Radiation Exposure Assessment during replacement of a Linear Accelerator

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St Vincent’s Hospital, Sydney

Australia’s Second Oldest Hospital

- Opened in 1857
- Moved in 1870

Major public hospital
Principal referral hospital
Mission to care for the sick, the poor and the homeless
Cancer Service – Radiation Oncology

Radium Department opened in September 1913, X-ray therapy capability added in 1928
Radiation Oncology Service moved to the current location in 2005
Comprehensive radiotherapy treatment services including brachytherapy and external beam treatment.

- Siemens Primus linear accelerator, multi-energy multi-modality
- Pantak superficial/deep therapy unit
- Nucletron High Dose Rate Brachytherapy unit
- CT simulator

Internationally recognised as a leader in prostate brachytherapy
Strong referral base from within the St Vincent’s campus, the local community and regional areas
Linear Accelerator Treatment Bunker

Siemens Primus Linear Accelerator

- Photon beams (6 MV and 10 MV)
- Electron Beams (6-21 MeV)
- Conformal 3D RT
- IMRT
- Megavoltage imaging

Replaced with an Elekta Versa HD Linear Accelerator in 2013

Linear Accelerator Treatment Bunker design included a window

- provide natural light into the treatment bunker
- improve the patient’s experience
Historical Radiation Monitoring

Presbytery building adjacent to the bunker window
Original Shielding Design considered radiation levels in the building.
• Below regulatory criteria – 1 mSv/a

Verification radiation survey by shielding consultant

Long term monitoring – Quartz Fibre
• Piano room 0.5 mSv above background in 280 days
• Corrected estimate of 0.65 mSv/a

Positional monitoring shows consistent dose rate over time.
Lead installed over the window
5 mm thickness
Replacement Linear Accelerator - 2013

Shielding assessment requested by St Vincent’s Hospital

Initial Radiation Survey undertaken for the old linear accelerator

Dose rate measured at the window of rooms on each of the 4 levels of the adjacent building:

- Beam field size 1600 cm² and Beam Energy 10 MV, with and without phantom
- Gantry positioned at 225°, 240° and 275° depending on floor
- 50 treatments per day, 5 days a week, 52 weeks per year
- 2.5 Gy and 0.5 min per treatment

Annual Dose estimated as measured dose rate for 25% of the treatment time.

Significantly higher than historical monitoring

Does the scenario accurately match operations?
Retrospective Dose due to historical operations?
## Review of Historical Operations

### Clinical Workload
- **Daily patients treatments**
  - 60% or less

### Annual Beam Usage
- **Greater than the assumed 108 hours**
- **75% to 80% of usage at a lower beam energy**
- **Includes beam warm up time**

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatments per day</th>
<th>Annual Beam Usage 6MV (h)</th>
<th>Annual Beam Usage 10 MV (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>21</td>
<td>95</td>
<td>19</td>
</tr>
<tr>
<td>2006</td>
<td>25</td>
<td>112</td>
<td>39</td>
</tr>
<tr>
<td>2007</td>
<td>27</td>
<td>124</td>
<td>43</td>
</tr>
<tr>
<td>2008</td>
<td>29</td>
<td>152</td>
<td>39</td>
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<td>2009</td>
<td>30</td>
<td>122</td>
<td>37</td>
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<tr>
<td>2010</td>
<td>27</td>
<td>107</td>
<td>35</td>
</tr>
<tr>
<td>2011</td>
<td>21</td>
<td>98</td>
<td>24</td>
</tr>
<tr>
<td>2012</td>
<td>15</td>
<td>80</td>
<td>21</td>
</tr>
</tbody>
</table>
Review of Historical Operations

Gantry Position
Cardinal angles ~ 80% of beam usage
In building dose rate unknown
Least fraction of use towards the adjacent building
13.6% - 225° to 315°
Retrospective Dose Estimate

Independent Consultant SGS Australian Radiation Services (SGS ARS)

Dose Rate 0.3 m inside the window on each floor
Dose Rate at occupied positions in rooms on floor 2 and 3
Dose rate measure for all combinations of the following linear accelerator settings:

• Beam Energy – 6 MV and 10 MV
• Beam Field Size – 1600 cm² and 400 cm²
• Gantry Position – 0°, 90°, 180°, 270°

Combined with historical beam time and gantry position data to estimate annual dose for the years 2005 to 2012
Estimated annual dose at the window

Conservative estimate

Full occupancy – 2000 h

80% of beam use at field size < 400 cm²

Annual Dose in the adjacent building has not exceeded 1 mSv/a

<table>
<thead>
<tr>
<th>Year</th>
<th>Room A (mSv)</th>
<th>Room B (mSv)</th>
<th>Room C (mSv)</th>
<th>Room D (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.13 – 0.20</td>
<td>0.38 – 0.51</td>
<td>0.31 – 0.42</td>
<td>0.04</td>
</tr>
<tr>
<td>2006</td>
<td>0.23 – 0.32</td>
<td>0.60 – 0.81</td>
<td>0.50 – 0.67</td>
<td>0.13</td>
</tr>
<tr>
<td>2007</td>
<td>0.26 – 0.37</td>
<td>0.68 – 0.91</td>
<td>0.56 – 0.76</td>
<td>0.15</td>
</tr>
<tr>
<td>2008</td>
<td>0.28 – 0.40</td>
<td>0.75 – 1.01</td>
<td>0.62 – 0.84</td>
<td>0.13</td>
</tr>
<tr>
<td>2009</td>
<td>0.23 – 0.34</td>
<td>0.62 – 0.84</td>
<td>0.51 – 0.70</td>
<td>0.12</td>
</tr>
<tr>
<td>2010</td>
<td>0.21 – 0.30</td>
<td>0.55 – 0.74</td>
<td>0.45 – 0.62</td>
<td>0.12</td>
</tr>
<tr>
<td>2011</td>
<td>0.16 – 0.23</td>
<td>0.43 – 0.58</td>
<td>0.36 – 0.48</td>
<td>0.07</td>
</tr>
<tr>
<td>2012</td>
<td>0.13 – 0.18</td>
<td>0.34 – 0.45</td>
<td>0.28 – 0.38</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Estimated annual dose at occupied positions

<table>
<thead>
<tr>
<th>Year</th>
<th>B North (mSv)</th>
<th>B South (mSv)</th>
<th>C North (mSv)</th>
<th>C South (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.13</td>
<td>0.03</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>2006</td>
<td>0.37</td>
<td>0.09</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>2007</td>
<td>0.42</td>
<td>0.10</td>
<td>0.06</td>
<td>0.01</td>
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<td>2009</td>
<td>0.34</td>
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<td>2011</td>
<td>0.19</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
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<tr>
<td>2012</td>
<td>0.15</td>
<td>0.04</td>
<td>0.02</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Conservative estimate based on dose rate measured at workstations

- Full occupancy – 2000 h
- 80% of beam use at field size < 400 cm²

Annual dose limit has not exceeded 1 mSv/a
Optimisation of bunker shielding

Opportunity to reduce exposure to the adjacent building

Primary and Secondary shielding of correct thickness

Exposure must be related to the window

Not due to direct patient scatter, head leakage radiation

Secondary scatter of head leakage and patient scatter radiation

Conceptually similar to maze scatter calculation for a single reflection, NCRP151
Window Shielding Calculations

Reduce the radiation scattered from Wall W towards the point of interest

Based on NCRP 151 methodology and factors

Shielding required at H dependent on key parameters:

Energy of the secondary scatter radiation from the wall
  • Determines TVL of the shielding
The scatter factor for the scatter wall
Distance from source to wall and wall to point of interest
  • Determined in the horizontal plane only

Wall Scatter Area
Wall Scatter Area

The wall scatter area was determined by mapping the back projection of the visible line of sight from the scatter wall to windows in the adjacent building.
Wall Scatter Area
Scatter Area as a function of height above window base

Scatter Area (sqm) vs Height Above Window Base (m)

- Red: Area 1
- Orange: Area 2
- Green: Area 3
- Purple: Area 4
- Black: Total Area
Relative Influence of the Combined Effects of Area, Distance & Albedo

Combined Factor

Height Above Window Base (m)

Area 1
Area 2
Area 3
Area 4

0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00

0 2 4 6 8 10
Window Shielding Calculation

Shielding thickness calculated using the following basic parameters

- Dose Criteria of 0.3 mSv/a
- Clinical workload of 50 treatments/day and 4Gy/treatment
- Energy of secondary scattered radiation at the window shielding – 0.5 MeV
- Scatter Factor for 45° incidence and 45° reflection
- Wall scatter area of 15 m²

The shielding thickness was tested for a range of variations in the basic parameters

- Calculated shielding thickness ranged from 0.3 m to 0.4 m
- Shielding blocks were installed at a thickness of 0.6 m
Shielding Verification

Measures dose rate 0.3 m inside the window of Room B, only
Linear accelerator matched to SGS ARS survey
Gantry position, Beam Energy and Beam Field Size

Dose rates also measured at a field size of 100 cm\(^2\)
Gantry position, Beam energy

Replicated the SGS ARS methodology
Beam Field Sizes of 400 cm\(^2\) and 1600 cm\(^2\)

Estimated radiation dose of 0.36 mSv/a at the window of Room B
SGS ARS Highest radiation dose estimated in the range of 0.75 - 1.01 mSv/a

Estimate varied to also account for 100 cm\(^2\) field size usage
Estimated Radiation dose ranged from 0.30 to 0.34 mSv/a
Rotational dose estimate

Radiation dose was recorded for a single arc beam.
1.5 min Arc time, 6 and 10 MV, with and without FFF

Average of 4 Arc beams in Rooms A, B and C

Annual dose estimated by scaling the arc measurement to annual historical beam workload

Room B: 0.29 mSv/a for VMAT,
A: 0.24 mSv/a, C: 0.25 mSv/a

Reminder 0.36 mSv/a for 3DCRT

Still need to determine a suitable proportion of Arc therapy to 3D conformal radiotherapy

For example 30% VMAT => 0.34 mSv/a in Room B - ???
Conclusion

Historical Dose below limit in the adjacent building
Additional shielding reduced exposure in the adjacent building
Radiation dose from future operations will remain below the limit
Long term radiation monitoring will be implemented
Personal and positional

Worse case methodology significantly overestimated radiation exposure
Carefully consideration is required before applying the worse case methodology to an existing practice
The methodology is most suitable for the design of new treatment bunkers
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Thank You