascade
- G4LElastic
- G4HadronElastic Process
- High-precision neutron
Nuclear Interactions: Branching Ratios

Six most probable reactions

160 MeV p beam
Nuclear data impact on proton radiation therapy calculations

TAKE-HOME MESSAGES

- Impact of nuclear interactions on dose
  Small effect in the organs at risk / beam path

- Neutron dose in proton beam therapy
  Important issue / uncertainties can be large

- PET imaging for quality assurance
  Uncertainties for PET emitters

- Monte Carlo benchmarking
  Difficult to do for reaction channels
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