Assessment of secondary radiation shielding requirements for diagnostic x-ray facility in Tanzania: Comparison of recently proposed model and area monitoring data

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Abstract. This paper presents a shielding assessment for secondary radiation barriers of an x-ray diagnostic facility at Muhimbili National Hospital in Tanzania. The studied x-ray facility does not have the usual rooms layout and dimensions, which make the use of standard shielding review procedures less applicable. The shielding review was based on the recently proposed shielding model that considers the contribution of unshielded scattered and leakage radiation at selected points around the examination table. The scattered dose was calculated from the product of dose in air per unit workload, x-ray tube workload, scaled scatter fraction and field size as corrected for inverse square effects. The unshielded leakage dose was determined from typical leakage radiation value per 1000 mA-min week^{-1} for modern x-ray unit also corrected for the existing tube workload, the field size in use and the inverse square effects. The calculations were compared to radiation level measurements carried out on the site to examine the usefulness of the proposed shielding concept. The measurements were performed inside the x-ray rooms and beyond secondary barriers for three months using calibrated Thermoluminescent Dosimeters. The results show that the ratio of the calculated to the measured dose level inside the x-ray rooms varied from 1.85 to 5.86 indicating that the radiation exposure inside the rooms was highly variable. Considering possible underestimation of the scattered radiation, uncertainty in thermoluminescent dosimetry and future increment of the patient population, the use of this model offers better optimization than when traditional shielding methods are employed.

1. Introduction

X-rays have over the years become an important tool in medical diagnosis and therapy. However, if the x-rays are not shielded such that they only interact with the intended locations, they are potentially hazard to the workers, patients and members of the public [1,2]. Often the x-ray facilities for diagnostic purposes in several third world countries are very few compared to the demand [3]. For example, the Muhimbili National Hospital in Dar es Salaam (Tanzania) has seven x-ray machines that provide services to a patient population of about 200-500 per day. Because of high patient workload and less preventive maintenance, breakdowns are common and sometimes even two x-ray machines are operational. In addition to that most rooms used to host x-ray facilities were not originally intended for the purposes and are often smaller than the recommended standard format of 6m x 4m for general-purpose x-ray machines. Furthermore, the locations of x-ray machines are not optimized relative to the layouts of the rooms. The review for optimal shielding requirements in such cases is further complicated to process because the composition of the building materials used to construct most walls are precisely unknown.

The review of radiation shielding conditions is necessary when the designing assumptions change [4,5,6]. Such review was done at Muhimbili National Hospital because the workload and occupancy factors had changed following the expansion of the x-ray services and premises respectively. Of more interest was the review of the secondary barriers because of the higher occupancy than previously predicted. The National Council on Radiation Protection and measurements report number 49 (NCRP49) provides the widely accepted traditional methodology for radiation shielding designing. It is known that this traditional technique for designing radiation barriers may be unrealistic because the assumptions taken in shielding designing do not reflect the existing situations. It has for example been established that these methods may underestimate or overestimate the scattered and leakage radiation respectively from modern x-ray units [7,8,9,10]. Because of the inherent limitations in the traditional methods, a new shielding concept recently developed by Simpkin and Dixon [8] was therefore adopted to derive the radiation dose levels at selected points. Further to that, the new model was chosen for use because it is one of the latest recommended shielding concepts for typical modern diagnostic x-ray units. The aim of the study was therefore to compare the radiation doses calculated using this model and area monitoring data prior to assessing the shielding adequacy of the existing barriers.

2. Methods

2.1. X-ray facility

The study was carried out in two out of the seven diagnostic x-ray rooms. The average workload distribution for the studied x-ray rooms had earlier been surveyed over four calendar weeks and is shown in table 1. In the dose calculation, a workload of 350 mA-min week^{-1} was chosen because of similarity with other workloads suggested elsewhere [11]. For instance by using the Simpkin [11] approach, a workload of 367.5 mA-min week^{-1} (i.e. 2.45 mA-min week $^{-1}$ x 150 patients week^{-1}) is obtained, which is close to the workload employed.

Table 1. Average workload distribution per x-ray room studied

Average patients per week	Average films per week	Workload mA-min week^{-1} at kVp range < 60 kVp	60-90 kVp	91-100kVp	>101 kVp
150	600	250	500	350	100

The two rooms used for the study have a common control room of size 4m x 3m where combined radiation exposures to any occupant beyond the barrier could be significant. The two rooms are further isolated from the rest x-ray rooms and this was advantageous in avoiding the radiation exposure from other rooms. X-ray room A of total area having 5.7m x 4.1m dimensions, houses the Philips radiographic x-ay machine model medio 50 CP, tube serial number 884173, manufactured in (1992) while the Shimadzu radiographic (model Circlex P 13c, tube serial number 036660018 and fluoroscopy unit model 501, serial number 87906 manufactured in 1993) is located in room B, which is of similar dimensions like room A. However the Shimadzu fluoroscopy unit has since its installation been out of order and therefore its consideration was excluded from this study. Each x-ray machine possesses a full wave rectification system coupled with a modern three-phase high voltage generator. Furthermore, the employed x-ray machines had passed basic physic tests and therefore the study was done to equipment of known performance.

2.2. Calibration of Thermoluminescent Dosimeters (TLDs)

The calibration of TLDs was carried out at the National Calibration Laboratory for ionizing radiation against dosimetry standard, 600-cm^3 ionization chamber NE 2575 (serial number 443) and electrometer NE 2570/1B(serial number 937). The calibration of the standard is traceable to the International measurement system through the International Atomic Energy Agency (IAEA) dosimetry laboratory**.** The Harshaw Thermoluminescent (TL) reader model 4000 (serial number 3190) was employed to read the TLDs with its determination limit being 0.02 ± 0.01 mGy at 95% confidence level according to a procedure explained in detail elsewhere [12].

The TLDs were calibrated to determine their dose and energy responses at 33, 48, 65, 83, 100 and 120 keV energies as recommended [13,14]. The dose non-linearity of the used TLDs was within ± 20% and ± 5% for air kerma (from ^{137}Cs -γ source) less than 0.5 mGy and greater than or equal to 0.5 mGy respectively. The response of TLDs to x-rays in the studied energies was matched within ± 10% for the x-ray qualities in the calibration laboratory with the overall uncertainty estimated to about 30% for the x-ray beams at the hospital. The TLDs uncertainty was determined by standard method [15] and experience [16].

2.3. Area monitoring survey

Area monitoring in the x-ray rooms and beyond secondary barriers was done for three months using calibrated TLDs. Although all barriers in general purpose diagnostic x-ray facilities are often considered primary barriers [7], the set up and local rules of the x-ray facility, ruled out the possibility of the primary beam to impinge on the secondary barriers. For the purpose of this area survey, a pair of two TLDs was attached on soft wooden stand at a height of 1 m from floor. The arrangement of such pairs was done in the North-South and East-West directions about the examination table with a 1m interval between the stands positions depending on the size of the x-ray room. The TLDs positioning was also extended beyond the barriers in line with those positioned inside the rooms. The TLDs were evaluated on the calibrated TL reader every week with the background radiation of the TLDs corrected accordingly. The mean TLD reading at a point was deduced from the weekly measurements over three months period.

2.4. Calculation of secondary radiation

2.4.1. Inside the x-ray rooms

The model by Simpkin and Dixon [8] was adopted to examine the secondary radiation. Table 2 lists the assumptions used in the calculation.

2.4.1.1. Scattered radiation

Unshielded scattered dose D_s(un) at 1m was determined according to equation (1):-

$$D_s(un)\,(kV_p,\theta) = \frac{a^1{}_1\,(kV_p,\theta)x10^{-6}}{D^2{}_s}\frac{xDo(kV_p)xW_oxF}{D^2{}_F} \quad (1)$$

Where: $a^1{}_1(kVp,\theta)$ = scaled scatter fraction per cm^2 field size at 1m primary distance
$D_o(kV_p)$ = dose in air per unit workload
W_o = x-ray tube workload (mA-min $week^{-1}$)
F = the radiation field area (cm^2)
D_F = primary distance (in m) at the stated radiation field area
D_s = the scattering distance (in m)

D_s (un)(100 kVp,90°) = $4.5x10^{-6}$ cm^{-2}x4.75mSvmA-min^{-1}x350 mA-min $week^{-1}$ x 1000 cm^2 / $1m^2x1m^2$
= 7.48 mSv $week^{-1}$

2.4.1.2. Leakage radiation

The unshielded leakage dose, D_L(un) was determined according to equation (2):-

D_L(un) (kVp, technique factors) = [D_L(un)/1000 mA-min x W_o]/$d^2{}_L$ (2)
D_L(un) was corrected for inverse square effects according to the distance of interest, d_L

Sample calculation:

D_L(un)/1000 mA-min is conservatively assumed to be 2.92 mSv at 1 m for all barriers of the radiographic rooms (typical leakage dose was less than 0.4 mGy in 1h at 125 kVp) and W_o is 350 mA-min $week^{-1}$ at 100 kVp.

D_L(un)/100kVp, 5mA) = 2.92 mSv/1000 mA-min x350 mA-min $week^{-1}$ = 1.02 mSv $week^{-1}$

2.4.1.3. Total unshielded secondary doses

The total unshielded secondary doses, D_{sec}(un) were obtained by adding Ds(un) and D_L(un). Hence, D_{sec}(un) at 1m is given as:

$$D_{sec}(un)(100kVp) = Ds(un)(100kVp, 90^o) + D_L(un)(100\ kVp, 5mA) \quad (3)$$
$$= (7.48 + 1.02)\ mSv\ week^{-1} = 8.5\ mSv\ week^{-1}$$

Similar calculations were performed for other barriers.

Table 2. Assumptions used to calculate unshielded secondary radiation doses by Simpkin and Dixon approach [8,9]

Workload, W_o	350 mA-min week^{-1}
Radiation field size, F	1000 cm^2
Primary distance at F, D_F	1 m
Scattering distance, D_s	1 m
Leakage distance, d_L	variable as shown in table 5
Unshielded leakage dose (100 kVp, 5mA)	2.92 mSv at 1 m
Scaled scatter fraction, a^1_1(100 kVp, 90^o)	4.5
Primary dose per unit workload, D_o	4.75 mSv mA-min^{-1}

3. Results and discussions

3.1. Radiation dose levels inside x-ray rooms

Tables 3(a) and 3(b) present radiation dose levels, D_m inside the x-ray rooms calculated from the model developed by Simpkin and Dixon [8] and the corresponding mean radiation dose levels from TLDs measurements. It can be seen that the ratio of the calculated to the measured doses varied from 1.85 to 5.86 indicating that the radiation exposure inside the rooms was highly variable. However, the higher D_m than the measured values seem to be of certain merit for shielding optimization purposes because the use of NCRP49 method [6] has found sometimes to underestimate the scattered radiation [8]. The higher D_m values can also accommodate uncertainties in thermoluminescent dosimetry and future increase of the patient workload. In particular, there is no specific pattern for the TLDs measurements, which is mainly attributed to the variations in scattered radiation that is a major contributor to TLDs radiation exposure. This view is supported by the fact that the observed leakage radiation was less than 0.4 mGy in 1 hour at 1 m and therefore negligible compared to the scatter component. It is further known that the scattered radiation intensity is not strictly proportional to radiation field area for diagnostic x-ray beams because of self-shielding effects [8], which may be the case in clinical situations, where different radiation field sizes are employed. Therefore the variations in radiation field sizes lead to variable scattered radiation hence TLDs readings of no pattern. Differences between the measured and calculated values can also be contributed to x-ray absorption by objects inside the x-ray rooms, which are not normally considered during radiation shielding designing.

3.2. Radiation dose levels beyond the barriers

The measured radiation dose levels beyond the barriers are shown in tables 4(a) and 4(b). Variations in measured doses are also mainly attributed to variations in radiological techniques being used in clinical situations, for example field sizes as well as to the influence of x-ray scattering and absorption from different objects. Although the radiation levels were not calculated beyond the barriers for lack of suitable model following in-exact knowledge on the composition of the walls, there is a similarity between the measured dose trends inside the rooms and beyond the barriers. Therefore the calculated dose levels inside the rooms can be useful to predict corresponding dose levels beyond the barriers.

Table 3: Measured (at 95% confidence level) and calculated radiation dose levels inside the x-ray room. The controlled area is located towards eastern and western direction for room A and room B respectively .

(a) X-ray room A

Direction	d_{sec} (m)	Measured values (mSv week^{-1})	Calculated values, D_m (mSv week^{-1})	Ratio of calculated to measured values
West	1	1.79±0.48	8.5	4.75
	2	1.15±0.25	2.13	1.85
	2.5	0.3±0.03	1.36	4.53
East	1	1.71±0.54	8.5	4.97
	1.6	0.86±0.15	3.32	3.86
North	1.7	3.86±1.43	-	-
	2	0.46±0.15	-	-
South	2	0.43±0.09	2.13	4.95
	3	0.21±0.04	0.94	4.48

(a) X-ray room B

Direction	d_{sec} (m)	Measured values (mSv week^{-1})	Calculated values, D_m (mSv week^{-1})	Ratio of calculated to measured values
West	1	1.76±0.07	8.5	4.83
	1.6	1.07±0.06	3.32	3.1
East	1	1.45±0.3	8.5	5.86
	2	0.72±0.11	2.13	2.96
North	1	4.45±1.85	-	-
	1.8	0.82±0.39	-	-
South	2	0.38 ±0.22	2.13	5.61
	3	0.19±0.05	0.94	4.95

3.3. Shielding adequacy of the existing barriers

The National Council on Radiation Protection and Measurements (NCRP) recommends a dose constraint of 0.1-mSv week^{-1} in controlled areas and 0.02-mSv week^{-1} in uncontrolled areas for new facility operations [17]. The controlled areas are located in east (room A) and west (room B) while the rest barriers are uncontrolled. The results of the TLDs measurements (table 3) show that both controlled and uncontrolled areas beyond the secondary barriers are inadequately shielded. However, under the present country's health care level the present shielding situation can be tolerated if some administrative controls are imposed.

4. CONCLUSIONS

A review of radiation shielding adequacy for diagnostic x-ray facilities that are housed in rooms that do not meet the standard layout has been presented. The calculated secondary radiation by a model recently developed was compared with the area monitoring data and found satisfactory if social and economic conditions are considered. The model and the area monitoring data have been found useful in optimizing radiation-shielding conditions in non-standard x-ray rooms where the standard methods may lead to excessive underestimation or overestimation.

Table 4. Measured radiation dose levels behind the barrier. The controlled area is located towards eastern and western direction for room A and room B respectively.

(a) X-ray room A

Direction	Barrier thickness /material	Barrier distance (m)	Measured values (mSv week^{-1})
West	0.2m, brick	2.5	0.1
East	0.2m, brick	1.62	0.12
North	0.35m, concrete	-	-
South	0.2m, brick	3.25	0.1

(a) X-ray room B

Direction	Barrier thickness /material	Barrier distance (m)	Measured values (mSv week^{-1})
West	0.2m, brick	1.62	0.21
East	0.2m, brick	2.25	0.08
North	0.35m, concrete	-	-
South	0.2m, brick	3.44	0.12

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