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TECHNICAL PAPER

Shielding of medical imaging X-ray facilities: a simple and practical method

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Abstract The most widely accepted method for shielding design of X-ray facilities is that contained in the National Council on Radiation Protection and Measurements Report 147 whereby the computation of the barrier thickness for primary, secondary and leakage radiations is based on the knowledge of the distances from the radiation sources, the assumptions of the clinical workload, and usage and occupancy of adjacent areas. The shielding methodology used in this report is complex. With this methodology, the shielding designers need to make assumptions regarding the use of the X-ray room and the adjoining areas. Different shielding designers may make different assumptions resulting in different shielding requirements for a particular X-ray room. A more simple and practical method is to base the shielding design on the shielding principle used to shield X-ray tube housing to limit the leakage radiation from the X-ray tube. In this case, the shielding requirements of the X-ray room would depend only on the maximum radiation output of the X-ray equipment regardless of workload, usage or occupancy of the adjacent areas of the room. This shielding methodology, which has been used in South Australia since 1985, has proven to be practical and, to my knowledge, has not led to excess shielding of X-ray installations.

Keywords Shielding · X-ray installations · Radiation protection · Scattering · X-rays

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Introduction

The shielding design method discussed in this work is based on the shielding principle used to shield X-ray tube housing to limit the leakage radiation from the X-ray tube at each rating of the specified tube potential to 1 mGy/h at a distance of 1 m from the focus [1]. The shielding of X-ray tube housing is straightforward, determined by only one parameter: the air kerma rate at a distance of 1 m from the focus "at the maximum specified energy input" of the X-ray tube [1]. Currently, the standard by which shielding requirements of medical imaging X-ray facilities are specified are those detailed in the National Council on Radiation Protection and Measurements (NCRP) Report 147 [2] and previously in the NCRP Report 49 [3]. The shielding methodology used in these reports is complex. It requires the knowledge of the values of the weekly clinical workload, W, use factor, U, and occupancy factor, T. Thus, in calculating shielding requirements for the primary, secondary and leakage radiation barriers, the shielding designer would need to make assumptions regarding the use of the X-ray room and the adjoining areas. Two different designers may make different assumptions resulting in different shielding requirements for a particular X-ray room [4]. In addition, it is difficult to foresee the changes with time that may occur in the clinical workload and use of the adjoining space.

The proposed shielding method has been used in the South Australia since 1985 and incorporated in the Radiation Protection and Control (Ionising Regulations) [5, 6], and is still being used (in the revised Regulations [7]). The clinical workload, use factor and occupancy factors described in the NCRP reports are replaced by a single parameter related to the radiation output of the X-ray apparatus to be installed in the X-ray room.

Methods

The philosophy behind the development of the shielding requirements expressed in this work is that X-ray machines are shielded so that in areas occupied by radiation workers and by members of the public the air kerma rate is such that the annual dose limits for radiation workers and general public would not be exceeded when the machines are operated at their maximum capacity. This is achieved if the air kerma rate 50 mm from outside boundaries of X-ray room does not exceed 25 µGy/h for:

1. general radiographic installations when the X-ray machines are operated at their maximum continuous X-ray tube current at the tube voltage of 100 and 125 kV, respectively, for radiography at the Table and Vertical Buckys. For radiography at the Table Bucky, it is reasonable to perform shielding calculation at the tube voltage of 100 kV for secondary radiation as most of the diagnostic examinations performed at this Bucky use tube potentials in the range 50–100 kV with most exposures being <100 kV [8]. For examinations performed at the Vertical Bucky, 125 kV is rarely exceeded. For the calculation of the scatter fraction, a scatter area of 35×43 cm^2 = ~1500 cm^2 should be used as the largest imaging receptor detectors are this size.
2. fluoroscopic installations when the X-ray machines are operated their maximum kV and at the maximum legal dose rate limit of 150 mGy/min [1, 7]. Rarely, fluoroscopic systems operate with tube voltages greater than 120 kV. For the calculation of the scatter fraction, the largest area of the imaging detector (flat panel or image intensify detector) should be used.
3. CT installations when the CT scanners are operated at the maximum continuous tube current at 130 or 140 kV depending on the scanner. For these installations, tertiary radiation from ceiling slabs should also be considered in specifying shielding requirement [9–11]. For the calculation of the scatter fraction, the largest scan volume of the patient should be used.

The shielding design limit of 25 µGy/h, which denotes the entrance skin dose rate of a person 50 mm from the boundary of the X-ray facility, was derived from the then annual occupational effective dose limit of 50 mSv (working 5 days a week and 8 h a day for 50 weeks of the year) for radiation workers when this novel shielding method was incorporated in the South Australian Ionising Radiation Regulations [5] in 1985. At that time, a comparison of the shielding design between the method used in NCRP 49 [3] and that in the South Australian Ionising Radiation Regulations [5] for an existing X-ray room in a large hospital where the workload could be determined accurately indicated that the shielding outcomes of the two methods were comparable [6]. The current annual occupational dose limit is 20 mSv which would correspond to a shielding design equivalent dose rate limit of 10 µSv/h. For legal reasons, shielding designers should use this dose rate limit in the shielding calculations. However, in this case the continuous constant current would be required to be divided by a factor of 2.5 to avoid excess shielding of the X-ray facilities.

As part of this work, an example of shielding calculations with the methodology proposed here for the X-ray room illustrated in Fig. 1 is provided. In the example, a shielding design absorbed dose rate of 25 µGy/h is used. The layout of the X-ray room shown in Fig. 1 is such that the main entrance door (at bottom of drawing) leads into a corridor and adjacent are two change rooms (Change 01 and Change 02). The wall between the change rooms and the X-ray room is designated as W1. Wall, W2, on the left separates this X-ray room (Room 1) with a second X-ray room (Room 2). At the top of the drawing is another corridor which separates Room 1 by the wall, W3, and on the right of the room are offices separated by walls W5 and W7 while the air duct separates the X-ray room and the offices. The radiation protection screen for the X-ray room is 2.0 m long and is fitted with a bench 0.6 m wide by 2.0 m long. The Table Bucky (Examination Table) and the Vertical Bucky are indicated in the drawing (Fig. 1). The useful clinical area of the room between the radiation protection screen, the change rooms, X-ray Room 2 and the air duct is about 4 m × 6 m. The ceiling and floor are concrete with honeycomb structure with the thinnest concrete thickness of 150 mm which has a lead equivalent of 2.1 mm for a 125 kV secondary X-ray beam. The concrete lead equivalent has been derived by first determining the secondary radiation transmission through it and then calculating the lead equivalent using, in both cases, the Archer et al. [4] equations with concrete coefficients from Simpkin [13] work. In addition to the critical distances shown in Fig. 1, for the calculation of the barrier thickness to limit leakage radiation when the X-ray tube is used for radiography at the Vertical Bucky (FID = 1.8 m), the following distances from tube focus are required: W1 1.5 m, W2 3.2 m, W3 5.4 m, radiation protection screen 2.6 m, W4 3.5 m, W5 and W7 3.4 m, and entrance door 3.4 m.

The X-ray machine installed in this room was an 80 kW unit with a high frequency generator. The maximum heat dissipation rate of the X-ray unit with fan air cooling was specified by the manufacturer of the X-ray unit to be 925 W at the anode and 740 W by the tube unit. For the calculation of the maximum continuous tube current, the heat dissipation rate of 740 W would need to be used as the heat dissipation by the tube housing determines the maximum radiation output capacity of the X-ray system. The radiation output of this X-ray unit was 117 µGy/mAs at 100 kV and 190 µGy/mAs at 125 kV at a distance of 0.8 m from the focal spot.

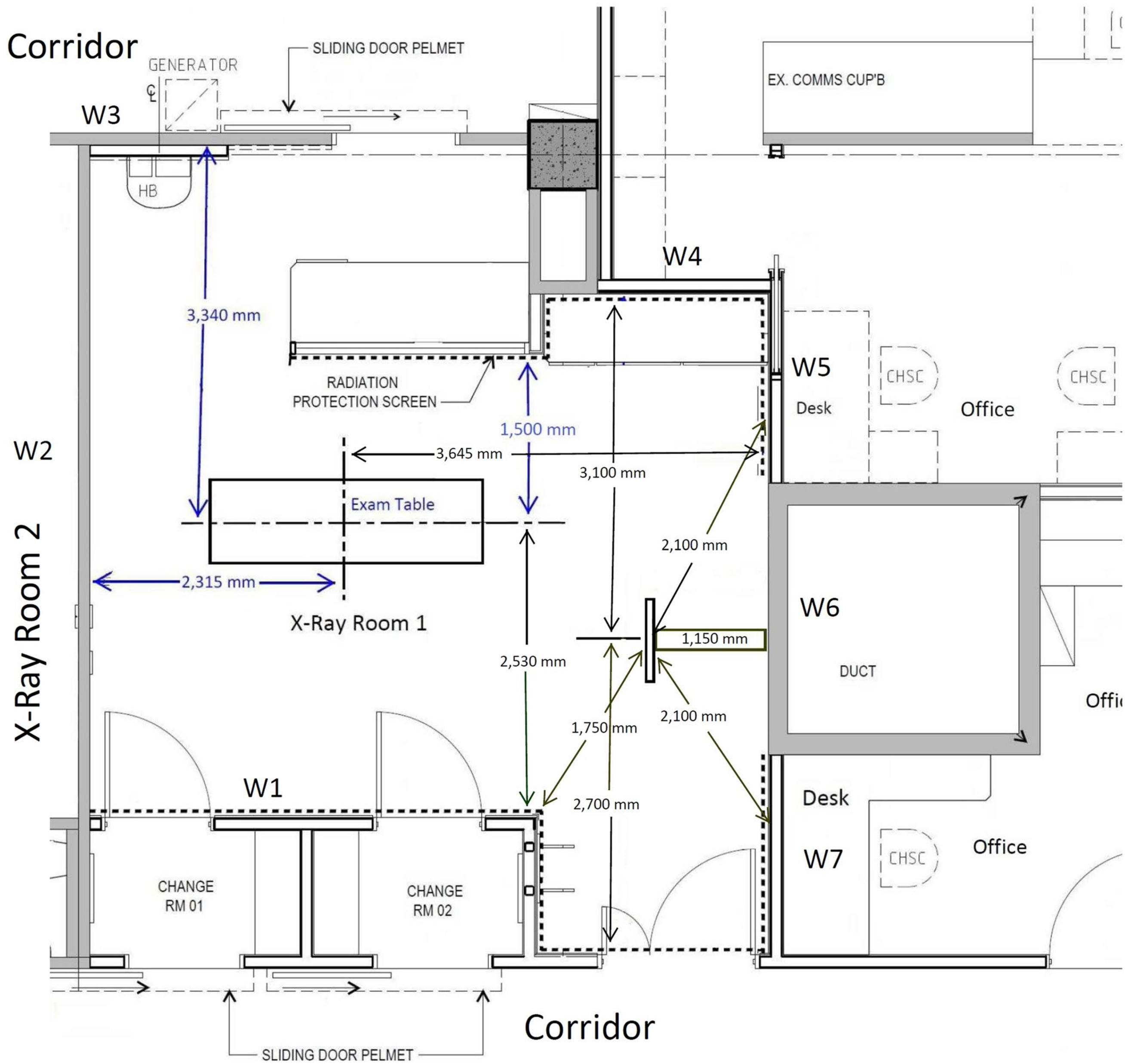

Fig. 1 Layout of X-ray Room 1 and adjacent areas

Calculation of the maximum continuous currents and air kerma rates

The thermal power dissipation by the X-ray tube expressed in watts is given by the equation:

$$P\,(W) = \text{rms} \times \text{peak tube voltage (Vp)} \times \text{tube current (A)} \tag{1}$$

where rms = root-mean-square factor of the tube potential which equals 1.0 for constant potential and high frequency generators.

From the thermal power dissipation formula above, the maximum constant current at 100 kV and a heat dissipation rate of 740 W for the tube unit with the cooling fan and a high frequency generator is:

$$I_{\text{max cont}} = \frac{P}{\text{rms} \times \text{kV}} = \frac{740}{1 \times 100} = 7.4\ \text{mA} \tag{2}$$

Similarly, at 125 kV, the maximum continuous tube current is 5.92 mA. Thus, the maximum air kerma rate at 0.8 m from the anode = 7.4 × 117 = 866 μGy/s at 100 kV and

5.92 × 190 = 1124.8 μGy/s at 125 kV. These air kerma rates correspond to 3117.6 and 4049.3 mGy/h respectively. The 0.8 m distance from the tube focus results in the assumptions that for all examinations at the Table Bucky, the focus-image-receptor-distance (FID) is 1 m and the thickness of the scatter is 0.2 m. For the Vertical Bucky, a 1.8 m FID is assumed for all examinations and thus, using the inverse square law, the air kerma rate at a FID of 1.6 m is 1012.32 mGy/h.

The next step in the shielding design is to calculate the secondary radiation produced by the 1500 cm^2 scatter at the Table and Vertical Buckys. This process is the same as that described in NCRP 147 report [2]. For this purpose the scatter fraction equation from Simpkin and Dixon [12] work which is also replicated in ICRP 147 [2] is used. Thus, at the Table Bucky, 100 kV tube voltage and scatter angle of 90°, the scatter fraction = 0.0071 and therefore secondary radiation rate at 1 m from the centre of the scatter = 0.0071 × 3117.6 = 22.135 mGy/h.

At the Vertical Bucky, because of the orientation and location of the Bucky, scatter fractions at 125 kV tube voltage and scatter angles of 45°, 90°, 120° and backscatter calculated at 140° are required. The scatter fractions corresponding at these angles were calculated to be 0.0079, 0.0077, 0.0094 and 0.0153 and the secondary radiation rates 7.997, 7.795, 9.516 and 15.488 mGy/h respectively at 1 m from the centre of the scatter.

The thickness of shielding material for both the primary and secondary barriers can be calculated from the Archer et al. [4] equation with coefficients for different materials from the work by Simpkin [13] which are also tabulated in NCRP 147 [2]. For the calculation of the barrier thickness for the primary beam at the Vertical Bucky it is assumed that no patient/scatter is in the primary beam. Leakage radiation after being transmitted through the shielded tube housing is highly hardened and thus it can be approximated by a monochromatic beam. However, in this exercise, leakage radiation from the X-ray tube has been treated the same way as the secondary radiation since most of the examinations at the Table and Vertical Bucky are performed at tube voltages less the 100 and 125 kV respectively and even though the beam is highly filtered the shielding of the X-ray room determined at 100 and 125 kV is sufficient to attenuate the leakage and secondary radiation below the 25 μGy/h limit. Thus, in calculating the barrier thickness of the X-ray room, the secondary and leakage radiation have been added together at the different critical distances and also calculated separately.

Barrier thickness calculations

For this exercise, the required material for the barriers is assumed to be lead. For the calculation of the barrier thickness of W1 from secondary radiation produced at the Table Bucky require the following information: secondary radiation rate at 1 m from the scatter (centre of the examination table) = 22,135 μGy/h and the distance W1 from centre of scatter 2.53 m. Using the inverse square law, air kerma rate at W1 = 3458 μGy/h. This radiation needs to be attenuated to 25 μGy/h, i.e. attenuated by a factor of 138.32. Using Archer et al. [4] equation and Simpkin [13] coefficients for lead at 100 kV, the thickness of the barrier is found to be 1.01 mm Pb. If leakage radiation from the X-ray tube of 1000 μGy/h at 1 m from focus is calculated in the same way (156 μGy/h at W1) and added to the secondary radiation (3614 μGy/h), the required barrier thickness for this radiation yields 1.02 mm Pb.

The complete shielding results of the calculation of the various barrier thicknesses for the X-ray room shown in Fig. 1 are reported in Table 1 for secondary radiation, the sum of secondary, leakage radiations and primary beam. Note that the final barrier thickness of the wall, W2, between X-ray Rooms 1 and 2 will also depend on the shielding requirements of the X-ray machine installed in Room 2. Also, for this exercise, barrier thicknesses have not been calculated for examinations performed at the Vertical Bucky with FID of 1.0 m.

Results

The barrier thicknesses shown in Table 1 are maximum thicknesses to limit the air kerma rate from primary, secondary and leakage radiations to 25 μGy/h at the boundaries of the X-ray room when the X-ray unit is operated at its maximum continuous current at 100 and 125 kV at the Table and Vertical Bucky respectively and with a scatter area of 1500 cm^2. Table 1 shows that the differences in barrier thicknesses for secondary radiation only and secondary plus leakage radiations are small, the maximum difference being 0.06 mm Pb, i.e., the inclusion of leakage radiation in the secondary radiation barrier thickness calculations only adds less than 0.1 mm Pb to the barrier thicknesses for X-ray rooms. Thus, with the proposed shielding design method, the contribution of leakage radiation can be ignored. This simplifies the shielding calculation process.

With the proposed shielding method, the barrier thicknesses are calculated separately when the X-ray tube is operated at the Table and Vertical Buckys and the thickest barriers are then recommended for the shielding specifications of the X-ray installation. This is different for the NCRP methodology. The NCRP method is based on a dose per week and, thus, the doses resulting when the X-ray tube is operated at the Table and Vertical Buckys must be added together before the barrier thicknesses are calculated. In Table 1, the maximum barrier thickness of 1.40 mm Pb is for the radiation protection screen for both

Table 1 Barrier thicknesses (mm Pb equivalent) for shielding of X-ray Room 1

Location	Barrier thickness (mm Pb equivalent) from	
	Secondary radiation	Secondary + leakage radiations
Radiation from table Bucky (Examination Table) position		
Wall: W1 (change rooms)	1.01	1.02
Wall: W2 (between 2 X-ray Rooms)	1.07	1.09
Wall: W3 (corridor)	0.79	0.80
Wall: W4	0.72	0.73
Walls: W5, W6 (offices)	0.87	0.88
Wall: W7	0.61	0.62
Entrance door	0.58	0.60
Protection screen		
At stand/view window	1.39	1.40
At operator's position: 0.6 m behind screen	1.14	1.16
Radiation from Vertical Bucky		
Wall: W1 (corner of change Room 1)	1.04	1.09
Wall: W2 (X-ray Room 2)	0.49	0.55
Wall: W3 (corridor)	Protection screen in path	< 0.01
Wall: W4 (office)	0.66	0.69
Wall: W5 (office)	0.97	0.99
Wall: W6	Solid brick walls with a Pb equivalent at 100 kV > 2.0 mm Pb	
Wall: W7 (office)	0.97	0.99
Entrance door	0.81	0.83
Protection screen		
At stand/view window	0.67	0.70
At operator's position: 0.6 m behind screen	0.57	0.60

secondary and leakage radiation when the X-ray tube is used for radiography at the Table Bucky as the centre of the examination table is only 1.5 m from the radiation protection screen. At the location of the operators, 0.6 m behind the radiation protection screen, the required barrier thickness is much less: 1.16 mm Pb. The next thickest barrier of 1.09 mm Pb is that required to shield the corner of Change Room 02 (Fig. 1) as this corner is only 1.75 from the scatter at the Vertical Bucky. Thus, considering the barrier thicknesses shown in Table 1, the recommended shielding specifications for the X-ray Room 1 would be:

1. all walls and radiation protection screen to be shielded with materials having a lead equivalent of 1.3 mm Pb (15 kg/m^2) at 100 kV.
2. the main entrance and change rooms doors to be lined with 0.9 mm Pb: 0.45 mm Pb (5 kg/m^2) on each side of the doors for balance.
3. to install behind the Vertical Bucky an extra layer of 1.3 mm Pb equivalent material (total barrier thickness 2.6 mm Pb) 1 m wide by 2 m high.

The actual shielding properties of the X-ray room shown in Fig. 1 are:

1. W2 and W3 are existing walls of barium-loaded "chalk" with a Pb equivalent of 2.2 mm measured at 100 kV.
2. the Vertical Bucky is against the existing air vent wall built of solid bricks. Each wall has a Pb equivalent > 2 mm (total barrier thickness > 4 mm Pb). Thus, this shielding is more than sufficient to attenuate the primary beam.
3. the walls W1, W4, W5 and W7 consist of 2 layers of 13 mm thick commercially available barium-loaded plasterboards with a lead equivalent at 100 kV of 1.5 mm and 1.0 mm at 125 kV.

Conclusion

The barrier thicknesses shown in Table 1 demonstrate that the shielding concept espoused in this work whereby X-ray installations shielded according to the maximum radiation output of the X-ray equipment does not lead to excess shielding. The shielding method has proven to be simple and practical. It eliminates the possibility of inadequately shielding X-ray rooms because of inappropriate assumptions made of clinical workloads, usages and occupancies of adjacent spaces of the X-ray rooms. In addition, the contribution of the leakage radiation to barrier thicknesses can be ignored. This shielding methodology, which has been used in South Australia since 1985, is still enforced in its legislation [7].

Compliance with ethical standards

Conflict of interest The author declares that he has no conflicts of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by the author.

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