Monte Carlo simulation with Geant4 for verification of rotational total skin electron therapy (TSET)

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Rotational total skin irradiation at UMAS

- Varian Clinac 2100 C/D
- 6 MeV electrons
- treatment SSD = 250 cm
- 36 cm x 36 cm field
- rotating platform
Aim of this study

- What is the absorbed dose in one rotation...?
- measure dose rate in a stationary geometry
- use the MC to relate to the treatment geometry

\[ R = \frac{\text{dose in a stationary geometry for 100 MU}}{\text{dose in one rotation}} \]

\[ R_{MC} = \frac{100 D_{MC}^{\text{stationary}}}{270 D_{MC}^{\text{rotation}}} \]
Simulated geometry

- beam incidence angle wrt phantom x-axis: $0^\circ \leq \vartheta < 360^\circ$
- the simulation scores energy deposition along x (‘z’)

$e$

X
The rotational depth dose distribution

\[ D_{MC}^{\text{rotation}} = \int_{\vartheta} D(z, \vartheta) \, d\vartheta \]

\[ D_{MC}^{\text{rotation}} \approx w_0 D_{MC}^{\vartheta=0^\circ} + 2 \sum_{\vartheta} w_\vartheta D_{MC}^{0^\circ < \vartheta \leq 90^\circ} + 2 \sum_{\vartheta} w_\vartheta D_{MC}^{90^\circ < \vartheta < 180^\circ} + w_{180^\circ} D_{MC}^{\vartheta=180^\circ} \]

\[ D_{MC}^{\text{rotation}} \approx w \left( D_{MC}^{\vartheta=0^\circ} + 2 \sum_{\vartheta} D_{MC}^{0^\circ < \vartheta \leq 90^\circ} \right) \]

\[ w = \frac{\Delta \vartheta}{360^\circ}, \quad \Delta \vartheta = 5^\circ, 10^\circ \]
The simulation

- geometry: homogeneous water phantom
- physics models: standard em and low-energy em
- production thresholds:
  - air: 10 keV for photons/electrons
  - water: 10 keV photons, 100 keV/10 keV
- maximum allowed step length: not set
**SteppingAction**

- score energy distributions
- grid of 0.5 mm along x-axis
- scoring volume: cylinder of radius \( r \) (not built in the geometry)
- check if step is in a water volume
- check if step is within/crossing cylinder
- find energy deposition in scoring volume
- split energy deposition in the grid
- fill energy histogram
Primary Generation: ‘OTP electrons’

- parametrization of a Varian 2100C/D accelerator with 25x25 applicator
- virtual source position: 85 cm upstream the isocenter
- exit phase space plane: 5 cm upstream the isocenter
- field size 36 cm x 36 cm (yz plane)
- y and z coordinates from flat distribution
- direction cosines corrected for scattering in accelerator
- correction independent of radial displacement
- only direct electrons simulated
- energy sampled from OTP spectrum
**OTP energy spectrum**

- extracted for PDD measured at SSD = 100 cm: $D_{meas}(z)$
- precalculated $D_{mono}(E, z)$ with VMC++
- $E$ is the kinetic energy of the primary electrons
- assuming an energy spectrum $F(E)$ with unknown constants
- PDD is given by: $D(z) = D_\gamma(z) + \int F(E)D_{mono}(E, z)dE$
- the unknown constants in $F(E)$ are calculated by fitting
- $D_{meas}(z)$ by $D(z)$
the distribution is fitted for $z > 4$ mm to neglect low-energy electrons that deposit energy close to the surface of the phantom.
Kinetic energy of primary electrons
Overview of the simulations (uniform thresholds)

Stationary geometries (r = 2 cm, cubic phantom 50 cm side):
- SSD = 100 cm, standard em physics
- SSD = 100 cm, low-energy em physics
- SSD = 250 cm, low-energy em physics

Rotational geometries (SSD = 250 cm, low-energy em physics):
- test runs: r = ?, \( \Delta \vartheta = ? \), \( N = ? \) if \( \sigma_{RC} \approx 2\% \)
  - ellipsoid phantom 35 cm in x, 50 cm in z, 25 cm in y
    - run 1: \( r = 2 \) cm, \( \Delta \vartheta = 10^\circ \) (10 M events/angle)
    - run 2: \( r = 0.5 \) cm, \( \Delta \vartheta = 10^\circ \) (100 M events/angle)
    - run 3: \( r = 0.5 \) cm, \( \Delta \vartheta = 5^\circ \) (100 M events/angle)
- ellipsoid phantom 20 cm in x, 40 cm in z, 25 cm in y
- cylindrical phantom 30 cm diameter, 25 cm height
Comparison MC/measurement at SSD=100 cm

![Graph showing comparison of MC/measurement at SSD=100 cm]
Comparison MC/measurement at SSD=250 cm

![Graph showing comparison of MC and measurement data at SSD=250 cm. The graph plots depth (mm) against dose (Gy/MU). Two curves are shown: one for measured data and another for low-energy data. The curves peak around depth 20 mm and then decrease rapidly.]
Results of test run 1 ($r = 2 \text{ cm, } \Delta \theta = 10^\circ$)

![Graphs showing depth (mm) vs. D (Gy/event) for different angles](image)

- Stationary
- 10 degrees
- 20 degrees
- 30 degrees
- 40 degrees
- 50 degrees
- 60 degrees
Results of test run 1 \((r = 2 \text{ cm}, \Delta \vartheta = 10^\circ)\)

Is the surface dose too high at large beam angles?

![Graph showing depth vs. dose for 70, 80, and 90 degrees angles.](image)
Results of test run 1 \((r = 2 \text{ cm}, \Delta \vartheta = 10^\circ)\)
Results of test run 1 ($r = 2 \text{ cm}, \Delta \vartheta = 10^\circ$)

- Stationary depth dose
- Rotational depth dose

![Graph showing R vs. depth and σ_{stat} vs. depth](image-url)
Test runs: difference in stationary depth dose
Test runs: difference in rotational depth dose

\[ D \text{ (Gy/event)} \]

\[ \Delta D_{\text{rot}} \text{ (Gy/event)} \]

- \( r = 2 \text{ cm}, \Delta \theta = 10^\circ \)
- \( r = 0.5 \text{ cm}, \Delta \theta = 10^\circ \)
- \( r = 0.5 \text{ cm}, \Delta \theta = 5^\circ \)

![Graph showing depth dose difference](image-url)
Test runs: difference in $R$
Simulation parameters

Subsequent simulations were run with the following parameters:

- a scoring volume radius of 2 cm
- a step $\Delta \vartheta = 10^\circ$ in angle of beam incidence
- 10 million events per angle for $\vartheta > 0^\circ$
- 40 million events for $\vartheta = 0^\circ$
Dependence on phantom cross-section

![Graph showing dependence on phantom cross-section](image-url)
Thresholds by region for the cylindrical geometry

- inner phantom with 10 keV threshold for electrons:
  - outer radius: 15 cm, inner radius: 11 cm
  - $\Delta \phi = 30^\circ$
Threshold dependence at SSD = 250 cm

![Graph showing depth (mm) vs. D_{stat} (Gy/event) at 10 keV and 100 keV, with a peak around 10 mm depth with decreasing values as depth increases.]

![Graph showing depth (mm) vs. D_{rot} (Gy/event) at 10 keV and 100 keV, with a decrease in values as depth increases.]
Threshold dependence at SSD = 250 cm

θ = 10°
- 10 keV
- 100 keV

θ = 20°
- 10 keV
- 100 keV
Threshold dependence at SSD = 250 cm

\[ D \text{ (Gy/event)} \times 10^{-13} \]

\[ \theta = 30^\circ \]
- 10 keV
- 100 keV

\[ D \text{ (Gy/event)} \times 10^{-13} \]

\[ \theta = 40^\circ \]
- 10 keV
- 100 keV
Threshold dependence at SSD = 250 cm

\[ \theta = 50^\circ \]

- 10 keV
- 100 keV

\[ \theta = 60^\circ \]

- 10 keV
- 100 keV
Threshold dependence at SSD = 250 cm

![Graph showing threshold dependence at SSD = 250 cm for different angles and energy levels.](image-url)
Absorbed dose in one rotation at the prescription depth (5 mm):

- without degrader:
  \[ R = 0.88 \]
  fraction dose = 2 Gy

- with degrader:
  \[ D^{rot} = 0.42 \text{ Gy}, \quad N^{rot} = 5 \]
  \[ D^{rot} = 0.23 \text{ Gy}, \quad N^{rot} = 9 \]
Threshold dependence at SSD = 100 cm

![Graph showing D (Gy/MU) vs. depth (mm) for different energies: measured, 100 keV, and 10 keV.](image-url)
Threshold dependence at SSD = 100 cm

- VMC++
- 100 keV
- 10 keV
Conclusions

- the low-energy em physics model gives a good agreement both with measurements and with VMC++
- the simulation has a dependence on the electron production threshold (when no limit on step length is set)
- $R$ can be calculated for 100 keV electron threshold
- step length distribution?
- dependence on beam angle?
- set maximum step length?
- ...