A novel technique to optimise the length of a linear accelerator treatment room maze without compromising radiation protection

I A M Al-Affan[†], S C Evans[‡], M Qutub[†,1] and R P Hugtenburg[†,‡]

[†]Swansea University, Swansea SA2 8PP, UK

[‡]Department of Medical Physics and Clinical Engineering, Singleton Hospital, Swansea, SA2 8QA, UK

[1]Department of Physics, Umm Al-Qura University, Makkah, Saudi Arabia

Key words:

Dose at maze entrance

Backscattered photons

Improving maze design

Abstract

Simulations with the FLUKA Monte Carlo code were used to establish the possibility of using lead to cover the existing concrete walls of a linear accelerator treatment room maze, in order to reduce the dose of the scattered photons at the maze entrance. In the present work, a pilot study performed at Singleton Hospital in Swansea was used to pioneer the use of lead sheets of various thicknesses to absorb scattered low energy photons in the maze. The dose reduction was considered to be due to the strong effect of the photoelectric interaction in lead resulting in attenuation of the back-scattered photons.

Calculations with FLUKA with mono-energetic photons were used to represent the main components of the X-ray spectrum up to 10 MV. The reason for using mono-energetic photons was to study the behaviour of each energy component from associated interaction processes. The results showed that adding lead of 1 to 4 mm thickness to the walls and floor of the maze reduced the dose at the maze entrance by up to 80%. Subsequent scatter dose measurements performed at the maze entrance of an existing treatment room with 1.3 mm thickness of lead sheets added to the maze walls and floor supported the results from the simulations. The dose reduction at the maze entrance with the lead in place was up to 50%. The variation between simulation and measurement was attributed to the fact that insufficient lead was available to completely cover the maze walls and floor.

This novel proposal of covering part or the entire maze walls with a few millimetres thickness of lead has implications for the design of linear accelerator treatment rooms since it has potential to provide savings, in terms of space and costs, when an existing maze requires upgrading in an environment where space is limited and the maze length cannot be extended sufficiently to reduce the dose.

1. Introduction

The design of a linear accelerator (Linac) treatment room maze can contribute significantly to the reduction of the radiation dose at the maze entrance. The design may involve the use of a shielded door or alternatively the construction of a long maze, typically with concrete walls, or a shorter maze with additional bends. Nibs, baffles and lintels may also be used to reduce the dose rate of the photons. Use of a shielded door, extending the length of the maze or introducing additional bends in the maze would certainly add to the construction cost of treatment rooms (Al-Affan et al 2015).

The dose at the maze entrance depends on the maze length, the number of bends in the maze and the area of the maze opening. The reflection coefficient of materials used in maze walls is also an important factor. The dose also depends on the number of photons which penetrate the Linac head (leakage) and travel through the treatment room wall adjacent to the maze entrance.

This study focussed on the primary-photo-beam only (leakage was not considered), whose contribution may exceed 50% of the dose at the maze entrance (Al-Affan et al 1998, Al-Affan 2000). When these photons are backscattered they will undergo further scattering in all directions in the concrete wall with some photons being absorbed due to the photoelectric effect. The degree of absorption for the photoelectric effect is inversely proportional to about E^3 to $E^{3.5}$ where E is the incident photon energy and proportional to Z^3 to Z^5, where Z is the atomic number of the wall material (Podgorsak 2010, Khan 2010).

The study investigated the radiation protection implications from a proposed modification of an existing Linac treatment room at Singleton hospital, Swansea, UK. The modification required the removal of a triangular concrete section of the maze wall and two concrete nibs within the maze (Figure 1a) in order to reduce the restriction of movement of patient's bed and maintenance equipment in and out of the treatment room.

Figure 1a

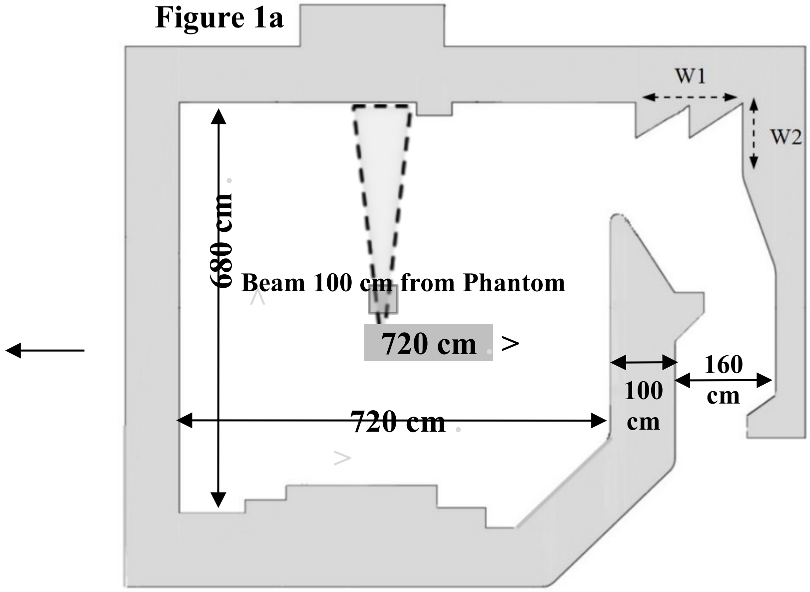

Figure 1b

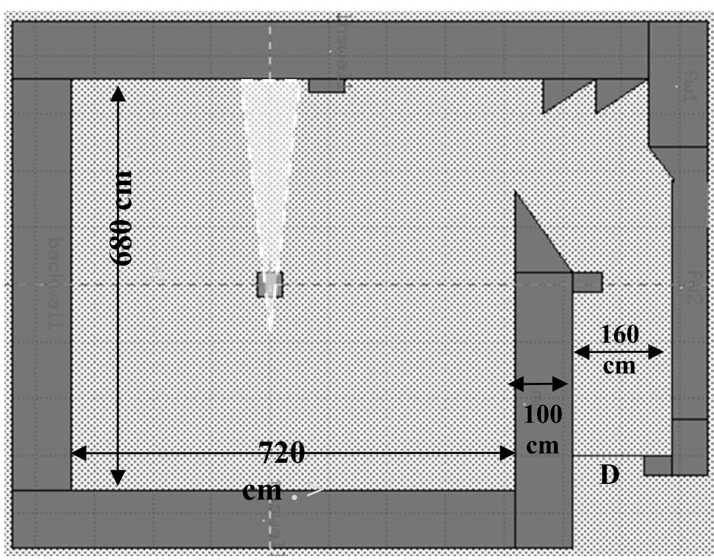

Figure 1. (a) Original drawing (scaled) of a radiotherapy room at Singleton Hospital in Swansea. (b) Simulation of the original design of the radiotherapy room.

The contribution of the concrete triangular section of wall and the nibs to the dose rate reduction of scattered photons at the maze entrance was investigated, in order to establish the impact of their removal and to consider an alternative method to optimise the level of protection.

The alternative method proposed was the introduction of lead-lined plywood boards mounted on sections of the maze walls as proposed by Al-Affan (2015). A pilot study was carried out to establish the reduction in dose-rate at the entrance to an existing radiotherapy room maze during operation of the Linac. This would have direct applications in:

1) optimisation of new radiotherapy room design;
2) modifying existing rooms with shortest mazes;
3) possible avoidance of using shielded doors for future room design (high energy x-rays).

2. Methods

2.1 Measurement

Two portable dose-rate meters were used to measure the dose-rate at the maze entrance at a height of 1 m above the floor, as shown in Figure (2). The first was an NE Technology PDM1 (general purpose ionisation chamber meter) and the second was an Alnor RD-10 (energy compensated GM universal survey meter). The average reading was taken from the two with the fluctuation error. The energy response of the two dose-rate meters was within ±20% over a photon energy range of 50 keV to about 1 MeV. No correction was made to the dose-rate meter response since the photon energy spectrum at the maze entrance was expected to be within this range.

The Linac treatment head was angled at 270 degrees in order for the primary X-ray beam to be directed at the wall closest to the opening to the maze (Figure 1a). In order to provide a representative source of photon scatter, the X-ray beam was incident on a PMMA phantom (dimensions 24.5 x 24.5 x 24.5 cm^3) positioned at 100cm from the X-ray source. The X-ray field size at the phantom surface was 20 x 20 cm^2.

In order to establish the effect of introducing lead shielding into the maze, dose-rates were measured at the maze entrance under the following conditions using both 6 MV and 10 MV Linac photon energies:

i. Without additional lead covering the maze walls.
ii. Using lead-lined plywood board (1.3mm lead thickness) to cover sections of the maze walls. The board dimensions were width 400 mm, height 2400 mm and thickness 6 mm. Four lead-lined plywood boards were positioned adjacent to each other in order to provide continuous coverage of the triangular concrete section of the wall, W1, located adjacent to the treatment room entrance (Figure 2). Four additional lead-lined plywood boards were used to cover the maze wall, W2, adjacent to W1 (Figure 2).
iii. As in condition (ii) but with two additional lead-lined plywood boards partly covering the maze floor (Figure 2).

Figure 2. Treatment room view of the maze showing lead-lined plywood boards partly covering triangular section of maze wall.

Figure 3. Maze entrance view showing lead-lined plywood boards partly covering Maze triangular section of maze wall, adjacent maze wall and floor. Two portable dose-rate meters are shown in position at the maze entrance.

2.2 Simulation of the Linac treatment room at Singleton Hospital by FLUKA code

FLUKA code is widely applied in a variety of areas ranging from shielding, dosimetry and proton therapy to the description of a high energy detector, etc (Ferrari et al 2011). FLUKA code was validated in a number of simulations related to backscattered photons in a radiotherapy environment (Al-Affan et al. 2015).

The treatment room at Singleton Hospital was simulated by the FLUKA code, as shown in Figure 1b, for maze walls and floor in their existing shape and dimensions. The room was also simulated when lead sheets of 1, 2 or 4 mm thickness were covering the concrete walls and floor. Room walls, the roof and floor were constructed from concrete of density 2.34 $g.cm^{-3}$, with the elemental composition of concrete taken from NCRP (2005). All external walls were 100 cm thick and both floor and roof were 50 cm thick (the assumption was used to reduce the required computation time without compromising the results). The photon source was fixed at 100 cm from the surface of the rectangular parallelepiped water phantom that had a symmetric size of 40 cm × 40 cm × 40 cm along beam axis. The reason for including a phantom was to generate scattering from tissue-equivalent material and to simulate the maximum dose at the maze entrance, as calculated by Al-Affan (2000) (i.e. the highest expected dose at the maze entrance). In the present work, the beam was assumed to contain only primary beam photons and therefore leakage photons and scattered photons from collimators were ignored. The photon beam had a radius of 5.65 cm (at 100 cm from the target) at the surface of the water phantom, giving an equivalent area of 10 x 10 cm^2.

The scattered and backscattered photons reaching the maze entrance were collected by a parallelepiped of water, D, with dimensions 200 cm height x 120 cm width x 1 cm thickness (Figure 1b). This large size was necessary to enhance the detector efficiency and reduce the computation time. The photon energy cut off was set to 30 keV and electron kinetic energy cut off was set to 300 keV. Rayleigh scattering was taken into account.

The entire geometry was surrounded by a large sphere of void of 1000 cm in radius and consisting of air, and this was surrounded by a larger sphere of blackhole of 10000 cm in radius. The irradiations were carried out for a range of photon energies (0.5, 1, 3, 7 and 10 MeV) to study several components of the X-ray spectrum, which are usually present in the primary beam (of energies up to 10 MeV). For each energy value, the FLUKA code was run for 5 cycles to determine the statistical fluctuation in the results. Moreover, 100-250 million photon histories were generated for each simulation to get a statistical uncertainty of better than 14%. Computation time of the doses was between 15 and 65 hours with 5 cycles for all situations.

3. Results and Discussions

Measurements were performed to establish the effect of adding lead-lined plywood boards to maze walls predicted by Al-Affan et al (2015). The measurements were carried out for 6 and 10 MV X-rays (Tables 1 and 2). The reduction in dose-rate at the maze entrance when lead-lined plywood boards covered sections of the concrete maze walls and floor was up to 50% of the dose-rate measured with concrete only.

It can be seen from Table 1 that for the 6 MV X-rays the contribution in dose-rate reduction when lead covered walls W1 and W2 was about 45% (each about 23%). The contribution in dose-rate reduction from the lead covering the floor was about 8% compared to the concrete floor alone. The percentage dose reduction factor, %DRF (column 4 in Tables 1 and 2) is the amount of reduction of the photon dose at the maze entrance when lead sheet is covering the maze walls, %DRF = %(1-D_{CL}/D_C) (Al-Affan et al 2015).

It can be seen from Table 2 that for 10 MV X-rays the situation was different, with the lead added to walls W1 and W2 and floor equally contributing to the dose-rate reduction. The difference in the results between 6 and 10 MV X-rays is considered to be attributed to the higher rate of pair production enhancement for the 10 MV X-rays, which reduced the dose rate reduction.

However, since the maze walls and floor were partially covered by lead it would be useful to establish the extent of dose-rate reduction achieved when all maze walls and the floor were completely covered with lead. In addition, a simulation was made to modify the design and shape and width of the maze to improve access for patient beds and equipment used for maintenance. The FLUKA code was very useful to run these simulations to optimise in shape and dimensions of the maze.

Table 1. Maze entrance dose-rate measurements for 6 MV X-rays incident on PMMA phantom (24.5x24.5x24.5 cm^3). 20 x 20 cm^2 field size.

Location of lead	**Average dose-rate (µSv/hr)**	**Dose-rate ratio D_L/D_c**	**%DRF**
No lead	16.3 (±2.5)	1	0
Wall W1	12.5 (±2.5)	0.77	23
Walls W1 and W2	9 (±1.5)	0.55	45
Walls W1 and W2, and floor	7.7 (±2.5)	0.47	53

D_C is dose-rate measured without additional lead and D_L is dose-rate measured with additional lead (1.3mm).

Table 2. Maze entrance dose-rate measurements for 10 MV X-rays incident on a PMMA phantom (24.5x24.5x24.5 cm^3). 20 x 20 cm^2 field size.

Location of lead	Average dose-rate (μSv/hr)	Dose-rate ratio DL/Dc	%DRF
No lead	17.5 (±2.5)	1	0
W1	14.8 (2.5)	0.85	15
W1 & W2	12.3 (±5)	0.7	30
W1 & W2 and floor	9.3 (±2.5)	0.53	47

D_C is dose-rate measured without additional lead and D_L is dose-rate measured with additional lead (1.3mm).

FLUKA simulations of the following maze configurations were considered in order to optimise the improvement of a Linac treatment room maze at Singleton Hospital.

1) Simulation (S1) of existing maze conditions (Figure 1b).
2) Simulation (S2) with triangular concrete wall section of maze removed.
3) Simulation (S3) with triangular concrete wall section and inner concrete nib of maze removed.
4) Simulation (S4) with triangular concrete wall section and inner concrete nib of maze removed, and lowering of treatment room entrance ceiling lintel height from 2.5 m to 2.2 m.

Table 3 presents results of these simulations when using a simulated detector, D, made of water. The statistical uncertainty given in the Table are to 2 standard deviation (SD 95% confidence) and for the rest of the calculations in the paper. The 2 SD are represented as a coefficient of variation, which is the standard deviation divided by the average and multiplied by 100% and written as a percentage.

When normalised to the existing maze conditions (S1) the calculated maze entrance dose increased by approximately 20% from the simulated removal of the triangular wall section alone (S2) and by approximately 260% from the simulated removal of both triangular wall sections and the inner nib (S3).

Again, when normalised to existing maze conditions (S1), the calculated maze entrance dose increased by approximately 228% from the simulated removal of both triangular wall sections and the inner nib and the introduction of a reduced ceiling lintel height (S4). The introduction of the lowered ceiling lintel effectively resulted in a 12% reduction in the calculated maze entrance dose. This level of dose reduction was found to be proportional to the reduction of the area in the opening between the treatment room and the maze.

Table 3. Results of FLUKA simulations of dose (Gy/photon) at maze entrance for 3Mev photon energy Numbers between parentheses are Statistical error of 5 run and 2SD (95%).

Configuration	**Dose (Gy/photon)**	**Ratio of S_i to S_1**	**Comments**
S1: No change in maze configuration	1.38E-21 (9%)	1	Normalized to the existing situation.
S2: Triangular section of wall removed	1.66E-21 (7%)	1.2	Maze entrance dose increased by 20% when the triangular section of wall removed.
S3: Triangular section of wall and inner nib removed	3.59E-21 (10%)	2.6	Entrance dose increased by 260% when triangular section of wall and nib were removed.
S4: Removal of triangular section of wall and inner nib plus lowering of ceiling lintel	3.14E-21 (12%)	2.28	Lowered ceiling lintel found to reduce maze entrance dose (compared with simulation S3) by 12%

Based on the results of these simulations it was proposed that the triangular wall sections and nib must be removed and the shape and size of the maze redesigned, including the covering of sections of the maze walls with lead of a few millimetres in thickness as proposed by Al-Affan et al (2015).

FLUKA code was used to investigate the use lead sheets of 2mm thickness applied to sections, or the entire, maze walls (shown in Figure 4). The first maze configuration simulated photons scattered from concrete walls (results presented in Table 4, column 2).

The following three maze configurations were then simulated;

1) Simulation (4WF) with 4 maze walls and floor covered with 2mm lead (results presented in Table 4, column 3);
2) Simulation (4W) with 4 maze walls and no floor covered with 2mm lead (results presented in Table 4 column 4);
3) Simulation (3W) with 3 maze walls covered with 2mm lead (results presented in Table 4, column 5).

Table 4 shows the contribution of each wall in dose reduction when covered by the 2mm lead. However, above 7 MeV the contribution of pair production dominates in all scattered photons which results in photon dose enhancement. This evidence is also shown in Figures 5 and 6, for 10 MeV photons, where the small peak at about 511 keV is due to annihilation photons is almost doubled when lead is covering the concrete walls.

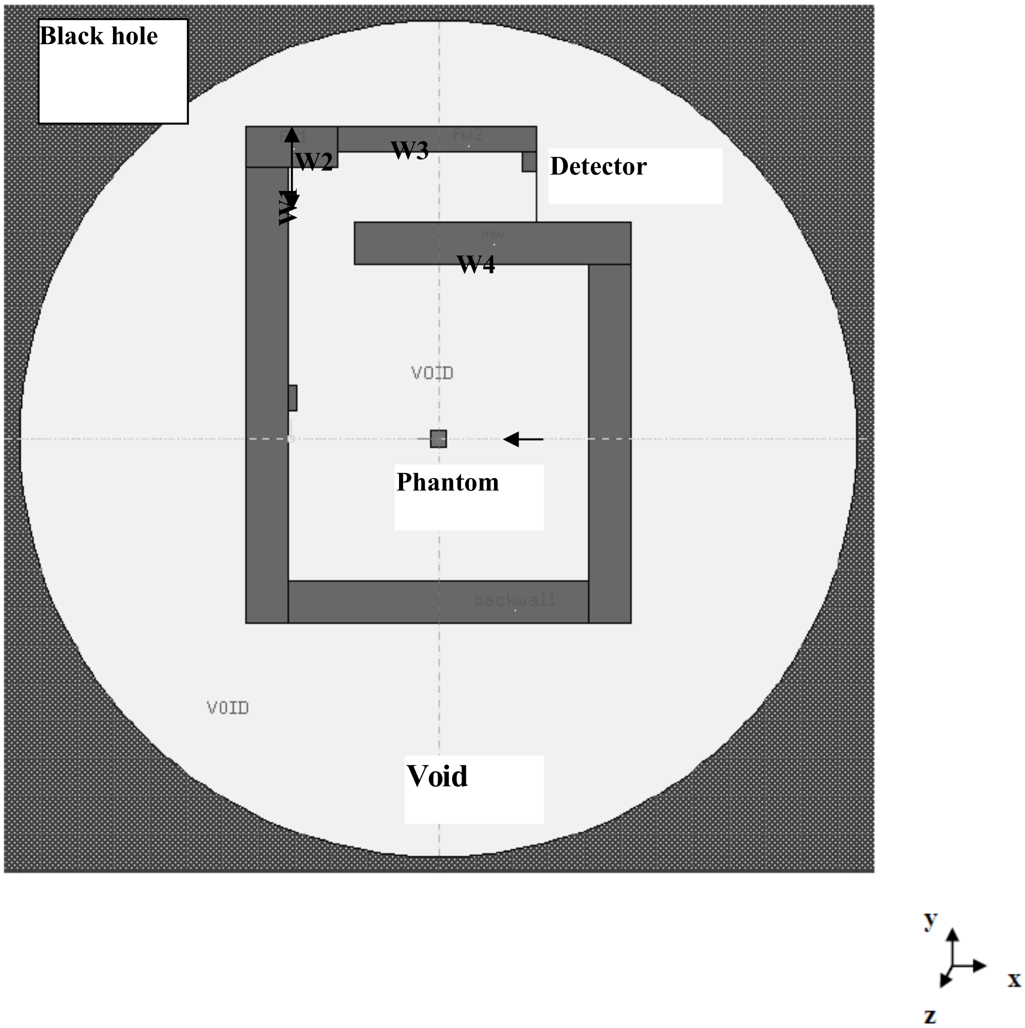

Figure 4. FLUKA simulation of the proposed modification of radiotherapy room at Singleton Hospital in Swansea. The diameter of the inner circle (void) is 2000 cm (for the scale).

Table 4. Dose at maze entrance calculated using FLUKA code for scattering photons from concrete walls, D_C, (column 2). Three maze configurations, D_{CL}, were simulated for maze walls covered with 2 mm lead; covering 4 walls and floor, 4WF (column 3), covering 4 walls and no floor, 4W (column 4), covering 3 walls, 3W (column 5).

Photon Energy MeV	FLUKA dose Gy/photon concrete only, D_C	FLUKA dose Gy/photon 2 mm lead+ concrete, D_{CL} (4WF)	FLUKA dose Gy/photon 2 mm lead+ concrete, D_{CL} (4W)	FLUKA dose Gy/photon 2 mm lead+ concrete, D_{CL} (3W)
0.5	6.19E-22±5%	1.23E-22±7%	1.53E-22±4%	1.65E-22±4%
1	9.93E-22±7%	1.81E-22±3%	2.33E-22±7%	2.47E-22±6%
3	1.16E-21±4%	2.77E-22±7%	3.34E-22±9%	3.59E-22±9%
7	1.32E-21±7%	8.53E-22±12%	8.18E-22±14%	8.12E-22±11%
10	1.42E-21±5%	1.84E-21±14%	1.73E-21±13%	1.65E-21±13%

The percentage dose reduction factor, %DRF for each of the above simulations is presented in Table 5. Uncertainties are in the range 7-16% (to 2 S.D.).

It can be seen from Table 5 (column 2) that adding 2 mm of lead to the concrete maze walls and floor would reduce the maze entrance dose by up to 80% for photon energies up to 3 MeV. Above 3 MeV the increased significance of pair production enhances the dose due to scattering photons resulting in lower dose reduction than that achieved at lower photon energy. Also from column 3, the %DRF is reduced by about 7% when 2 mm lead is simulated to cover the four maze walls but not the floor. However, the reduction remains greater than 35% for all energies below 7 MeV.

Table 5. Percentage Dose Reduction Factor (%DRF) at maze entrance calculated from Table 4 for three simulations of maze walls covered with 2 mm lead; covering 4 walls and floor, 4WF (column 2); covering 4 walls and no floor, 4W (column 3); covering 3 walls, 3W (column 4).

Photon Energy MeV	%DRF (Simulation 4WF)	%DRF (Simulation 4W)	%DRF (Simulation 3W)
0.5	80 (8.6%)	75 (6.4%)	73 (6.4%)
1	82 (7.6%)	77 (9.9%)	75 (9.2%)
3	76 (8.1%)	71 (9.8%)	69 (9.8%)
7	35(13.9%)	38 (15.7%)	39 (13%)
10	-29 (14.9%)	-22 (14%)	-16 (14%)

Table 5 column 4 presents results of simulating 2 mm of lead covering three of the maze walls only. The maze floor and wall 4, W4 in Figure 4, located between the treatment room and maze were not covered by lead. The %DRF is reduced by only about 3% for photon energies below 3 MeV thus demonstrating that the contribution from scattered photons from wall 4 is less significant than that from walls 1, 2, 3 and the maze floor. This is because these walls would absorb first and second scattered photons while wall W4 would absorb third and further scattered photons.

The room configurations used to measure the dose at maze entrance (i.e. with and without 1.3mm thick lead plywood boards covering sections of the concrete maze walls and floor) were also simulated using FLUKA code. Table 6 presents the results of these simulations and there is good agreement, in terms of the level of dose reduction, between the simulated and measured results (presented in column 4 of Tables 1 and 2), taking into account that the main components of the photon primary beam in the 6 MV X-rays and 10 MV X-rays has an average photon energy of about 1.8 MeV and 2.6 MeV respectively (Nelson and LaRiviere 1984).

The actual spectrum components for 6 MV photon primary approximately consists of 0.5 MeV (15%), 1.5 MeV (49%), 3.5 MeV (34%) and >4 MeV (2%) and for 10 MV approximately consists of 0.5 MeV (10%), 1.5 MeV (33%), 3.5 MeV (40%) and for >5 MeV (17%).

Therefore, the %DRF is about 80% for primary photons below 3 MeV and up to 64% for energies between 3 and 7 MeV, which can be effective for most of the components in the 10 MV spectrum. Above 3 MeV the increased significance of pair production enhances the dose due to scattering photons resulting in lower dose reduction than that achieved at lower photon energy.

The measurements that were carried out confirmed the results from the simulations for 6 and 10 MV X-rays (Tables 1, 2). The dose reduction at the maze entrance when lead covered the concrete walls and the floor was up to 50%. Differences were due to the fact that not all of the concrete walls and floor were able to be covered with lead. Also, the lead thickness used in the measurements was 1.3 mm, which was not optimal but felt to be a reasonable compromise to maintain acceptable weights of the lead-lined plywood boards. Measurements showed that leakage was a relatively small component of the dose at the maze entrance.

Table 6. Dose at maze entrance calculated using the FLUKA code for scattering photons from concrete wall with lead simulating the situation of the measurements. Lead sheets (1.3 mm thickness) covering sections of walls and floor as shown in Figures 2 and 3.

Photon Energy MeV	FLUKA dose Gy/photon concrete only d_c	FLUKA dose Gy/photon 1.3mm lead + concrete d_{cl}	Ratio= d_{cl}/d_c	Dose Reduction Factor % (%DRF)
0.5	6.19E-22±5%	2.06E-22±4%	0.33	67

1	9.93E-22±7%	3.53E-22±7%	0.36	64
3	1.16E-21±4%	5.21E-22±4%	0.45	55
7	1.32E-21±7%	8.21E-22±14%	0.62	38
10	1.42E-21±5%	1.51E-21±9%	1.06	-6

Table 7 presents the calculated percentage dose reduction factor, %DRF, for various lead thicknesses and photon energies. The most effective lead thickness is about 2 mm since this is about the half value layer for the back-scattered photon for energies less than 400 keV.

Table 7. Dose Reduction Factor, %DRF, for various lead thicknesses and photon energies.

Photon MeV	%DRF 1mm	%DRF 2mm	%DRF 4mm
0.5	78	80	81
1	77	88	83
3	68	76	81
7	27	35	41
10	-36	-29	-30

Figures 5 and 6 present photon energy distributions of scattered photons at the maze entrance with concrete maze walls only and for concrete maze walls covered with 2 mm lead respectively. It can be seen from figure 6 that the main process of reducing the photon number is the photoelectric effect. Figures 5 or 6 also present the evidence of annihilation photons from pair production. at 511 keV. However, the contribution of pair-production in lead in figure 6 is almost twice that of the concrete in figure 5.

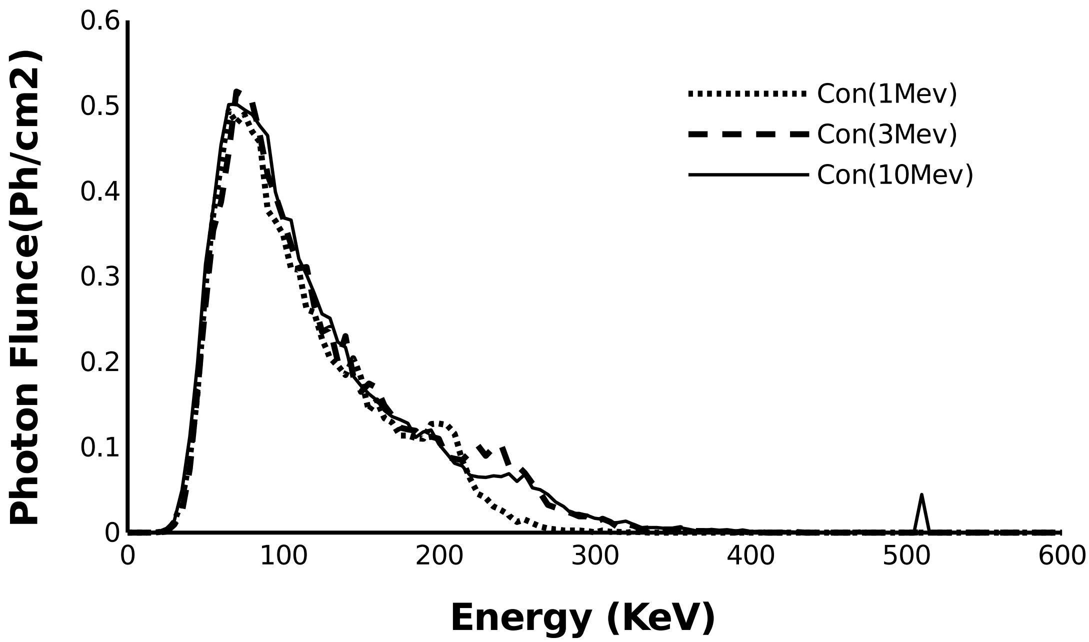

Figure 5. Calculated energy distribution of scattered photons at the maze entrance with concrete maze walls.

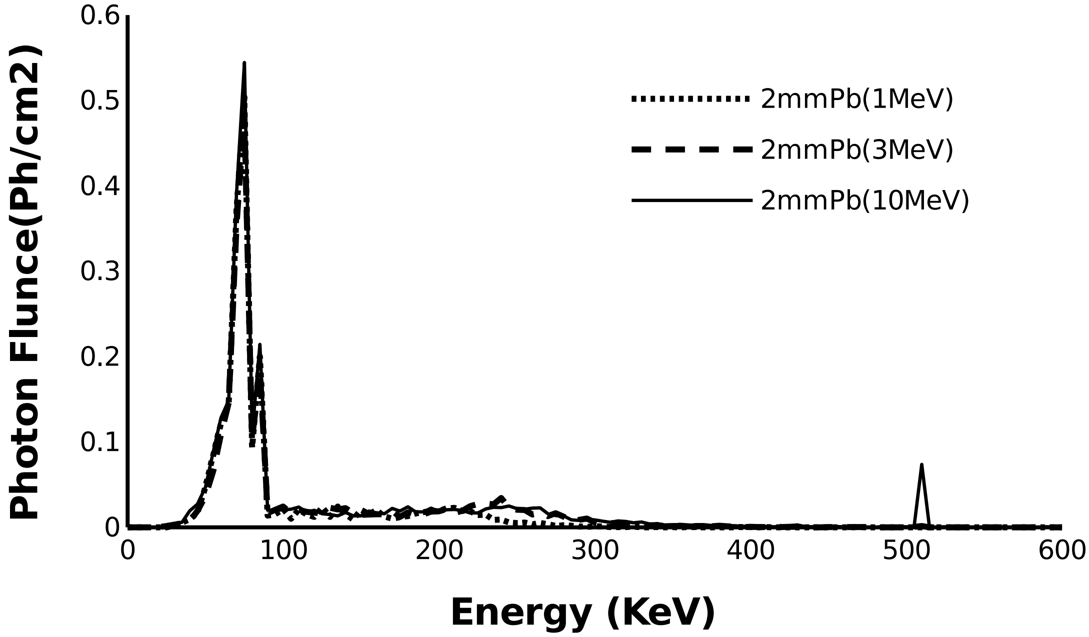

Figure 6. Calculated energy distribution of scattered photons at the maze entrance with concrete maze walls covered with 2 mm lead.

4. Conclusions

The study showed that covering maze walls with only a few millimetres of lead can reduce the dose rate at the maze entrance by up to 80%. The main reason for that is the effect of the photoelectric interaction, which is proportional approximately to Z^4 of the materials used. Covering sections or the entire maze walls with lead could be a cost effective radiation protection solution for facilities with space restrictions. This design method could be particularly beneficial when modifying the use of an existing treatment room, e.g. from Co-60 to X-ray from Linacs of higher energy. FLUKA proved to be a useful tool in simulating different maze configurations to predict results. Hence, Monte

Carlo codes may be used as a guide to design of future treatment rooms (Smith et al 1997).

The use of lead sheets to cover sections of maze walls is considered to be a useful optimisation tool when modifying treatment rooms with short mazes and may be cost effective when modifying rooms with limited space. It could also be used to replace the need for heavy maze doors or extended mazes when using mobile radiation sources in non-destructive testing (NDT) (Kim 2016). Further investigation is required to simulate other scenarios including the effects of leakage radiation. The FLUKA Monte Carlo code was found to be a very useful tool to guide the design and shape of the treatment room maze, including issues relating to access for patients and machine maintenance without compromising radiation protection. FLUKA confirmed that lead cladding has excellent potential for modifying rooms with short mazes. It also showed that cladding can be added selectively for certain walls in the maze where the dose reduction is higher than other locations.

Acknowledgements

Part of his work was supported by IPEM Award for Research and Innovation 2014. The contributions of Dindar S Bari and Georgina Grundy are appreciated. A thank you is also extended to Colin Craven for his assistance with the fabrication of the lead-lined plywood boards.

References

Al-Affan I A M 2000 Estimation of the dose at the maze entrance for X-rays from radiotherapy linear accelerator. Medical Physics, **27** 231-238.

Al-Affan I A M, Hugtenburg R, Bari D S, Saleh W, Piliero M, Evans S, Al-Hasan M, Al-Zughul B, Al-Kharouf S and Ghaith, A 2015 Dose reduction of scattered photons from concrete walls lined with lead: implications for improvement in design of megavoltage radiation therapy facility mazes. Medical Physics, **42** 606-704.

Al-Affan I A M, Smith C W, Morgan H M and Llillicrap S C 1998 Dose rate and energy distributions of X-rays from a linear accelerator at the maze entrance of a radiotherapy room by measurement and Monte Carlo Simulation. Radiat. Prot. Dosim. **78** 273-277.

Biggs P J 1991 Calculation of shielding door thicknesses for radiation therapy facilities using the ITS Monte Carlo Program. Health Physics **61** 465-472.

Ferrari A, Sala P, Fasso A, and Ranft J 2011FLUKA: a multi-particle transport code. [Online]. Available at: http://www.fluka.org/content/manuals/FM.pdf .

Khan F M 2010 The Physics of Radiation Therapy. Fourth Edition. Woters Kluwer Lippincott Williams and Wikins.

Kim S 2016 Gamma radiation transmission along the multiband mazes. Applied Radiation and Isotopes **114** 45-40.

McGinley P H and James J L 1997 Maze design methods for 6- and 10-MeV accelerators. Rad. Prot. Manage. **14** 59–64.

NCRP 2005 Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities. NCRP Report **151** 71-73.

Nelson W R and LaRiviere P D1984 Primary and leakage radiation calculations at 6, 10 and 25 MeV. Health Physics **47** 811-818.

Podgorsak E B 2010. Radiation Physics for Medical Physicists. 2ns Edition, Springer, Berlin.

Smith C W, Al-Affan I A M and Green S 1997 The use of Computer Programs in Treatment Room Design. Chapter 7 in IPEM Publications entitled ‘ The design of Radiotherapy Treatment Room Facilities’, Eds: B. Stedeford, H.M. Morgan and W.P.M. Mayles, The Institute of Physics and Engineering in Medicine, IPEM Report **75,** York.