Validation of linac bunker shielding calculations

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Photo 1 - Steel reinforcing also present in concrete walls

Photo 2 – External primary and secondary shielding for T4 bunker,

Photo 3 –Penetrations such as ducts for service supply present in secondary barriers

Introduction

A recommended method for determining shielding requirements for linear accelerator bunkers is to use the formulae described in NCRP 151.

These straightforward formulae use published data (tenth value layers, scatter fractions and reflection coefficients) along with the user's bunker dimensions and linac output data to determine dose rates in the surrounding environment.

The objective of this work was to validate design calculations by comparing the dose rates calculated using NCRP 151 methodology to actual measured values for our linac bunker (photo 2).

Method

Input data for the calculations:

Dimensions (relevant path lengths, ***d***; barrier thickness, ***t***; exposed wall areas, ***A***) were electronically measured from a scaled drawing imported into ImageJ (v1.44p) software.

Tenth value layers (***TVL***), scatter fractions (a_θ) and wall reflection coefficients (α) were taken from NCRP 151 data tables.
A 40 cm x 40 cm field size (as specified in NCRP 151) was assumed and the leakage factor (L_f) taken as 0.1%.

Prior to the bunker construction, instantaneous dose rate at the isocentre (IDR_0) was determined from the linac technical specifications and this was confirmed following linac commissioning (the IDR_0 value for both energies was 300 Gyh^{-1}).

Primary and secondary barrier calculations:

Equations 1-4 were used to calculate the expected dose rates behind primary and secondary barriers. The position behind the primary barrier required a contribution for primary attenuation (equation 2) and scatter and leakage contributions (equations 3 and 4) were calculated using a scatter angle of 10 degrees. Secondary barriers only required scatter and leakage components.

Maze entrance calculations:

The total dose rate at the maze entrance (equation 5) requires the user to visualise the paths for 4 components: radiation scattered from the patient down the length of the maze (equation 6, IDR_p), primary beam attenuated by the inner maze wall and scattered off the outer maze wall (equation 7, IDR_w), linac leakage radiation scattered down the length of the maze (equation 8, IDR_L) and linac leakage radiation attenuated by the inner maze wall to the maze entrance (equation 9, IDR_T).

Our bunker design closely resembled one of the examples worked through in IAEA report 47 and this was used to assist visualisation and determine which angle reflection coefficients, wall areas and path lengths data to use. Annotations are consistent with equations given in this reference.

Measurements:

Dose rate measurements were made using a Victoreen 450P ion chamber (S/N 3452). Measurement positions were at 30 cm from wall surfaces, at the maze entrance and the operator's position at the control desk.

Primary barrier measurement was made with a 40 cm x 40 cm field size, gantry directed towards the primary barrier, 45 degree collimator rotation and with nothing in the radiation beam.

All other measurements (secondary barriers and maze entrance) had the gantry pointing towards the maze entrance; 30 cm of solid water scattering material at the isocentre and the same field size and collimator rotation.

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Equations

$$IDR = IDR_{1^\circ} + IDR_{sca} + IDR_L \tag{1}$$

$$IDR_{1^\circ} = \frac{IDR_0 10^{-\left\{1+\left[\frac{(t-TVL_1)}{TVL_e}\right]\right\}}}{d_{pri}^2} \tag{2}$$

$$IDR_{sca} = \frac{IDR_0\left(\frac{F}{400}\right)a_\vartheta 10^{-\left(t/TVL_{sca}\right)}}{d_{sca}^2 d_{sec}^2} \tag{3}$$

$$IDR_L = \frac{IDR_0 L_f 10^{-\left\{1+\left[\frac{(t-TVL_{L1})}{TVL_{Le}}\right]\right\}}}{d_L^2} \tag{4}$$

$$IDR_{maze} = IDR_p + IDR_w + IDR_L + IDR_T \tag{5}$$

$$IDR_p = \frac{IDR_0 a_\vartheta \left(F/400\right)(\alpha_1 A_1)\ldots(\alpha_{n-1}A_{n-1})}{(d_{sca}\times d_1\ldots d_n)^2} \tag{6}$$

$$IDR_w = \frac{IDR_0 10^{-\left\{1+\left[\frac{(t-TVL_1)}{TVL_e}\right]\right\}}(\alpha_p A_p)}{(d_p d'')^2} \tag{7}$$

$$IDR_L = \frac{IDR_0 L_f (\alpha_1 A_1)}{(d_i d'')^2} \tag{8}$$

$$IDR_T = \frac{IDR_0 L_f 10^{-\left\{1+\left[\frac{(t-TVL_{L1})}{TVL_{Le}}\right]\right\}}}{d_t^2} \tag{9}$$

Results

Dose rates measured and calculated from equations 1-9 are displayed in Figure 1 and Table 1 below.

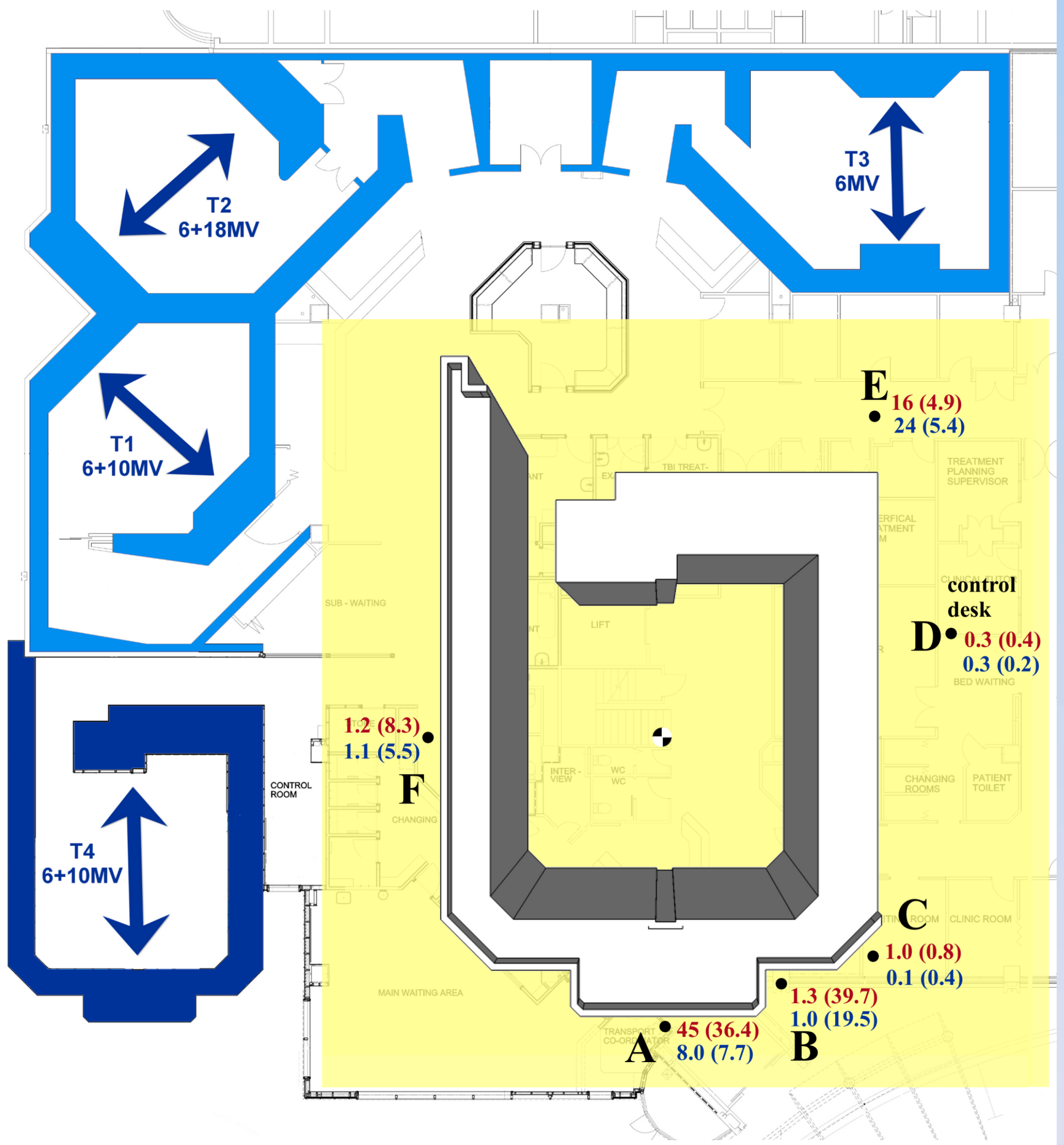

Figure 1: *Plan showing the location of 4 linacs at Christchurch Hospital. Inset gives measured and calculated (in brackets) dose rates around T4 linac bunker. 10MV results shown in red, 6MV in blue. All readings in μSvh^{-1}*

Position	6MV (μSvh^{-1})		10MV (μSvh^{-1})	
	Measured	Calculated	Measured	Calculated
A	8.0	7.7	45.0	36.4
B	1.0	19.5	1.3	39.7
C	0.1	0.4	1.0	0.8
D	0.3	0.2	0.3	0.4
E	24.0	5.4	16.0	4.9
F	1.1	5.5	1.2	8.3

Table1: *Calculated and measured dose rates*

Discussion

Results are presented for both 6 MV and 10 MV photon energies. From the limited data the following observations were made:

Primary:	Calculations tend to under estimate the actual dose rates at both energies.
Secondary:	In the area adjacent to the primary shield (position B, figure 1) the calculation does not take into account the extra concrete from the primary barrier and so the actual dose rates are overestimated.
Maze entrance:	Dose rates for the maze were underestimated in this case.

The calculations provide a quick and simple method of determining likely dose rate beyond barriers. Our bunker is one of simple design with uniform thickness barriers and straightforward geometry. It therefore provides a useful test for the calculations. Equations used are simplistic and some differences between model and reality are listed below:

Limitations of the calculation:

- IDR_0 is a component in all calculations. This was taken from the linac technical manual. The specification will differ from the actual value for IDR_0.
- The concrete material of the barriers also contains large amounts of steel (see photo 1). Other materials are also in the path of the radiation and not accounted for (furniture, services etc (photo 3)).
- The TVL data presented in NCRP is for solid concrete of uniform density 2.35 gcm^{-3} and broad beam radiation fields.
- NCRP data is calculated/measured for radiation fields that may differ from the characteristics of our x-ray beam.
- NCRP scatter fraction data is for a 20 cm x 20 cm field size. Our calculation uses these scatter fractions scaled to compensate for the larger field size used when performing the radiation survey.
- The maze calculations depend on a subjective determination of scatter paths. They make no account for variations in ceiling height, partial irradiation of barriers or other structures that may be in the scattered radiation field.
- The inverse square distance correction is only strictly valid for a point source. Scatter and leakage radiation are not point sources.
- The maze entrance calculations do not account for attenuation of radiation within the scattering material.
- Typical leakage is 5 times or more lower than the 0.1% value used in calculations.
- Barrier thicknesses were taken at the minimum dimension (i.e. slant thicknesses were not used for radiation incident at an angle to the barrier).

Conclusion

Calculations were found to be fit for purpose for this bunker design. There is no instantaneous dose rate limit in NZ, however dose rates measured were used to confirm likely occupational doses would not exceed an annual dose limit of 1 mSv.

Bunkers of a more complex shape particularly mazes with multiple bends and non-standard angles, may require more realistic modelling using methods such as Monte Carlo.