Fluence correction factors for graphite calorimetry in clinical proton beams using Geant4

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Overview

- Background
- Formalism for dose conversion and fluence correction factor
- Monte Carlo simulations: Geant4 and TotalAbsorber
- Results
- Future work and ideas
Background

- Quantity of interest in clinical proton beams is absorbed dose to water: no primary standards currently exist
- Water calorimeters have been successfully used
- Prototype graphite calorimeters also developed & demonstrated
- Graphite calorimetry: largest uncertainty in absorbed dose-to-water determination is conversion of dose-to-graphite to dose-to-water
- Dose conversion requires accurate determination of water-to-graphite stopping power ratios and fluence correction factors.
- This work: fluence correction factors determined initially for 60 & 200 MeV monoenergetic proton beams using Geant4.
Dose conversion and fluence correction factor

- **Fluence based approach** ($k_{fl}$, $k'_{fl}$):

  Dose to water: (in terms of $\Phi_g$)
  \[
  D_w(z_{w-eq}) = D_g(z_g) \cdot s_{w,g}(\Phi_g) \cdot k_{fl}
  \]
  with:
  \[
  z_{w-eq} = z_g \cdot \frac{r_{0,w}}{r_{0,g}}
  \]

  \[
  s_{w,g}(\Phi_g) = \sum_i \left[ \int_0^{E_{max,i}} \Phi_{E,g,i}(E) \cdot \left( \frac{S_{c,i}(E)}{\rho} \right)_w \cdot dE \right] / \sum_i \left[ \int_0^{E_{max,i}} \Phi_{E,g,i}(E) \cdot \left( \frac{S_{c,i}(E)}{\rho} \right)_g \cdot dE \right]
  \]

  Dose to water: (in terms of $\Phi_w$)
  \[
  D_w(z_{w-eq}) = D_g(z_g) \cdot s_{w,g}(\Phi_w) \cdot k'_{fl}
  \]

- **Alternatively, dose based approach** ($k_{fl}$):

  \[
  k_{fl} = \frac{D_w(z_{w-eq})}{D_g(z_g) \cdot s_{w,g}(\Phi_g)}
  \]
Monte Carlo simulations: **TotalAbsorber**

- **TotalAbsorber:** calculates depth dose and particle fluence distributions differential in energy at depths in a large slab phantom in a proton beam

- **Geometry / Beam line**
  - Cylindrical phantom with internal cylindrical-slab regions (replicated)
  - Pencil beam or full CCC passive beam line (mod wheel, range shifter etc)
Monte Carlo simulations: TotalAbsorber

- **Physics** (based on Hadrontherapy advanced examples)
  - **G4 (v9.0):** EM: ‘Low energy’ models, Nuclear (x3): Precompound, QGSP+BIC, QGSP+BERT
  - ICRU49 stopping power parameterisation
  - Production cuts (EM): 0.005mm, StepMax: 0.005mm

- **Scoring/tracking**
  - Total energy deposited per step (dose)
  - Stopping power data dumped for each particle type (G4EmCalculator)
  - Particle fluence spectra differential in energy (most common particle types, fixed bins widths, every 10th slab)

- **Simulations**
  - $10^6$ – $10^7$ initial proton events (NPL Distributed Computing Grid)
  - Post processing with Excel and/or Python scripts
Fluence correction: 60 MeV protons (G4 v9.0)

- Fluence method: \( k_{fl} \): thick lines, \( k_{fl}' \): symbols
- Dose method: \( k_{fl} \): thin line

With G4 stopping power data

With ICRU49 stopping power data

Stopping power ratios: 60, 200 MeV protons (G4 v9.0)

Water-to-graphite ratio vs depth for 60 MeV protons

Water-to-graphite ratio vs depth for 200 MeV protons
**Fluence correction: 60 MeV protons (G4 v9.0)**

Fluence correction formula:

\[ k_f = 0.9964 + 0.0024 \cdot z_{w-eq} \]

Dose correction formula:

\[ k_f = 0.9947 + 0.0024 \cdot z_{w-eq} \]

\( z_{w-eq} \) in g cm\(^{-2} \)

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**Graphical Representation**

- **Graph 1:**
  - Title: Fluence correction
  - X-axis: \( z_{w-eq} \) / g cm\(^{-2} \)
  - Y-axis: \( k_f \)
  - Data points for different models:
    - QGSP + BERT
    - QGSP + BIC
    - Precompound

- **Graph 2:**
  - Title: Dose correction
  - X-axis: \( z_{w-eq} \) / g cm\(^{-2} \)
  - Y-axis: \( k_f \) (from dose)
  - Data points for different codes:
    - Geant4
    - FLUKA
    - SHIELD-HIT
    - MCNPX

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Fluence correction: 200 MeV protons (G4 v9.0)

- Fluence method: $k_{fl}$: thick lines, $k_{fl}'$: symbols
- Dose method: $k_{fl}$: thin line

With G4 stopping power data

With ICRU49 stopping power data
60 MeV protons (G4 v9.6.p01): early results

$k_{fl}$ (fluence method): with G4 stopping power data

G4 stopping power data vs ICRU49
Summary and Future work

- Overview of the formalism, methods and issues for determining fluence corrections using Geant4 in two monoenergetic proton beams of clinical interest:
  - $k_{fl} < 1$ at surface, up to 1% (60 MeV) or 6% (200 MeV) above unity near BP
  - $k_{fl}$ and $k_{fl}'$ (fluence method) agree (within <0.05%)
  - $k_{fl}$ (fluence method): influence of stopping power data is small
  - Dose and fluence methods consistent when using actual stopping power data used in the simulations.
  - $k_{fl}$ (60 MeV): no significant dependence on nuclear interaction model
  - Stopping power data dumped by Geant4 appears quite different to ICRU49 over certain energy ranges

- Ongoing and future work:
  - Update with new releases of Geant4 (improved stopping power data?)
  - Extend to other materials e.g. water-equivalent plastics, design study (unity $k_{fl}$)
  - Simulate actual clinical beam lines e.g. CCC, scanned (TOPAS)
The National Measurement System is the UK’s national infrastructure of measurement Laboratories, which deliver world-class measurement science and technology through four National Measurement Institutes (NMIs): LGC, NPL the National Physical Laboratory, TUV NEL, The former National Engineering Laboratory, and the National Measurement Office (NMO).