A prototype calorimeter for HDR $^{192}$Ir brachytherapy sources

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Overview

- Absorbed dose measurements for brachytherapy
- MC calculations for calorimeter design parameters
- MC calculated correction factors
- Heat transfer simulations
- Conclusions
- Future work
Proposed measurement method: calorimetry

- Objective: investigate feasibility of calorimetry for brachytherapy
- Alternative method to current air kerma based approach (using reference air kerma rate (RAKR), dose rate constant $\Lambda$ and TG-43 to derive absorbed dose)
- Direct measurement of absorbed dose

$$D_{\text{point}} = \frac{E_{\text{rad}}}{m} = c_p \Delta T$$
Problems in brachytherapy dosimetry

- High dose gradient over clinically relevant range (0.5 cm to 5 cm from source centre) resulting in heat flow down temperature gradients

- Self-heating of radioactive source

- Huge variety of brachytherapy source designs
Schematic drawing of prototype calorimeter (RZ-geometry)

- $R = 10\,\text{cm}$
- $Z = 14\,\text{cm}$

Absorber:
- Graphite ring, 2 mm x 5 mm, $R = 2.5\,\text{cm}$
- 1 mm vacuum gap
- Various aspects of calorimeter modelled with DOSRZnrc

- Source (Nucletron microSelectron Classic):
  - Bare $^{192}\text{Ir}$ spectrum used for $^{192}\text{Ir}$ cylinder
  - AISI 316L stainless steel encapsulation
Build-up curves in water and graphite

Nucletron microSelectron Classic Ir-192 source in water and graphite

- $(\mu_{en}/\rho)^{w_g} = 1.11$ for mean $^{192}$Ir energy
- Energy dependent $\rightarrow$ calculate fluence spectrum
Scatter build-up along R-axis

ROI = 1 mm x 1 mm
Scatter build-up in graphite

Min. R required at ROI to get 99.9% and 99.5% of $D_{\text{full scatter}}$

\[ y = 4.0377x \]

<table>
<thead>
<tr>
<th>min. R, cm</th>
<th>99.9% of max.</th>
<th>99.5% of max.</th>
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Radial distance of ROI from source centre, cm
Variation of $D_{\text{average}}$ with core height

$D_{\text{average}}(\text{core height}) / D_{\text{full scatter}}$ at various ROIs
## Summary of MC simulations

<table>
<thead>
<tr>
<th>Source to core, cm (graphite)</th>
<th>Build-up</th>
<th>Min. R, cm</th>
<th>Min. Z/2, cm</th>
<th>Max. core height, cm</th>
<th>Dose gradient over 2 mm, %</th>
<th>Dose rate from 370 GBq source, Gy/s</th>
<th>ΔT in 120 s, K</th>
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<td>1</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>X</td>
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<td>✓</td>
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</tbody>
</table>
Calorimeter correction factors

\[ k_{\text{vol}} = \frac{D_{\text{point}}}{D_{\text{core}}} = 1.0033 \]

\[ k_{\text{inh}} = \frac{D_{\text{core, graphite}}}{D_{\text{core, graphite+air+metal}}} \]

\[ k_{\text{gap}} = \frac{D_{\text{core, graphite}}}{D_{\text{core, graphite+vacuum gap}}} \]

‘point’ = 0.1 mm x 0.1 mm

core = 2 mm x 5 mm

vol

inh

gap

Z

R

point' = 0.1 mm x 0.1 mm

core = 2 mm x 5 mm

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Inhomogeneity correction due to aluminium tube

Percentage change of dose to core due to absorption and scatter in aluminium tube

![Graph showing percentage change of absorbed dose vs. thickness of aluminium tube. The x-axis represents thickness in cm, ranging from 0 to 0.1, and the y-axis represents percentage change in absorbed dose, ranging from -0.25% to 0.05%. The graph shows a linear trend with data points at various thicknesses and their corresponding percentage changes.]
Inhomogeneity correction due to stainless steel tube

Percentage change of dose to core due to absorption and scatter in stainless steel tube

![Graph showing the percentage change of dose to core due to absorption and scatter in stainless steel tube. The graph plots the thickness of the stainless steel tube against the percentage change of absorbed dose, with a clear downward trend.]
Gap correction factor

Percentage change of dose to core due to vacuum gap

Percentage change of absorbed dose, %

Thickness of vacuum gap, mm

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Displacement correction factor, Z-axis

\[ k_{\text{disp},Z} = \frac{D_{\text{central}}}{D_{\text{displaced}, Z=0.25\text{mm}}} = 1.0002 \]

Absorbed dose to core with respect to source position

Absorbed dose, Gy

Source position relative to centre, cm

Series1
Poly. (Series1)
Displacement correction factor, R-axis

\[ D(r) \propto \frac{1}{r^2} \]

\[ D(r + \varepsilon) \]

\[ \varepsilon = d \cos \theta \]

\[ \iint d\theta dr D(r + d \cos \theta) \]

Taylor expansion

\[ \frac{D_{\text{displaced}}}{D_{\text{symmetric}}} \approx 1 + \frac{3}{2} \frac{d^2}{r^2} \]

0.1%

With \( r = 25 \text{ mm} \)

\[ \Rightarrow d = 0.64 \text{ mm} \]
• Maximum source activity = 550 GBq
• Self-heating due to gamma radiation = 1.04E-2 W
• Self-heating due to electrons = 1.59E-2 W
• Total self-heating power = 2.63E-2 W
Heat transfer simulations

- Main modes of heat transfer:
  - Conduction
  - Thermal radiation
- Heat equation: solved by finite element modelling
- Stationary and transient solutions
Example: heat conduction from self-heating and radiative heating

Change of core temperature, K

Time, s

No conduction
Self-heating and radiative heating, $T_{\text{init}} = 10$ K
Self-heating, $T_{\text{init}} = 10$ K
$T_{\text{init}} = 0$ K
Control of self-heating effect, stationary solution, thermostatic mode

Thermistor 1+2:
-45.55 W m⁻²
Modes of operation

- Adiabatic mode
- Measurement of temperature difference

- Thermostatic mode
- Electrical substitution method
- Advantage: rapid repetition of calorimeter runs is possible
Conclusions + future work

• **Prototype calorimeter for HDR brachytherapy sources:**
  – Suitable dimensions and materials derived from MC simulations
  – Vacuum gap around core to control self-heating effect of radioactive source
  – Heat transfer simulations used to find optimum position for thermistors and maximum heating power required per component

• **Future work:**
  – Build, test and characterise calorimeter + refine correction factors for final design
  – Work out conversion from absorbed dose to graphite → water
  – Measure absorbed dose and compare with RAKR approach and TG43
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