A Real Time Dosimetric System using CMOS Sensors for Secondary Neutrons in Radiotherapy

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Out-of-field dose

- Technological developments to reduce the out-of-field dose:

Radiotherapy (photon)

Hadrontherapy (proton, ion)
Out-of-field dose

- Technological developments to reduce the out-of-field dose:
  → primary exit dose (photons, protons)

Radiotherapy (photon)

Hadrontherapy (proton, ion)

Figure 6. Overview of the lateral dose profiles measured for all radiation types and delivery techniques. The measurements were obtained with the diamond detector in the depth of maximum dose (15 mm for 6 MV photons, 31 mm for 18 MV photons and 125 mm for protons and carbon ions) during an irradiation with a 5×5 cm² field.

In fact, irradiations with smaller fields correspond to a higher number of primary ions stopped in the collimator and thus a larger yield of secondary neutrons. For scanned protons as light increases of the out-of-field dose is observed increasing fields size.

The higher number of primary protons necessary to produce a larger homogeneous field with the scanning technique is translated into a higher number of scattered protons which deposit their energy outside the target. Unlike protons, the dependence of the lateral dose distribution on the field size is very strong for carbon ions. A larger field size is translated into an increase of the out-of-field dose by up to one order of magnitude. This behavior is the direct consequence of the increasing yield of secondary particles produced through nuclear fragmentation with increasing number of primary ions required to irradiate a larger field. The irregular trend in the region up to 50 mm from the field edge is due to the fact that the experiment was not performed in the medical cave of GSI; therefore, the beam tuning quality was not as high as for the other measurements.

Finally, the behavior of the lateral dose profile for different delivery modalities was investigated. The comparison between passively delivered and scanned protons for a given field size (5×5 cm²) is shown in figure 5 (a) and (b). The beam shaped with passive elements is characterized by a sharper penumbra because of the presence of the collimator close to the water phantom which stops the primary protons scattered outside the field. At larger distances from the region directly irradiated (above 100 mm), the dose profile of the passively modulated beam flattens at around 2×10⁻⁴ Gy·treatment-Gy⁻¹ and stays rather constant up to 200 mm from the field edge, while the dose curve of the scanned beam drops sharply below 10⁻⁵ Gy·treatment-Gy⁻¹.

The overview and comparison of the results collected with the diamond detector are shown in figure 6 for 6 and 18 MV photons and ions of 125 mm range in water.

Independent of the radiation type and delivery technique, the lateral dose drops down to 10% of the target dose within 10 mm from the field edge; however, at increasing lateral distances the values for photons are a factor of 50–400 higher than that for charged particles.

Out-of-field dose

- Technological developments to reduce the out-of-field dose:
  - primary exit dose (photons, protons)
  - secondary dose (photons, neutrons, ions)

⇒ irradiation far away from the tumor (whole treatment room)
⇒ low dose region (less than 1% of the total dose)...but not without risks


Secondary neutrons production

- **External production:**
  - photo nuclear reactions \(\rightarrow\) X-ray radiotherapy (E > 10 MeV)
  - protons/ions nuclear reactions \(\rightarrow\) passive protontherapy

- **Internal production:**
  - beam interaction with the patient \(\rightarrow\) passive / active protontherapy

\[\text{Fluence (A.U.)} = 1.0E-09 \times \text{E (MeV)}\]

\(\Rightarrow\) thermal / fast neutrons separation very important for dose calculations

\(\Rightarrow\) neutrons always produced in a photon / neutron mixed field

Neutron measurements

- Neutrons production depends on various parameters:
  - room and accelerator design
  - beam (energy, field size, angle, ...)
  - patient (irradiated volume, morphology, ...)

⇒ large disparity of available neutron dosimetric data
Neutron measurements

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⇒ large disparity of available neutron dosimetric data

- Most widely used detectors: solid nuclear track detector (SNTD)

CR-39

✓ gamma transparent
✓ small size (in phantom measurements)
✗ thermal/fast neutrons separation (internal dose measurements)
✗ calibration (tracks ⇔ dose) dependent on neutron spectrum
✗ chemical etching (time consuming, no reuse)

⇒ new detector development to expand (simplify) neutron monitoring
Neutron detection

• **Fast neutrons**
  \[ n + H \rightarrow n + p \]
  Hydrogenated converters \((CH2)_n\)

• **Thermal neutrons**
  \[ n + ^{10}B \rightarrow \alpha + ^7Li \]
  Boron converters

\begin{itemize}
  \item 0.01 eV: Thermal
  \item 0.5 eV: Intermediate
  \item 200 keV: Fast
  \item 10 MeV: Relativist
\end{itemize}
CMOS-based neutrons counter

- Specially designed CMOS sensor for parallel detection of thermal and fast neutrons
- Compact and easy to use (real-time, integrated electronic, low power consumption)

64x64 micro-diodes

Neutron detection

- Neutrons are converted into:
  - protons ($n_{\text{fast}}$, PE)
  - 1.4 MeV alpha particles ($n_{\text{therm}}$, $^{10}\text{B}$)

Diagram showing:
- proton ($E > 0.6 \text{ MeV}$)
- alpha proton ($E < 0.6 \text{ MeV}$)

Layer details:
- Silicon layer ≈ 7-8 µm
- Epitaxial layer ≈ 14 µm
- Bulk
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- Neutrons are converted into:
  - protons ($n_{\text{fast}}, \text{PE}$)
  - 1.4 MeV alpha particles ($n_{\text{therm}}, ^{10}\text{B}$)
- Maximum proton energy loss $E_{\text{loss}} \approx 1$ MeV

Silicon layer $\approx$ 7-8 µm
Epitaxial layer $\approx$ 14 µm
Bulk
**Gamma transparency**

- High gamma transparency thanks to its very thin epitaxial layer (14 µm)
- Study gamma/neutrons (protons) signal distribution from 6/15 MeV LINAC

⇒ 100 keV cut on energy loss ⇔ 99.9% rejected photons (≈ 15% neutrons)
Fast / thermal neutrons separation

- Hardly achievable with CR-39 passive detectors
- Study signal distribution for various particle types in protontherapy

65 MeV proton beam experiment (CAL – Nice (France)):

Protons 65 MeV

PMMA 8cm

CMOS

Bragg peak \( d \approx 3\text{cm} \)

GATE Monte Carlo simulations

<table>
<thead>
<tr>
<th>Particle</th>
<th>Gamma</th>
<th>Electron</th>
<th>Secondary proton</th>
<th>Neutron</th>
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<tbody>
<tr>
<td>Energy [MeV]</td>
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</tbody>
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Fast / thermal neutrons separation

- Hardly achievable with CR-39 passive detectors
- Study signal distribution for various particle types in protontherapy

⇒ High purity selection with CMOS sensor by applying amplitude threshold
External neutrons monitoring (radiotherapy)

- Experiment on two Varian LINAC (16 MV TrueBeam (HCL), 15 MV NovalisTx (CPS))
- Fast / thermal neutrons production as a function of field size (jaws, 120 leaf MLC)
External neutrons monitoring (radiotherapy)

• Experiment on two Varian LINAC (16 MV TrueBeam (HCL), 15 MV NovalisTx (CPS))
• Fast / thermal neutrons production as a function of field size (jaws, 120 leaf MLC)
• About 5% (statistical) uncertainty with a unique 3 mm² CMOS sensor

Monte Carlo dose calculations

- Real-time neutron dosimetry using CMOS sensors and Monte Carlo algorithms

1. Neutrons measurements
   - CMOS sensors
   - \( (\Phi_{\text{therm}} + \Phi_{\text{fast}}) \)

2. Dose calculations
   - GATE simulation
   - Variance reduction techniques

⇒ time consuming process (≈ 250h to produce a dose map with 5% uncertainty)
Track Length Estimate (TLE)

- Variance reduction method applied to low-energy X-rays
- Continuous energy deposition between successive interaction point
- Local dose approximation

\[ \Phi = \frac{\sum_i T_i}{V} \]

\[ D = \Phi E \frac{\mu \rho n}{\rho} \]

Neutron interactions

Neutron

Thermal

Tissue C,N,O,H

Capture $^{14}\text{N}(n,p)^{14}\text{C}$

$E_{\text{th}}=0.62$ MeV
$E_{\text{p}}=0.58$ MeV
$E_{\text{recoilN}}=0.04$ MeV

$R_{\text{p}}$
$\sim 10\mu\text{m}$ in tissue

Capture $^{1}\text{H}(n,\gamma)^{2}\text{H}$

$E_\gamma = 2.2$ MeV
if $E_{\gamma\text{-max}} = 2$ MeV

$R_{\text{g}(2\text{MeV})}$
$\sim 1$ cm in tissue

Fast

Tissue C,N,O,H

Elastic Scattering

$E_{\text{tr}}(\text{H}) = E/2$ (avec $0\leq E_{\text{tr}}\leq E$)

$E_{\text{tr}}(\text{C}) = 0.142E$
$E_{\text{tr}}(\text{N}) = 0.124E$
$E_{\text{tr}}(\text{O}) = 0.083E$

$R = f(E_n)$

$\gamma$ - rays = Dominant contribution to the dose from thermal and intermediate neutrons

Recoil protons = Dominant contribution to the dose from fast neutrons
Neutron TLE (nTLE)

• Develop a dedicated TLE algorithm for neutron dose calculations

\[
\text{Dose} = \text{Kerma factor } (F_n) \times \text{neutron flux } (\Phi)
\]

• Kerma factors \((F_n)\) depend on materials composition

\[
F_n = 1.602 \times 10^{-8} \, \sigma \, N_t \, m^{-1} \, E_{tr} \, [\text{cGy} \cdot \text{cm}^2/\text{n}]
\]

cross-section \quad \text{atomic density} \quad \text{Energy transferred to charged particles}

• Local dose approximation :

\[\rightarrow\text{ OK for fast neutrons} \text{ (mean recoil protons range about 0.1mm)}\]

\[\rightarrow\text{ more difficult for thermal neutrons} \text{ (2.2 MeV gamma produce high energy electrons)}\]
Dose and Variance reduction

- Test dose algorithm on voxelized geometry (water)
- Good accuracy of dose estimates
- Uncertainty reduction from 6 to 20 (about 40 to 400 less computing time)
Heterogeneous materials

- Dose calculations for tissues, bones and lung materials

⇒ Promising results for 3D patient dose map calculations
Summary / Outlook

• Specially designed CMOS sensor for neutrons monitoring in radiotherapy

• First application of CMOS based counter for external / internal neutrons production
  —→ high gamma transparency
  —→ fast / thermal neutrons separation
  —→ easy to use (real-time, compact, 3V battery, ...)

• Coupling with fast Monte Carlo dose algorithm for patient 3D dose maps

• On-going system miniaturization ($\approx 1 \text{ cm}^2$) to realize in phantom measurements

Thanks for your attention