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Dose reduction of scattered photons from concrete walls lined with lead: implications for improvement in design of megavoltage radiation therapy facility mazes

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ABSTRACT

PURPOSE: This study explores the possibility of using lead to cover part of the radiation therapy facility maze walls in order to absorb low energy photons and reduce the total dose at the maze entrance of radiation therapy rooms.

METHODS: Experiments and Monte Carlo simulations were utilized to establish the possibility of using high-Z materials to cover the concrete walls of the maze in order to reduce the dose of the scattered photons at the maze entrance. The dose of the back-scattered photons from a concrete wall was measured for various scattering angles. The dose was also calculated by the FLUKA and EGSnrc Monte Carlo Codes. The FLUKA Code was also used to simulate an existing radiotherapy room to study the effect of multiple scattering when adding lead to cover the concrete walls of the maze. Mono-energetic photons were used to represent the main components of the x-ray spectrum up to 10 MV.

RESULTS: It was observed that when the concrete wall was covered with just 2 mm of lead the measured dose rate at all backscattering angles was reduced by 20% for photons of energy comparable to Co-60 emissions and 70% for Cs-137 emissions. The simulations with FLUKA and EGS showed that the reduction in the dose was potentially even higher when lead was added. One explanation for the reduction is the increased absorption of backscattered photons due to the photoelectric interaction in lead. The results also showed that adding 2 mm lead to the concrete walls and floor of the maze reduced the dose at the maze entrance by up to 90%.

CONCLUSIONS: This novel proposal of covering part or the entire maze walls with a few millimeters of lead would have a direct implication for the design of radiation therapy facilities and would assist in upgrading the design of some mazes, especially those in facilities with limited space where the maze length cannot be extended to sufficiently reduce the dose.

I. INTRODUCTION

In radiation therapy (RT) rooms, the length and shape of the maze play an important role in reducing the radiation dose at the maze entrance (radiation exit). Previously, steps taken were to use a door at the maze entrance, to extend the maze length in order to achieve the required reduction in dose, or to add a turn with a small length in the maze (called a leg) in a different direction. In addition, nibs, baffles and lintels are often used to reduce the dose rate of the photons emerging from the RT rooms.

Using a door or extending the length of the maze, whether in one direction or adding another leg in a different direction, would add to the building cost of RT rooms and also occupy more space, which may be a significant issue when an existing RT room is to be upgraded within an area of very limited space.

A few studies have shown the level of dose due to scattered photons at the maze entrance and also the characteristics of the photon energy due to scattering in the patient, collimators and walls, and leakage from the accelerator head.[1,2,3] Photons reaching the maze entrance may be divided into two groups; photons that are generated from primary beam scattering and photons that penetrate the machine head (leakage).

Photons that are generated from the primary beam scattering off collimators, the patient, leakage and air in the room undergo a multiple scattering process through the maze itself. The energy spectra of these photons are found not to exceed 400 keV with an average of about 100 keV. [2,3,4] The dose at the maze entrance from this group of photons depends on the maze length, number of turns (legs), area of the maze opening and the reflection coefficient of materials in the maze walls.

Leakage photons travel directly through the wall adjacent to the maze entrance. The energy distribution of these photons may range from below 100 keV to a value almost approaching the maximum value in the primary beam.[2] The dose at the maze entrance from this group will depend on the energy spectrum of the leakage radiation, the thickness, elemental composition and density of the concrete wall.

In this study, the aim was to focus on the first group (scattered radiation) which is more difficult to predict, yet can contribute more than 50% of the dose at the maze entrance. [2,3]

As mentioned above, some fraction of photons or photon dose reaching the maze entrance is from scattered photons. The energy spectra of these photons were calculated by Al-Affan[3] who showed that there were photons below 200 keV as well as higher energy components between 200 and 400 keV. On impact with the maze walls, floor and ceiling, these photons scatter at various depths in the concrete. The energy distribution of these photons will follow the Compton scattering equation, which depends on the incident energy of the photon, the backscattering angle and the material type, i.e. electron density. The maximum energy of these backscattered photons is less than 0.4 MeV for

Co-60 and Cs-137 gamma sources. For photons generated from a high energy Linear Accelerator the maximum energy of backscattered photons approaches 0.511 MeV.

When these photons are backscattered (90^o-150^o, see Fig. 1a) they experience further scattering in all directions in the concrete wall, with many photons being absorbed due to the photoelectric effect. The degree of absorption for the photoelectric effect is proportional to Z^3 for the high atomic number constituents in the wall material. For example, when a thin sheet of lead (Z=82) is placed in front of the concrete wall (average Z=14) the ratio of photoelectric effect will be about 200 times more efficient in absorbing the backscattered photons through the photoelectric process than the concrete wall alone, although the lead itself would contribute to the photon backscattering.

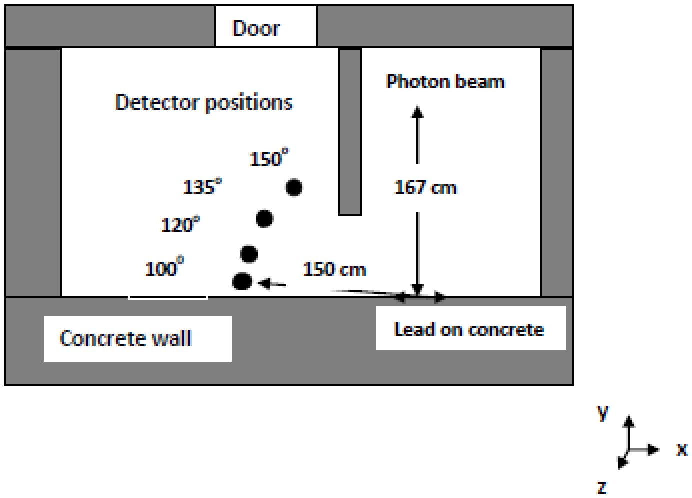

Figure 1a. Schematic diagram of the experiment (not to scale). Incident primary photon beam (solid arrows) on the concrete wall is perpendicular on the x-axis. Detector was positioned at various angles (at 150 cm from the centre of the photon field at the wall) with respect with y-axis to measure the backscattered photons. Dashed arrows: scattered photons. Lead sheet of $1 m^2$ was placed on the concrete wall facing the photon beam.

In the following sections several methods are described to measure the reduction in the dose of backscattered photons when lead was placed in front of the concrete wall compared to that of concrete alone. In addition, simulations of the measurements were carried out using two Monte Carlo codes to confirm the measurements. Monoenergetic photons were used for the experiment and simulations in order to provide a better indication of the photon reflection as a function of photon energy. This is preferable to conducting the experiment in a RT room, where the Linear Accelerator x-ray spectrum is more complex. The leakage radiation from a Linear Accelerator is also appreciable and would affect the measurement.

II. EXPERIMENTAL METHOD AND MATERIALS

All measurements were carried out at the laboratory of the Royal Scientific Society in Jordan. The schematic diagram of the experiment is shown in Fig. 1a. Two radiation sources were used for the measurements, Co-60 and Cs-137, both stored inside a shield. The sources were driven to the position of irradiation by remote control. The diameter of the aperture of the collimator for the source was 1 cm. The height of the source from the ground was 101 cm. The room walls were made from concrete mixed with small iron pieces to reduce the photon transmission through the laboratory walls. The effective density of the concrete laboratory walls was not known. The source to wall distance was 167 cm and was incident on the concrete wall in the –y direction, parallel to the floor

(Fig. 1a). The activities of the Co-60 and Cs-137 sources used were 13.107 GBq and 1.587 TBq respectively.

A few measurements were made to establish the width of the photon beam incident on the concrete wall. It was found that the irradiated area of the wall had a diameter of about 25 cm, where beyond the dose rate was less than 10% of the dose rate at the centre of the irradiated area, D_o. This arrangement ensured that the 1 m^2 of lead used to cover the wall, facing the primary radiation, would include most of the incident beam.

However, the radiation leakage from the source head (Co-60 and Cs-137) contributed to a high level of background radiation which was greater than the dose from the backscattered photons, which were measured at a distance of 100 cm from the wall. Therefore, the detector was moved back another 50 cm and placed at the side of a lead shield to reduce the leakage radiation dose (background) by about 75% (from 65 µR/h to 15 µR/h). The detector used was a calibrated plastic scintillation counter (Portable Dose Ratemeter, Type PDR2-5V, Serial Number 823 by Nuclear Enterprises Ltd). The dose rate measured at 167 cm from the source, D_o, for Co-60 was 103mR/h and for Cs-137 was 1513 mR/h.

The average background in the room at the points of measurement with the beam off was 15 µR/h. The backscattered radiation was measured at a radius of 150 cm from the wall at angles of 100, 120, 135 and 150 degrees with respect to y-axis (Fig. 1a). These measurements were made for three situations; 1- the radiation incident on the concrete wall only, with a dose rate of D_c, 2- the radiation incident on a 2 mm thickness of a square sheet made of lead (100 cm x 100 cm) lining the concrete wall, with a dose rate of D_{cl2} and 3- the same as 2 but with a lead thickness of 4 mm, and dose rate D_{cl4}.

III. MONTE CARLO SIMULATION

FLUKA and EGS Monte Carlo codes were used to simulate the above experiments. FLUKA is a general-purpose particle interaction and transport code with roots in an extended range of applications starting from proton and electron accelerator shielding, to target design, radiotherapy, neutrino physics and many other areas.[5,6] EGS, initially developed at SLAC, has been further developed for a range of applications with standard megavoltage x-ray beams, principally by the National Research Council (NRC) of Canada.[10] For both codes the radiation source particle and its energy, the number of particles, the position of the beam, the materials, geometry, and their properties are defined in an input file. The whole system of the radiation source and geometry is surrounded by a large region known as ‘the void’, which in the case of FLUKA is surrounded by a larger region known as the ‘black-hole’. A black-hole has an infinite absorption cross-section and all particles disappear when they reach it.

An important feature of FLUKA is Flair, the Graphical User Interface (GUI), which is an advanced and user-friendly interface used to facilitate the editing of FLUKA input files, execution of a code and visualisation of the output files.[7] In Flair, everything is visually organised, and the user can freely create a code defining the simulation in any order they wish, such as modifications to the geometry.[7]

The computer configuration was a 32-bit Linux operating system (Mint 14) on an Intel quad-core (i5-2310) cpu running at 1.9 GHz.

A. VALIDATION AND SIMULATION OF THE FLUKA CODE

Calculation of the percentage depth-dose for a photon beam was simulated by FLUKA. The results were compared with known and published experimental data in order to confirm the reliability of FLUKA in this energy range, as well as to check the effect of beam attenuators on the beam penetration properties of photons. For the depth-dose curve calculations, the geometry used in this simulation consists of a conical photon beam impinging on a rectangular parallelepiped water phantom. The photon beam had a radius of 5.65 cm at the surface of the water phantom giving an equivalent area of 10 x 10 cm^2 at the phantom surface. The distance between the radiation source and phantom surface was 80 cm (for 1.25 MeV photons from Co-60) and 100 cm for higher energies. The rectangular parallelepiped water phantom had a length 40 cm (facing the source), a width of 40 cm, and a height of 40 cm. A smaller concentric rectangular parallelepiped had a length of 29.3 cm (parallel to the floor), a width of 4 cm, and a height of 4 cm (perpendicular to the floor) was positioned inside the water phantom to define the dose-scoring region. This smaller rectangular parallelepiped was divided into 31 slabs. The first slab was 0.3 cm thick and the second and third slabs were 0.5 cm thick respectively to demonstrate further details in the build-up region. These were followed by the remaining 28 regions of 1.0 cm thickness positioned at the centre at each centimeter along the depth axis. The whole geometry was placed inside a sphere of radius 500 cm and of air medium and this was surrounded by a larger sphere of radius 5000 cm defined as a black-hole. Monoenergetic sources of 1.25 MeV, 2.35 MeV, and 3.5 MeV were representing the mean energies of Co-60 gamma-rays, and filtered 6 MV and 10 MV x-ray beams respectively. Simulations were performed for 5 cycles to calculate the standard deviation in order to obtain the required statistical uncertainty of 1–3%. One million photon histories were followed for each simulation. The running time of the depth-dose calculations for Co-60, 6 MV, and 10 MV was 2 hours for 5 independent simulations (cycles). The calculated percentage depth-dose agreed well with that published by the British Journal of Radiology Supplement 25 (1996) [8] for Co-60 and also corresponded to the internal data obtained from Singleton Hospital of 6 MV and 10 MV beam, within a 3% error for both codes.

The experimental condition in the above section was simulated as follows: a concrete wall of 300x300 cm^2 was assumed to have a density of 2.34 $g.cm^{-3}$ and an elemental composition of 0.92% hydrogen, 49.83% oxygen, 1.71% sodium, 4.56% aluminum, 31.58% silicon, 1.92% potassium, 8.26% calcium and 1.22% iron (by weight). [9] The thickness of the wall was assumed to be 50 cm. The photon beam was collimated by selecting parallel and very small beam sizes (0.1 x 0.1 cm^2). A sheet of lead of density 11.34 $g.cm^{-3}$ and various thicknesses (1 mm, 2 mm, and 4 mm) was simulated covering the concrete wall (facing the photon beam) to calculate the effect of adding lead to the wall. The whole geometry was placed inside a large sphere of 700 cm in radius and of air medium, which was then surrounded by a larger sphere defining the black-hole which was 7000 cm in radius (Fig. 1b). The backscattered photons were collected by a parallelepiped of water with dimensions of 200 cm height (perpendicular to the floor) x 100 cm width (parallel to the floor) x 1 cm thickness. This large size was necessary to enhance the detector efficiency and reduce the computation time. The photon energy cut off was set to 10 keV and the electron kinetic energy cut off was set to 10 keV (the total energy cut off was 0.521 MeV). Rayleigh scattering was taken into account.

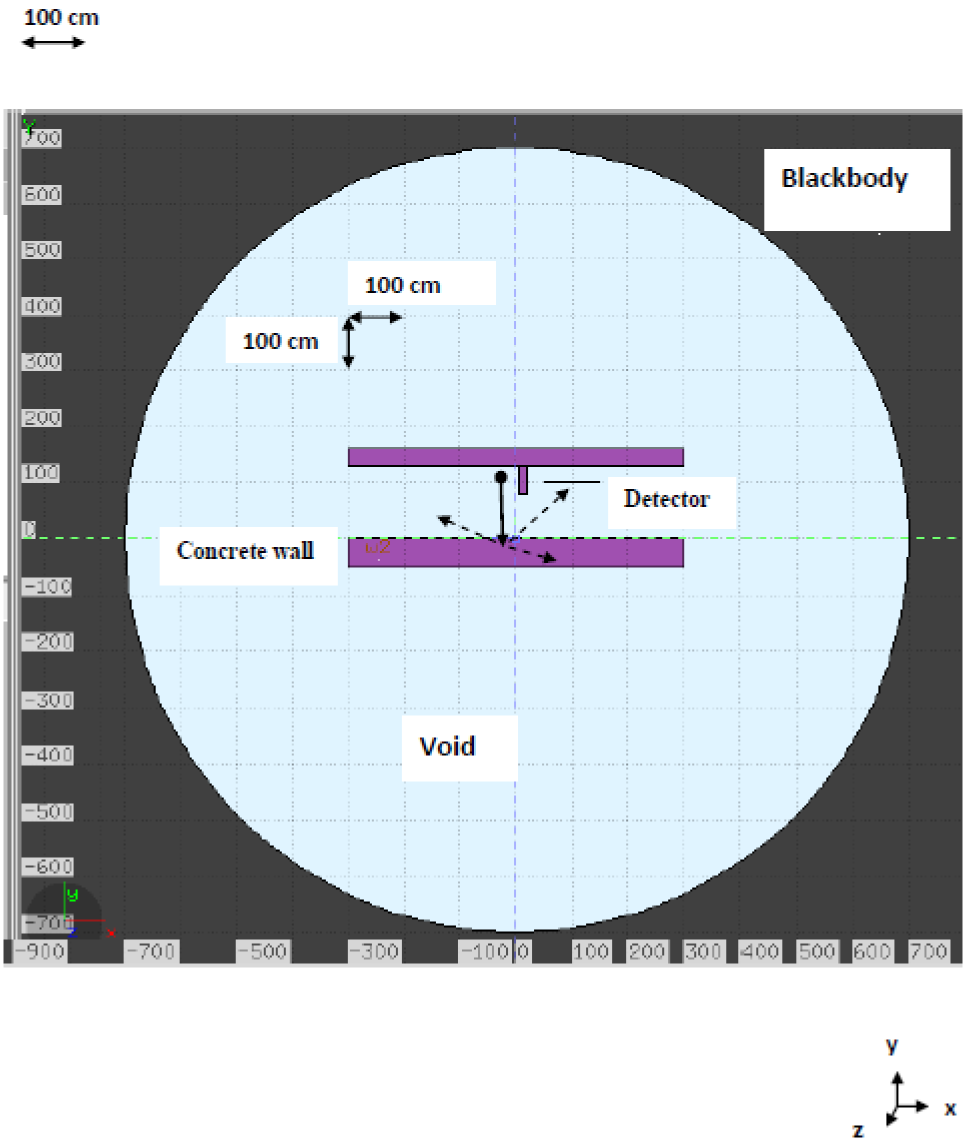

Figure 1b. Monte Carlo simulation of the above experiment as shown in Flair (the circle diameter is 1400 cm). Photon beam (solid arrow) is incident from the x-axis (i.e. in the -y direction on the concrete wall perpendicular to the y-axis). Detector is 100 cm in the x-direction by 200 cm in the z direction and 1 cm in y direction. Scattered photons were represented by dashed lines. Void is filled with air. Area in black is black-hole.

B. VALIDATION AND SIMULATION OF THE EGS CODE

The DOSXYZnrc user-code from the BEAMnrc package, which is based on the Monte Carlo code-base, EGS4, is a rectilinear geometry code used predominantly for phantom studies in radiation therapy. An equivalent geometry has been used to that of the FLUKA calculation (for the depth dose and backscattering dose calculations), with a voxel geometry employed instead of geometrical bodies. The ICRU defined composition of air was used, the concrete was chosen to be the same atomic composition as the FLUKA calculation. Similarly, the cutoff for photon transport was 10 keV and the cutoff for electron transport was 0.521 MeV (total).

C. SIMULATION OF A RADIOTHERAPY ROOM AT SINGLETON HOSPITAL BY THE FLUKA CODE

A typical RT room was simulated by the FLUKA code (as shown in Fig. 2). EGSnrc was not used to simulate the RT room because additional coding would have been required to model the complex geometry. The room walls, ceiling and floor were made of concrete of density 2.34 g.cm^{-3}. Also, in this simulation, the elemental composition of concrete was taken from NCRP[9] as shown above. All walls had 100 cm thickness and both floor and ceiling thicknesses were 50 cm (an assumption was used to speed up the computation without compromising the results). The maze walls and floor were lined with a 2 mm lead sheet of density 11.34 g.cm^{-3}. The photon source was fixed at 100 cm away from the surface of the rectangular parallelepiped water phantom that had a symmetric size of 40 cm × 40 cm × 40 cm along the beam axis. The reason for including a phantom was to simulate the maximum dose at the maze entrance, as calculated by Al-Affan[3] (i.e. the highest expected dose at the maze entrance). Although the photon source from the Linear Accelerator is divided into primary photons, scattered and leakage photons, in the present work the beam was assumed to have only primary photons and therefore leakage photons were not taken into account. The photon beam had a radius of 5.65 cm (at 100 cm from the phantom surface) at the surface of water phantom giving an equivalent area of 10 x 10 cm^2.

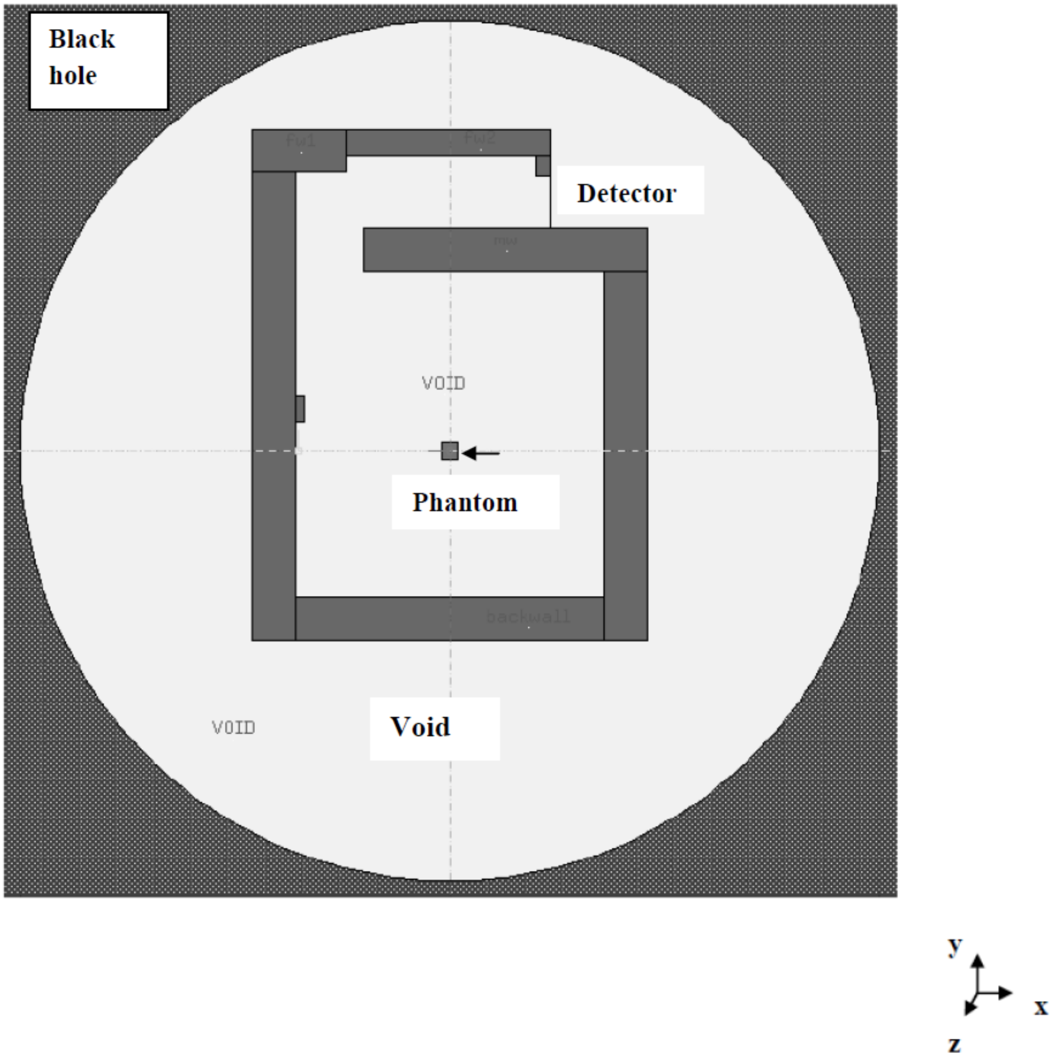

Figure 2. A FLUKA generated diagram of the radiotherapy room, which was used to calculate the dose for scattered photons at the maze entrance (the diameter of the white void region is 2000 cm). The primary photon beam is in the –x direction.

A large rectangular parallelepiped water detector was used to calculate doses of backscattered photons and positioned at the entrance of the maze and covered the maze as a door (Fig. 2). The detector was 120 cm in width in the y direction, 1 cm in depth in the x direction, and 200 cm in height in the z direction. The main advantages of using large detector were to increase its efficiency and reduce the computing time and statistical error.

The whole geometry was surrounded by a large spherical void of a radius of 1000cm consisting of air and this was surrounded by a black-hole region, with an outer sphere of a radius of 10000 cm. The simulated 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 MV). For each energy, the FLUKA code was run for 3 cycles to determine statistical fluctuations in the results. Moreover, 60 million photon histories were generated for each simulation to obtain a statistical uncertainty of better than 30%. Computation time for the calculation of the doses ranged from a few hours to about 35 hours with 3 cycles of the calculation for all situations. The transport cut-offs for photons and electrons (kinetic energy) were set to 10 keV and 100 keV respectively, to maintain a reasonable computation time and acceptable statistical error for this application.

IV. EXPERIMENTAL RESULTS

The measured dose rates are shown in Table I for Co-60 and Table II for Cs-137 for photon beams normally incident on the wall. Measured dose rates D_c, D_{cl2} and D_{cl4} are shown as a function of the backscattered angle. However, when a 2 mm thick lead sheet was placed on the concrete wall the dose rate was reduced for all angles. The reduction

Table I. The dose rate as a function of the reflecting angle for a Co-60 beam incident perpendicular on the concrete wall (D_c) and also on the concrete wall lined with 2 mm (D_{cl2}) and 4 mm lead (D_{cl2}). The dose rate at reference is D_o = 103 mR/h is measured at a distance of 167 cm from the source. The background reading was 15 µ R/h. The data below shows the average measurement, minus the background reading.

Angle (Degrees)	D_c (µ R/h) for concrete wall only	D_{cl2} (µ R/h) for concrete wall lined by 2 mm lead	D_{cl4} (µ R/h) for concrete wall lined by 4 mm lead
100	134	131	130
120	196	162	158
135	211	172	170
150	258	213	210

Table II. The dose rate as a function of the reflecting angle for Cs-137 beam incident perpendicular on the concrete wall and also on the concrete wall lined with 2 mm and 4 mm lead. The dose rate at reference is D_o = 1513 mR/h measured at a distance of 167 cm from the source. The background reading of 15 µR/h was subtracted from the readings below.

Angle (Degrees)	D_c (µ R/h) for concrete wall only	D_{cl2} (µ R/h) for concrete wall lined by 2 mm lead	D_{cl4} (µ R/h) for concrete wall lined by 4 mm lead
100	613	240	240
120	1256	347	318
135	1443	389	348
150	1668	484	423

was very small at an angle of 100 degrees. The reduction was about 20% for angles of 120 degrees and above for Co-60 and more than 70% for Cs-137. Also, above 120 degrees the ratio of reduction was nearly constant, as shown in Tables III and IV. It can also be noticed from Table I and Table II that when 4 mm lead was used, the dose rate was reduced by only a small amount more than 2 mm. Therefore, 2 mm lead may be used as the optimum thickness which would reduce the dose rate of the radiation reflected from the concrete wall for both Co-60 and Cs-137. It was found that the half value layer of lead was between 1 and 4 mm for photon energies of 150 and 400 keV, respectively.

Table III. The ratio of the dose rate for the Co-60 beam incident perpendicular on the concrete lined with lead, to that of concrete.

Angle (Degrees)	Ratio D_{cl2}/D_c for concrete wall lined by 2 mm lead	Ratio D_{cl4}/D_c for concrete wall lined by 4 mm lead
100	0.98	0.97
120	0.83	0.81
135	0.82	0.81
150	0.83	0.81

Table IV. The ratio of the dose rate for the Cs-137 beam incident perpendicular on the concrete lined with lead, to that of concrete.

Angle (Degrees)	Ratio D_{cl2}/D_c for concrete wall lined by 2 mm lead	Ratio D_{cl4}/D_c for concrete wall lined by 4 mm lead
100	0.39	0.39
120	0.27	0.25
135	0.27	0.24
150	0.29	0.25

These energies are typical of backscattered photons for Co-60 and Cs-137 using the equation of Compton scattering. For photon energies above 1.5 MeV, the situation may be different, as pair production will play an important role in reversing the dose reduction (Table VIII). Moreover, this finding has important implications for reducing the dose rate at the maze entrance of RT rooms if selected maze walls are lined by an appropriate thickness of lead, in effect trapping the backscattered photons. The data in Table I show the average of the measurements, minus the background reading.

The resulting estimated combined uncertainty was about 24%. The above results consider the scattered spectrum of Co-60 and Cs-137 interacting with the plastic scintillator detector. The largest contribution to the uncertainty, due to the calibration and energy response of the instrument, will not affect the ratios determined; the interest was to study the relative reduction in dose. The results were not corrected for changes in spectrum, but this effect is expected to be small in the energy range considered.

V. FLUKA AND EGS MONTE CARLO RESULTS AND DISCUSSION

The calculated doses of scattered photons from the wall are shown in Tables V to VIII for photon energies 0.25, 0.662, 1.25 and 2 MeV, respectively, using the Monte Carlo codes FLUKA and EGS. It can be seen that there is a good agreement between the FLUKA and EGS calculations. The statistical error was between 2% and 8% for all calculations.

The small error shows that both EGS and FLUKA can be used to simulate backscattering photons of various energies by the concrete wall and also when a lead sheet is covering the wall. The ratio of the simulated dose by the FLUKA Code for a beam of Cs-137 incident perpendicular on the concrete lined with lead to that of concrete only is shown in Table VI. Table VII shows the calculations for Co-60. Total computing time for the calculations was between 2 and 45 minutes for each run.

Table V. Comparison between FLUKA and EGS codes for backscattering photons from concrete wall with lead for a photon energy of 0.25 MeV. The source to wall distance was 101cm. 0 mm lead = concrete only. Column 5 shows the ratio of dose when the concrete walls are covered with lead of various thicknesses to that of concrete only using the FLUKA Code.

Lead mm	FLUKA dose Gy/photon	EGS dose Gy/photon	EGS/FLUKA	FLUKA Dose ratio d_{Cl}/d_C
0	1.43E-18±2%	1.39E-18±1.6%	0.97	1
1	2.15E-19±9%	1.88E-19±4%	0.87	0.15
2	2.1E-19±1.5%	1.82E-19±4%	0.87	0.15
4	2.06E-19±7%	1.91E-19±4.2%	0.93	0.14

Table VI. Comparison between the FLUKA and EGS codes for backscattering photons from concrete wall with lead. Photon energy: 0.662 MeV (Cs-137). Photon cutoff energy: 10 keV. Also, column 5 shows the ratio of dose when the concrete walls are covered with lead of various thicknesses to that of concrete only using the FLUKA Code.

Lead mm	FLUKA dose Gy/photon	EGS dose Gy/photon	EGS/FLUKA	FLUKA Dose Ratio d_{Cl}/d_C
0	1.91E-18±3.2%	1.81E-18±1.8%	0.95	1
1	5.01E-19±2.6%	4.81E-19±3.6%	0.96	0.26
2	2.70E-19±2.3%	2.58E-19±5.3%	0.95	0.14
4	2.01E-19±1.3%	1.90E-19±6.1%	0.95	0.11

Table VII. Comparison between the FLUKA and EGS codes for backscattering photons from concrete wall with lead. Photon energy: 1.25 MeV (Co-60). Photon cutoff energy: 10 keV. Also, column 5 shows the ratio of dose when the concrete walls are covered with lead of various thicknesses to that of concrete only using the FLUKA Code.

Lead mm	FLUKA dose Gy/photon	EGS dose Gy/photon	EGS/FLUKA	FLUKA Dose Ratio d_{Cl}/d_C
0	1.76E-18±5.4%	1.65E-18±2.1%	0.94	1
1	1.14E-18±6.4%	1.13E-18±4.3%	0.99	0.65
2	8.32E-19±2.9%	8.20E-19±5.5%	0.99	0.47
4	7.91E-19±8.7%	7.20E-19±6.3%	0.91	0.45

Table VIII. Comparison between the FLUKA and EGS codes for backscattering photons from concrete wall with lead. Photon energy: 2 MeV. Photon cutoff energy: 10 keV. Also, column 5 shows the ratio of dose when the concrete walls are covered with lead of various thicknesses to that of concrete only using the FLUKA Code.

Lead mm	FLUKA dose Gy/photon	EGS dose Gy/photon	EGS/FLUKA	FLUKA Dose Ratio d_{Cl}/d_{C}
0	1.82E-18±4%	1.6E-18±2.4%	0.88	1
1	2.2E-18±6.1%	2.34E-18±4.5%	1.06	1.21
2	2.0E-18±2%	2.13E-18±4.9%	1.07	1.10
4	1.89E-18±2.8%	2.12E-18±5.0%	1.12	1.04

Table IX. Calculations of dose and %DRF at the maze entrance using the FLUKA code for scattering photons from concrete wall with 2mm lead (for a situation of 4 walls and a floor). 10X10 cm^2. Lintel height=220cm. Width=160cm.

Photon Energy MeV	FLUKA dose D_c Gy/photon	FLUKA dose D_{cl2} Gy/photon	Ratio= D_{cl2}/D_c	% DRF
0.5	6.83E-22±12%	4.61E-23±23%	0.07	93
1	1.11E-21±12%	8.00E-23±27%	0.07	93
3	1.27E-21±18%	1.2E-22±27%	0.1	90
7	1.37E-21±9%	4.98E-22±36%	0.36	64
10	1.53E-21±6%	1.47E-21±13%	0.96	4

It can be seen from Tables V and VIII that introducing lead sheets of various thicknesses in the simulation reduced the dose of the scattered photons by a factor of between 50% and 80% for Co-60 and 70% to about 90% for Cs-137. This was a higher reduction of dose than the measurements that were recorded and the main reason for this is expected to be due to the higher attenuation of the concrete due to the presence of iron in the measurements. In addition only 1 m^2 of the concrete walls was covered by lead compared to all of the wall area being covered by lead in the Monte Carlo simulation. Again, the most optimal thickness was 2 mm where a reduction in the dose was achieved of about 53% for Co-60 and 85% for Cs-137. This is interesting since it shows that although the reduction was higher for the FLUKA simulation, there is an appreciable improvement when the energy of the photon was reduced from Co-60 to Cs-137 (column 5 in the Tables). The reason for the trend is that the photoelectric effect for lead is effective up to about 1 MeV and increasingly dominant below that energy; hence more greatly attenuating scattered photons of lower energies.

Above 1.02 MeV pair production begins to contribute and will increase with increasing photon energy. The pair production contributions to the total cross section in lead at energies 1, 1.5, 2, 5, 10 MeV are 0, 3.2, 10.9, 50 and 73% respectively.[11] Also the photoelectric effect will decrease with increasing photon energy and will be negligible compared to the pair production (the ratio of PE to pair production cross sections in lead dropping from 4.8 to 0.015 in the energy interval 1.5 to 10 MeV). [11] The result is the emission of electron-positron pairs, and subsequent annihilation to produce photons travelling in all directions including towards the dosemeter. The process enhances the dose of the backscattering photons and increases the total dose as shown in Table VIII for 2 MeV photons. Therefore above 2 MeV using a lead sheet to cover the concrete wall would enhance the dose of the backscattering photons and would not be useful. For this reason, careful thought is required about where to place lead in the RT rooms to achieve maximum scattered photon absorption and hence dose reduction at the maze entrance.

There are a few differences between the experimental set up and the FLUKA and EGS simulation. The first is that the amount of iron in the concrete compound is not the same. The amount of iron in the wall is higher than that in the simulation, as the concrete wall at the Royal Scientific Society had small pieces of iron mixed with the concrete to enhance the photon absorption and keep the wall thickness optimum. The second factor is that the photon beam emitted from the Co-60 and Cs-137 had been collimated, which in turn scattered some of the beam in all directions, whilst the beam from FLUKA was narrow, parallel and monoenergetic. The third factor was that the lead only covered 1 m^2 of the concrete wall, not the whole wall as simulated by FLUKA and EGS. Another factor was the fluctuation in the dose rate reading and the dosemeter response as a function of the photon energy. However, it is clear that adding between 1 and 4 mm of lead to the concrete wall will significantly reduce the backscattered photons. This should have a direct implication for the design of mazes for RT rooms.

Table IX shows that the ratio of the dose at the maze entrance when 2 mm lead was used, compared to that with no lead (only concrete wall), varies from 0.07 to about 0.96, depending on the energy of the primary beam. Therefore, it is necessary to know the spectrum of the primary beam to be able to simulate the dose calculations at the maze entrance. However, for photon energies of up to 3 MeV there is little variation, with an average ratio of about 0.1. This study shows that using a 2 mm lead lining in the maze could reduce the dose scattered through the maze by about 90%.

It is useful in this study to introduce the concept of Dose Reduction Factor (DRF), the amount of reduction in photon dose at the maze entrance when lead is covering the maze concrete walls (Table IX column 5).

Dose Reduction Factor can be represented by the equation DRF= 1- (d_{cl}/d_c). Tables IX shows the percentage DRF for lead thickness of 2mm and various photon energies. Therefore, the DRF is about 90% 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. In an earlier study Baker and Thomas[12] showed that cladding the maze concrete walls with either wood, polyethylene or a commercially available plastic, resulted in a reduction of the neutron dose by about 40% and photon dose by 10% at the maze entrance. Wang et al [13] have studied the change of the neutron and photons dose rate at the maze entrance during the upgrading of the RT room from 6 MV x-rays to 18 MV. They found that cladding the maze concrete wall with a thickness of 2.5 cm borated polyethylene boards reduced the measured dose of neutrons and photons at the maze entrance by 41% and 59%, respectively. This method was found to be more economical and feasible than increasing the door thickness, by mainly reducing the capture gamma dose arising from neutron-capture induced gamma emission. Low Z borated polyethylene boards were used to reduce the neutron dose and consequently the photon dose was reduced.

VI. CONCLUSIONS

This study shows that a few millimeters of a suitable high atomic number element such as lead could be used to cover the maze walls to reduce the photon dose rate at the RT room maze entrance by as much as 90%, depending on the maze shape and photon spectrum reaching the maze entrance. This is due to the effect of the photoelectric interaction on scattered photons, which is proportional to the Z^3 of the materials used. Covering part or all of the maze walls with lead may be cost effective, especially in situations where extending the maze length or changing its shape would not be possible because of space restriction. This would be particularly useful in the case of upgrading the RT room use, e.g. from Co-60 to x-rays from Linear Accelerators of a higher energy. FLUKA has shown to be a useful tool to simulate different complex scenarios to predict such results in advance of construction. In fact, Monte Carlo simulations can also be extremely useful in guiding the design of a new RT room. [14]

It should also be noted that this proposal would be viable only when the dose rate from leakage photons to the maze entrance is not dominant compared to that from the scattered photons throughout the maze, since the spectrum reaching the maze entrance due to the leakage has high energy photon components. [3] This novel technique could be developed further to include certain materials that absorb neutrons which may be present in the maze for Linear Accelerators of high energy x-rays. In general, with these methods, it may be possible to avoid the use of doors in future RT room design. More studies are required to simulate the various scenarios that may occur, including the presence of leakage. Further measurements are also required to confirm the estimated DRF calculated with Monte Carlo simulations.

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