



Evaluation of radiation doses at diagnostic X-ray control panels and outside patient entrance doors in Aizawl district, India

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Abstract

The purpose of this research was to measure the radiation level and estimate the dosage at the control panel (CP) and outside the patient entrance door (PED) of diagnostic X-ray installations. This is important for ensuring the safety of workers and the public, particularly in the study area, where there is no proper radiation monitoring service. A water phantom, 10-L fresh water in a plastic container, was used as the source of scattered radiation. Using an ion-chamber survey meter, the stray radiation rate was measured at the CP and outside the PED for both chest and couch missions. The CPs were fully covered by a protective barrier, providing a negligible exposure rate (i.e., 0.07–4.2 mR/h for chest and 0.21–3.8 mR/h for couch). By contrast, installations that did not properly cover the CP showed relatively high exposures (from 18 to 205 mR/h for chest and 2.4–270 mR/h for couch). The radiation rates outside the PED in installations having lead-lined doors were negligibly low; whereas, in installations having no lead-lining, exposure rates reached as high as 95 and 110 mR/h for chest and couch missions, respectively. The occupational doses were well below the Atomic Energy Regulatory Board dose limit (i.e., 40 mR/week). However, excessive doses were observed in public spaces outside the PED, compared with the dose limit for the public (i.e., 2 mR/week).

Keywords Conventional diagnostic X-ray · Occupational dose · Public dose · Protective barrier · Patient entrance door · Radiation safety

1 Introduction

Shortly after the discovery of X-rays by Wilhelm Conrad Roentgen in 1895, the harmful effects of radiation exacerbated by inadequate protection were widely known [1]. However, until the 1950s, scientific reports concerning late radiation effects caused by low-level exposure did not appear [2]. The recent study of solid cancer incidence among Chinese medical diagnostic X-ray workers by Sun et al. showed that the risk for solid cancers increased significantly as cumulative radiation exposure increased [3]. In developed countries, the contribution of diagnostic X-rays to cancer ranged from 0.6 to 1.8% of the cumulative risk of cancer to age 75 years [4]. Because of the potential health effects of

ionizing radiation, recommendations and protection guidelines were made by experts and national/international bodies to reduce the health effects of X-rays for workers and members of the public [1, 5, 6]. The main objective of radiation protection is to ensure that the doses received by workers and members of the public are kept below permissible levels [7]. The International Commission for Radiation Protection is the pertinent international regulatory body, and in India, the Atomic Energy Regulatory Board (AERB) is the national counterpart. These bodies recommend norms for permissible dose limits for the public and for workers [8].

Among man-made ionizing radiation sources, a major contributor to public and occupational exposure is medical diagnostic X-rays [9, 10]. Diagnostic X-ray examinations account for approximately 51% of the population doses [11]. Radiation workers and the general public are mainly exposed to radiation from primary and scattered varieties. However, they receive very small amounts of primary radiation, so that most of the doses result from scattered radiation [12]. When primary radiation interacts with matter, it is either absorbed or changed via energy level and/or direction of

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motion, after which it becomes scattered radiation [13]. Photon interactions involve three important mechanisms: photoelectric, coherent–incoherent scattering, and pair production [14]. However, in medical diagnostic radiology, only the photoelectric effect and coherent–incoherent scattering are important, because the energy employed ranges up to 150 keV [15].

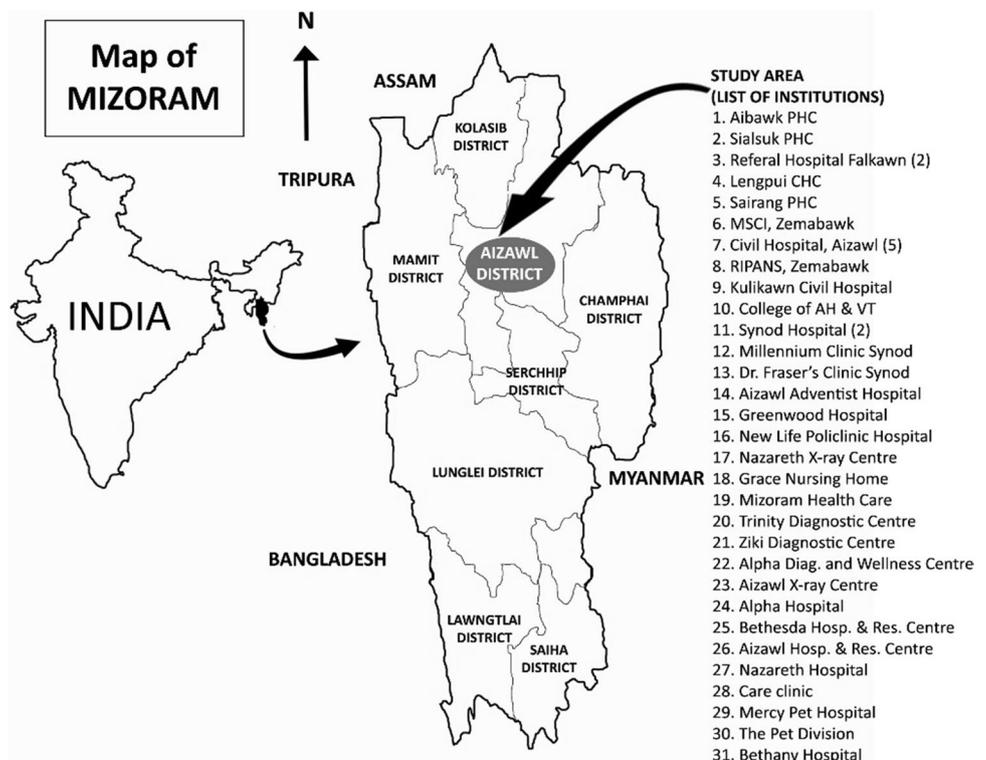
The use of protective shields can significantly reduce radiation exposure of X-ray operators and the general public [16]. Protection can be ensured, and risks can be controlled by suitable design and commissioning of equipment [17]. It is well known that the essential requirement in the practical approach to radiation protection is measurement of the hazard [18]. Using a survey meter, the authors measured stray radiation from X-ray tubes as leakage radiation and scattered radiation from the water phantom, ceiling, wall, etc., at the control panel (CP) and outside the patient entrance door (PED). The primary radiation transmitted through the patient to the couch and floor in couch missions, or through the patient to the chest stand and wall in chest missions, was negligible [19]. Using calculated workload (W) (mA-min/week) and exposure rates, doses were calculated in units of mR/week and compared to safety standards. Possible reasons for excessive doses were also discussed. In a study of occupational exposure in Brazil by Cunha et al. and a national survey of occupational exposure among diagnostic technologists in South Korea by Lee et al., radiation workers were monitored [10, 20]. However, in this study, none

of the workers or the public were properly monitored using personal monitoring devices, which is the reason the authors followed the method described.

2 Materials and methods

The number of fixed and mobile-fixed X-ray machines in the present study area was 37, which were installed at 31 different institutions (Fig. 1). Mobile X-rays were used as fixed in this study. Workloads of 3022.45 mA-min/week (58.4% of all workload across the state (i.e., Mizoram) were performed using this equipment. Among these, 83.8% were AERB-type approved units, and 16.2% machines had unknown approval statuses because of missing information. Some of the machines were very old. Among these institutions, some of the CPs were properly covered by protective barriers, whereas others were partly covered by a barrier or had no barrier at all. Only a few PEDs had lead-lined doors, whereas others employed typical wooden doors, plywood lined doors, or aluminum plane sheet-lined doors. The nature, type, and thickness of CP barriers and PEDs were measured and recorded. The authors also examined product manuals for accurate information. The protective barriers used by the X-ray users were lead lined, 6-feet high, 2.5–3-feet wide, with a lead thickness equivalent to 1.5–1.7 mm. The lead-lined doors were 1.5-mm lead thickness equivalent.

Fig. 1 Location of the present study area (37 machines installed in 31 different institutions)



Sketches were made for all X-ray installations indicating X-ray source, couch, chest stand, protective barrier, CP, PED, etc. Distances from the CP to the couch and chest stand and from the couch and chest stand to the PED were measured and recorded (Fig. 2). A water phantom, 10-L fresh water in a plastic container, was used as a source of scattered radiation. The plastic container was a perfect cube structure where all the sides (i.e., length, width, and height) were equivalent (i.e., 31 cm each). The thickness of this container was 1 cm, and it was uniform throughout the body (Fig. 3). It was positioned on the couch for vertical exposure (couch mission) and at a chest stand for horizontal exposure (chest mission). Field sizes were adjusted to the maximum and focused on the water phantom. Exposure rates were measured at the CP and outside the PED separately for both chest and couch missions. For measuring exposure rates, a pressurized ion-chamber survey meter (Model 451 P, Fluke Biomedical, Everett, WA, USA) was used. It had a 230-cc active volume air ionization chamber pressurized to eight atmospheres. The calibration measurements are traceable to the National Institute of Standards and Technology (NIST, Gaithersburg, MD, USA) [21]. All measurements were performed in freeze mode.

The stray radiation levels at the CP and outside the PED were measured using the maximum accelerating potential setting (i.e., 85–120 kVp) and minimum input-tube current (i.e., 25–50 mA) with fixed exposure time of 1 s [22]. The survey meter was placed at a height in relation to the

water phantom base with its measuring surface towards the water phantom [23]. In this configuration, the survey meter could measure stray radiation scattered from the phantom, the walls, the floor, and the ceiling, including leakage from the X-ray tube [24]. The workload for each piece of equipment was calculated in mA-min/week using Eq. (1) [25, 26]. Patients per day were calculated based on patient records kept by the institutions. The total number of patient exams throughout a year was divided by the total number of working days during that period.

$$W = \frac{\text{patients}}{\text{day}} \times \frac{\text{films}}{\text{patient}} \times \frac{\text{mAs}}{\text{film}} \times \frac{\text{days}}{\text{week}} \times \frac{1 \text{ min}}{60 \text{ s}}. \quad (1)$$

Then, the radiation dose in units of mR/week was calculated from the workload and stray radiation rates using Eq. (2) [27, 28]:

$$\begin{aligned} \text{Dose} \left(\frac{\text{mR}}{\text{week}} \right) &= \text{workload} \left(\frac{\text{mA} - \text{min}}{\text{week}} \right) \\ &\times \text{Exposure Rate} \left(\frac{\text{mR}}{\text{h}} \right) \\ &\times \left(\frac{1}{60} \right) \times \left(\frac{1}{\text{mA used}} \right), \end{aligned} \quad (2)$$

where mA is the input-tube current from the survey. The authors measured tube voltage for each machine to improve clarification using a wide-range digital kVp meter (model 07-494, Fluke Biomedical, Cleveland, Ohio, USA). For evaluating kVp accuracy, the authors considered the tube

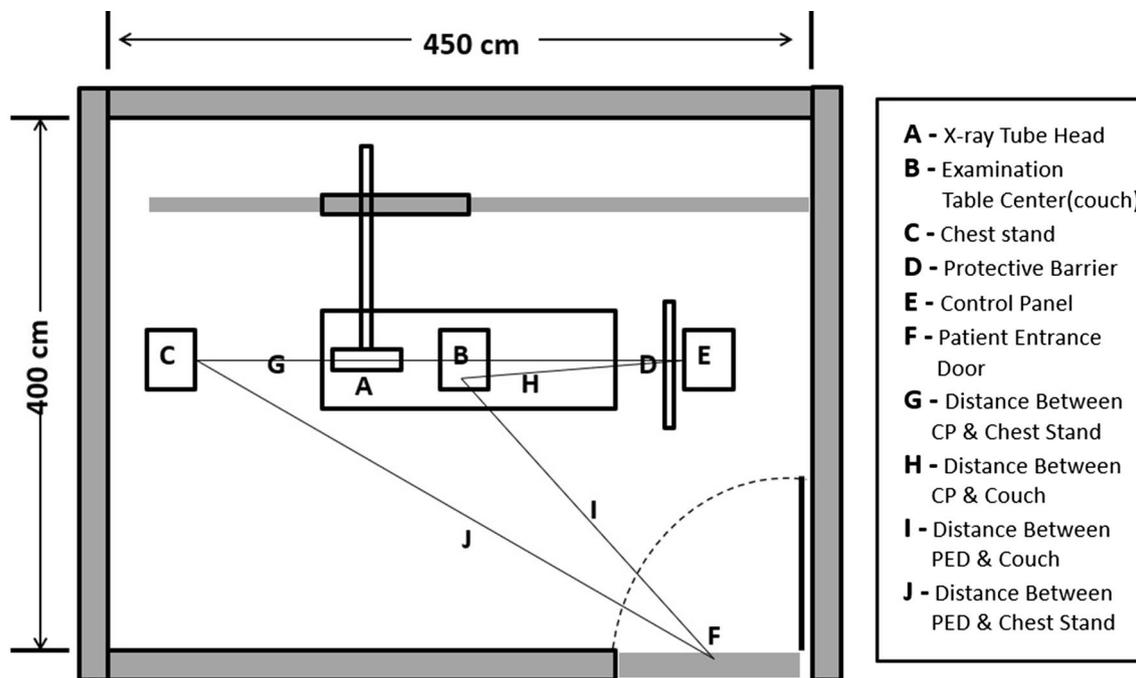


Fig. 2 Layout of the X-ray installation room

Fig. 3 A water phantom setting to measure stray radiation for vertical exposure (couch mission)



voltage between 50 and 150 kVp with 5 kVp steps, and the tube loading and focus-to-detector distance (FDD) were set as per the Fluke manual [29, 30]. To calculate mean, range, and standard deviation (SD), SPSS Statistics for Windows, v.17.0 was used (SPSS, Inc., Chicago, IL, USA).

3 Results and discussion

3.1 Exposures rate at CP for both chest and couch missions

The CPs were located at different distances from the couch and chest stand. 94.4% of CPs were within 300 cm for couch missions and 62.5% were so for chest missions. This is in contrast to the recommended distance, which should be more than 300 cm [6]. The stray radiation measured at the CPs was mostly scattered and originated from two main sources: the phantom on the couch and the one on the chest stand. Exposure rates at the CPs in different installations varied from 0.07 to 360 mR/h (Fig. 4). For chest missions, 16 CPs were properly protected by barriers from stray radiation, whereas seven were partly covered by barriers, and nine had no barriers at all. For couch missions, 16 CPs were properly protected by barriers, whereas seven were partly covered by barriers and 13 had none. For the chest and couch missions where CPs were properly covered by barriers, significantly lower exposure rates were found for different units. By

contrast, installations with partial or absent barriers showed very high exposure rates: 50 times more than cases with CPs properly covered with barriers (Table 1).

3.2 Comparison between different utilization of CP barriers

The exposure rates for chest missions in installations with CPs properly covered by a protective barrier, CPs with insufficient covers, and those with no barriers at all are shown in Fig. 5. The CPs that were fully covered by protective barriers had relatively negligible exposure rates (i.e., 0.07–4.2 mR/h with mean \pm SD of 0.68 ± 1.03 mR/h). Contrastingly, installations in which the CPs were not properly covered had relatively high exposure (18–205 mR/h with mean \pm SD of 74.29 ± 68.40 mR/h). Furthermore, it was found that the exposure rates at CPs where barriers were absent ranged from 1.1 to 235 mR/h with mean \pm SD of 50.36 ± 86.86 mR/h (Table 1). There were institutions that showed low exposure rates, but they had no barriers installed. These types of equipment were mobile-fixed devices with low electronic input parameters and were lower-efficiency units (Fig. 5). By comparing the exposure rates at institutions without barriers and with inadequate barriers covering the CPs for chest missions, barriers that did not properly cover CPs had relatively high exposure rates (Table 1). The reason was that, for barriers not covering CPs properly or improperly installed barriers, the operators considered only stray radiation from the couch.

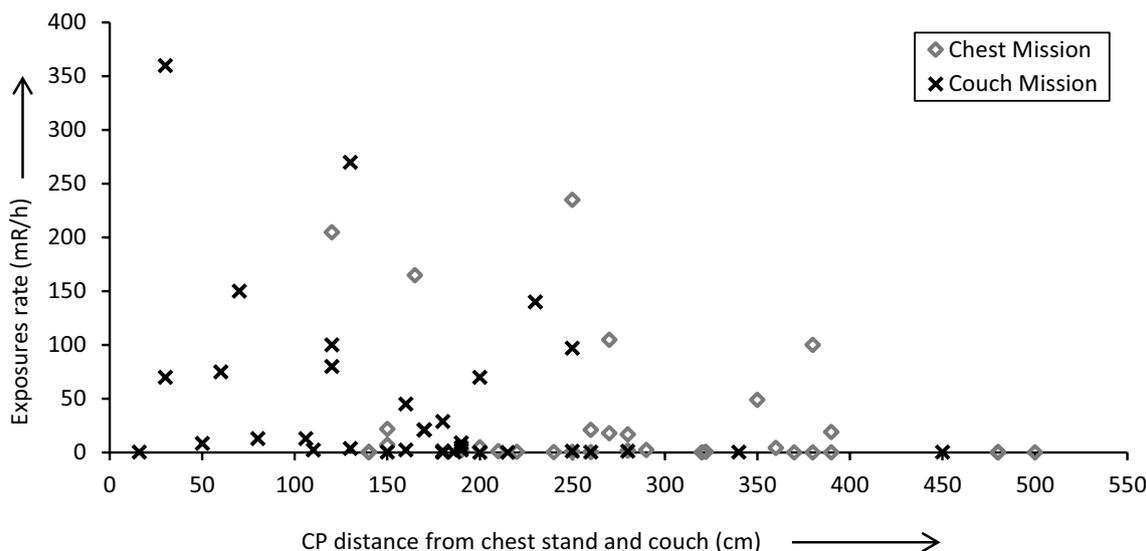


Fig. 4 Exposure rates measured at CPs for both chest and couch missions

Table 1 Exposures rates measured at CPs behind different arrangements of protective barriers at different installations

Barrier	No. of machines	Minimum exposure rate (mR/h)	Maximum exposure rate (mR/h)	Range (mR/h)	Mean (mR/h)	SD (mR/h)
Chest mission						
Barrier covering CP properly	16 (50%)	0.07	4.2	4.13	0.68	1.03
Barrier not covering CP properly	7 (21.9%)	18	205	187	74.29	68.4
Barrier not available	9 (28.1%)	1.1	235	233.9	50.36	86.86
Couch mission						
Barrier covering CP properly	16 (44.4445%)	0.21	3.8	3.59	1	1.04
Barrier not covering CP properly	7 (19.4444%)	2.4	270	267.6	73.86	99.8
Barrier not available	13 (36.1111%)	8.5	360	351.5	81.65	93.75

For that, they adjusted the barrier. As such, the CPs were fully opened for chest-scattering radiation. In some installations, there were chest stands located adjacent to the CPs. Moreover, for other parameters, such as variation in distance between the chest stand and CP, the generator type may have affected exposure rates.

Exposure rates for couch missions in installations covering CPs properly with protective barriers with inadequate CP covers and with no barriers at all are shown in Fig. 6. For couch missions, the exposure rate for barriers covering the CPs properly varied 0.21–3.8 mR/h with mean ± SD of 1.00 ± 1.04 mR/h. Similar to the chest-mission exposure rates measured at fully covered CPs, these were significantly low. There was not much difference between the exposure rates at CPs with no barriers and those with partial barriers. The former had 8.5–360 mR/h with mean ± SD of 81.65 ± 93.75 mR/h, whereas the latter ranged from 2.4 to 270 mR/h with mean ± SD of 73.86 ± 99.8 mR/h (Table 1).

In the present study, the significant effects of distance on the exposure rates were not recognized, even though each piece of equipment was operating with nearly equal parameters. One of the main reasons is that none of the X-ray equipment followed the same installation geometry and even the same models at different institutions showed different efficiencies, such as with kVp reproducibility (Fig. 7) [26, 30].

3.3 Exposure rates outside the PED for both chest and couch missions

For evaluating public doses, exposure rates outside the PED were measured, where exposure was mainly caused by stray radiation scattered from the phantoms. These were located at different distances from the PED (Fig. 8). For chest and couch missions, only two and three installations, respectively, were equipped with lead-lined doors. A large number (> 90%) of installations used solid

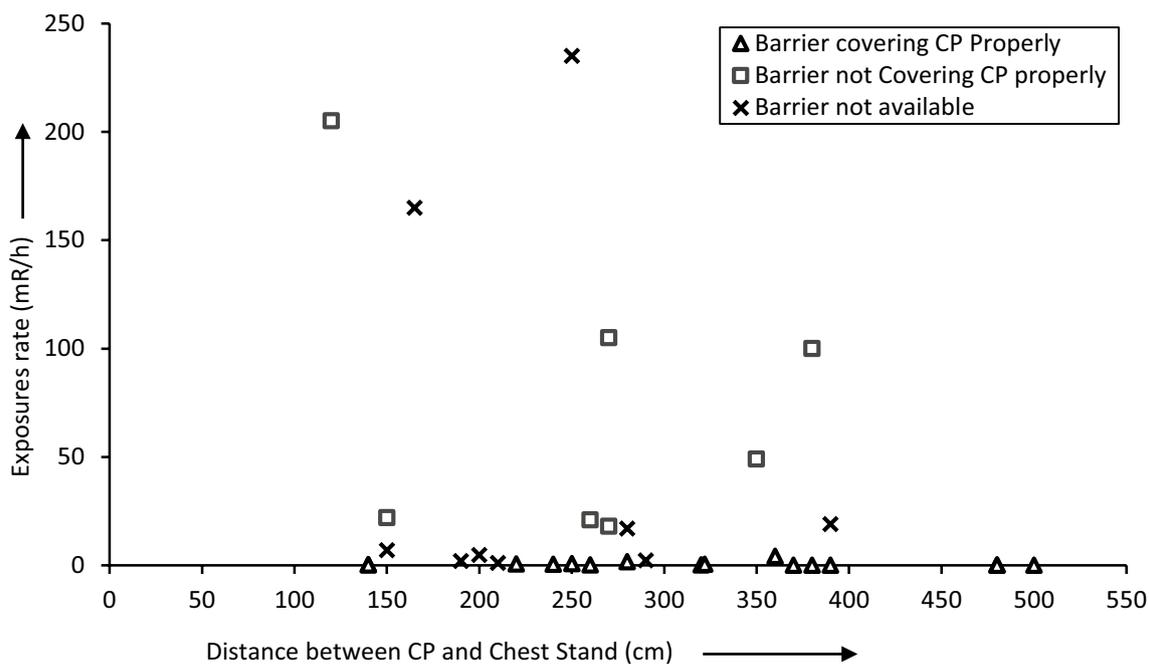


Fig. 5 Exposure rates measured at CPs for chest missions (comparing different barrier utilizations)

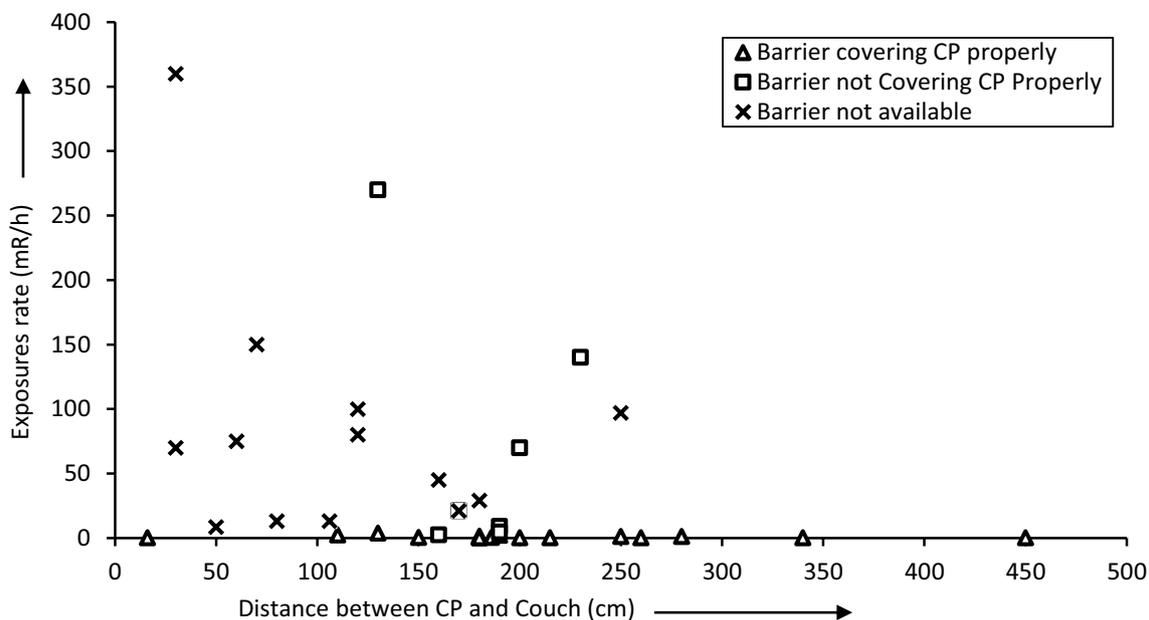


Fig. 6 Exposure rates measured at CPs for couch missions (comparing different barrier utilizations)

wooden doors, plywood doors, aluminum plane sheet doors, etc. (Table 2). It was found that all institutions had at least a simple traditional PED. The mean of the exposure rate outside lead-lined PEDs was mean ± SD of 0.05 ± 0.04 mR/h and mean ± SD of 1.78 ± 2.79 mR/h

for chest and couch missions, respectively. Those institutions that did not employ lead-lined doors had a mean exposure rate of mean ± SD of 18.03 ± 22.22 mR/h and mean ± SD of 30.83 ± 30.46 mR/h for chest and couch missions, respectively. These figures show that lead-lined doors had significantly greater effect on attenuation of

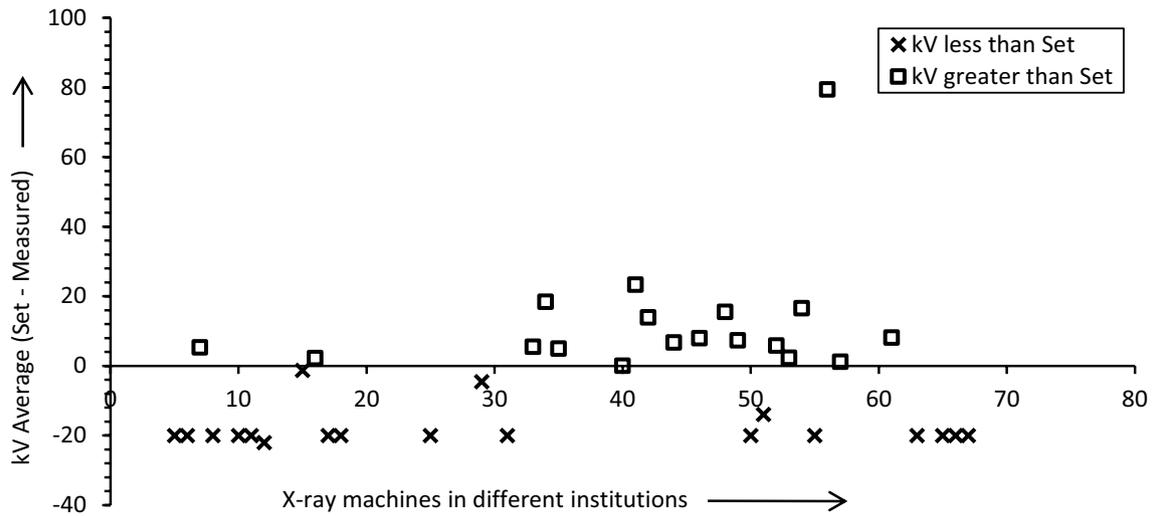


Fig. 7 Accelerating potential reproducibility of different X-ray machines

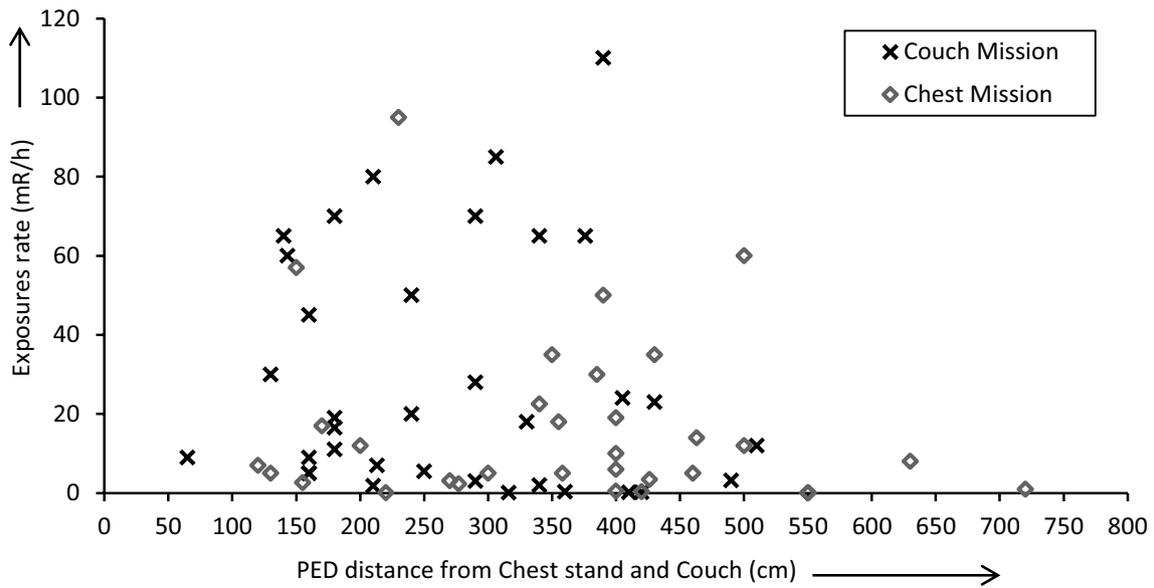


Fig. 8 Exposure rates measured at the PEDs for both chest and couch missions

Table 2 Exposure rates measured behind different types of PEDs in different installations

Type of door	No. of units	Minimum exposure rate (mR/h)	Maximum exposure rate (mR/h)	Range (mR/h)	Mean (mR/h)	SD (mR/h)
Chest mission						
Lead-lined door	2 (6.25%)	0.03	0.08	0.05	0.05	0.04
No lead-lining	30 (93.75%)	0.1	95	94.9	18.03	22.22
Couch mission						
Lead-lined door	3 (8.33%)	0.16	5	4.84	1.78	2.79
No lead-lining	33 (91.67%)	0.13	110	109.87	30.83	30.46

the exposure rate compared to the alternatives observed in this study (Table 2).

3.4 Comparison between lead-line PEDs and other typical PEDs

The radiation exposure rates outside PED in installations having lead-lined doors or typical doors for both chest and couch missions are shown in Figs. 9 and 10. The rates outside the PED for chest missions with lead-lined doors

installed were negligibly low (0.08 and 0.03 mR/h). Similarly, for couch missions where lead-lined doors were installed, the rates outside the PEDs ranged from 0.16 to 5 mR/h (Table 2). These exposure rates show that lead-lined doors are very good shielding materials, which are recommended by a variety of different bodies [6, 25]. However, in installations without lead-lining, exposure rates ranged up to 95 mR/h for chest missions to 110 mR/h for couch missions (Table 2). The high exposure rates in these installations show that alternatives, such as wooden doors, plywood

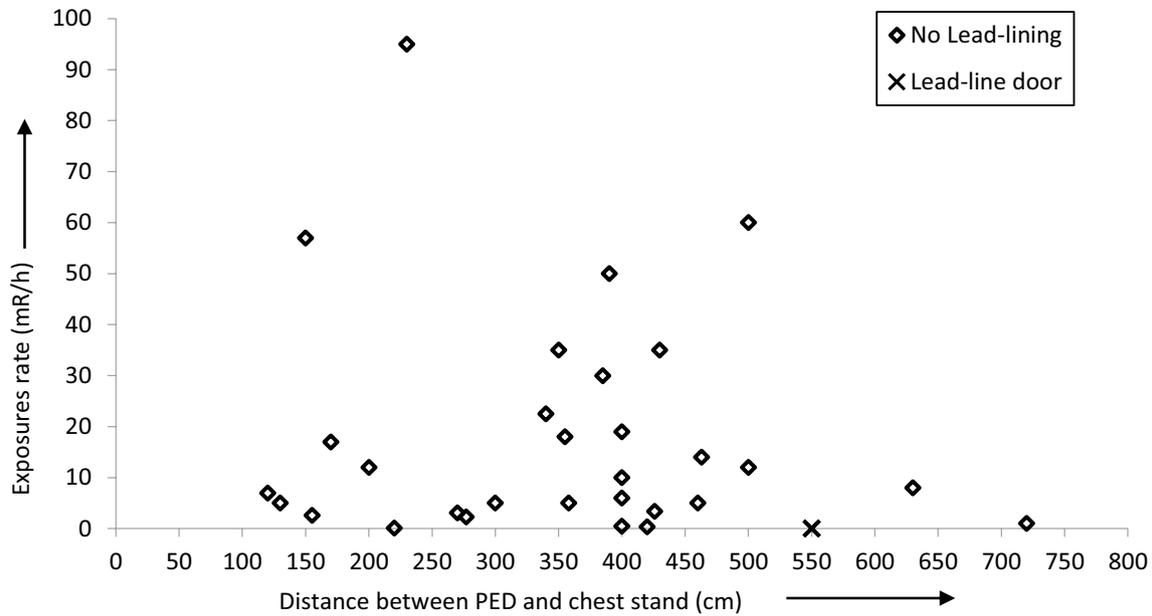


Fig. 9 Exposure rates measured at the PEDs for chest missions (comparing different barrier utilizations)

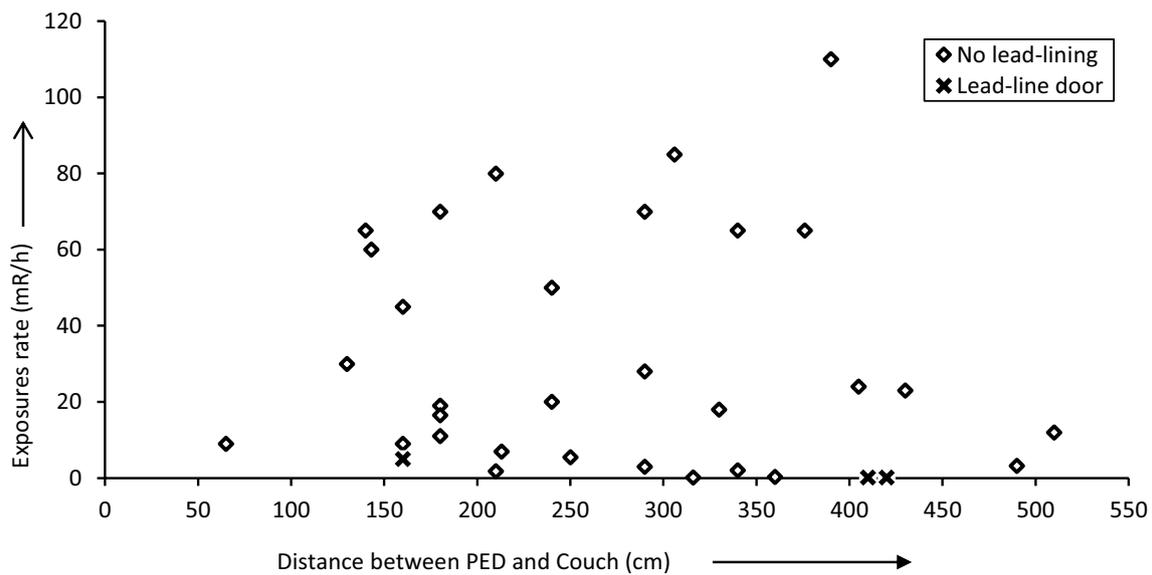


Fig. 10 Exposure rates measured at the PEDs for couch missions (comparing different barrier utilizations)

doors, and aluminum plane sheets, are not nearly as effective as lead. This was similar to the results for measuring the CP exposure rates. Lower exposure rates were found in few installations where lead-lined doors were not installed. The reason was the same for CP exposure.

3.5 Workloads for chest and couch examinations

General diagnostic X-ray examinations are classified as chest, skull, abdomen, pelvic, intravenous pyelogram, and extremities. At all institutions, X-ray teams work 6 days per week. The number of patients examined per day varies amongst institutions. With intravenous pyelograms, 5–6 X-ray films are used; whereas, all other examinations use 1 or 2 X-ray film(s). For chest X-ray, the range of 6–50 mAs tube loading is applied, whereas other examinations use 20–120 mAs, such as when considering Table 3 unit 6, where chest, abdomen, skull, and other extremities are examined. For chest X-ray, workload is calculated using Eq. (1) as follows:

$$W = \frac{1 \times 1 \times 25 \times 6}{60} \text{ mA-min/week}$$

$$= 2.5 \text{ mA-min/week for chest X-ray.}$$

Similarly, other examinations are calculated and summed to get the total workload for a particular installation. The calculated workload shows that the couch workload is greater than that of chest work in almost every institution, because examinations using the chest stands require horizontal projection of the X-ray, whereas all other examinations use vertical projection (Fig. 11).

3.6 Public and occupational dose levels

Radiation doses calculated as milliroentgen per week at the CPs and outside the PEDs are considered occupational and public doses, respectively. As indicated in Eq. (2), these doses not only depend on the exposure rates but also on the workload [27]. This is why most of the high doses result from high exposure rates and high workloads. However, at a few installations, these two parameters compensated each other (Table 4). It can be seen from Table 4 that those installations having high doses had parameters higher than the mean value. Interestingly, some high exposure rates did not always result from high radiation doses. As shown in Figs. 2, 3, and 7, high exposure rates arising from improper barriers, non-protected, or unlined doors did not lead to high doses because of low workloads. Some of these were only used for couch missions, whereas others were not used (i.e., there was no workload). Moreover, X-ray units 29, 46, and 52 showed high workloads, but had significantly lower exposure rates because of proper CP covering and lead shielding of the PED. This is why these doses were negligibly low (Table 5).

The occupational doses (which varied from ~0.01 to 24.18 mR/week) were compared with dose limits for radiation workers prescribed in the AERB Safety Code: 40 mR/week [6, 27]. All these institutions were well below this dose limit, as indicated in a previous study in rural areas [31] (Fig. 12). The highest dose found was 24.18 mR/week, which is 60.45% of the dose limit. These doses are still relatively high compared to the others, and the reason may be as follows. First, the control panel was at a distance of 200 cm from the chest stand and only 70 cm from the couch, which contradicts the recommended distance of 300 cm [6]. Second, despite the short distance, the machine was operated without any barrier[s]. Third, the workload of

Table 3 Workload of diagnostic X-ray facilities in the present study area

Unit	Patient per day	Film per patient	Tube loading (mAs)	Days per week	Workload (mA-min/week)	Total workload (mA-min/week)	Examinations conducted
5 ^a	1	1	80	6	8	20	Chest
	3	1	40	6	12		Others
6 ^a	1	1	25	6	2.5	20	Chest
	0.2	2	50	6	2		Abdomen
	0.1	1	50	6	0.5		Skull
	3	2	25	6	15		Others
7 ^a	10	1	40	6	40	250	Chest
	5	2	60	6	60		Abdomen
	5	2	45	6	45		Skull
	2	5	60	6	60		IVP
	15	1	30	6	45		Others

^aWorkload for each piece of equipment was calculated as with units 5, 6, and 7. It can be seen that some diagnostic units examined chest, abdomen, skull, intravenous pyelogram, and other extremities, whereas others examined only one, two, or more

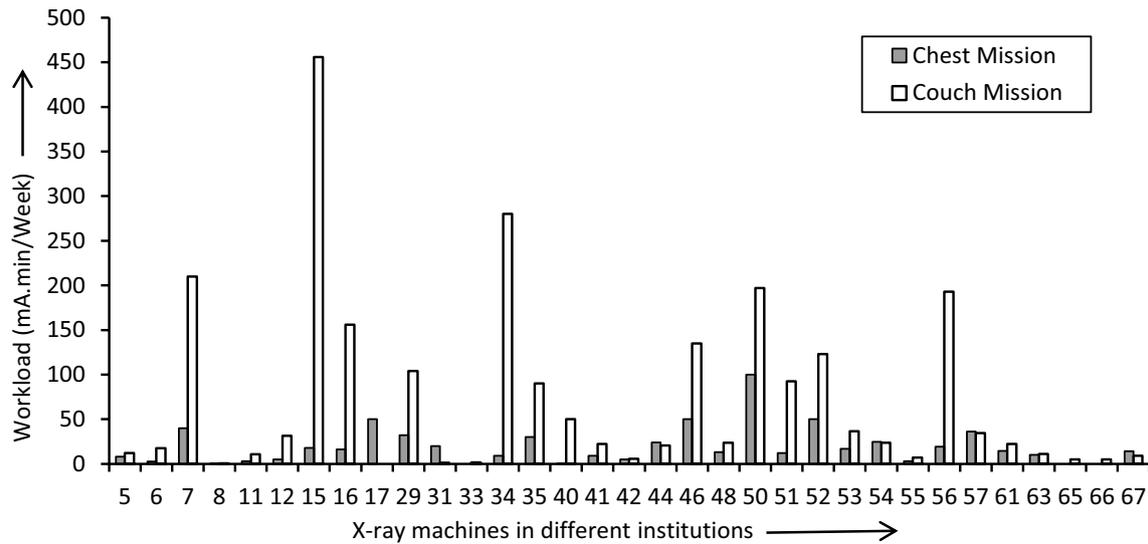


Fig. 11 Workload of different institutions for both chest and couch examinations

Table 4 Exposure rates and workload for the three highest public and occupational doses

High public dose						High occupational dose					
Dose (mR/week)		Exposure rates (mR/h)		Workload (mA-min/week)		Dose (mR/week)		Exposure rates (mR/h)		Workload (mA-min/week)	
Unit ^a	Dose ^b	Chest ^c	Couch ^d	Chest	Couch	Unit	Dose ^e	Chest	Couch	Chest	Couch
15	3.72	12	24	18	456	34	8.35	100	140	9	280
34	1.64	6	28	9	280	56	24.18	4.8	150	19.2	192.84
50	7.11	95	60	100	197	57	4.356	105	270	36	34.4
Mean	0.71	14.62	27.65	19.2	72.3	Mean	1.34	26.6	43.1	19.2	72.3

Mean value was calculated from each and every unit

^aA particular X-ray unit/machine

^bCalculated dose outside PED

^cChest mission/horizontal exposure

^dCouch mission/vertical exposure

^eCalculated dose at CP

Table 5 Exposure rates and workload for low occupational and public doses

Public dose						Occupational dose					
Dose (mR/week)		Exposure rates (mR/h)		Workload (mA-min/week)		Dose (mR/week)		Exposure rates (mR/h)		Workload (mA-min/week)	
Unit	Dose	Chest	Couch	Chest	Couch	Unit	Dose	Chest	Couch	Chest	Couch
10	0	50	80	0	0	11	0.62	0	100	3	10.6
18	0	0	70	0	0	25	0	0	360	0	0
25	0	0	50	0	0	40	1.53	235	0	0.2	50
33	0.02	0	65	0	1.6	49	0	165	0	0	0
63	0.7	57	0	10	11.2	53	1.26	205	0	16.8	36.48
29	0.1	3.1	2	32	104	29	0.02	0.49	0.35	32	104
46	0.52	14	18	50	135	46	0.01	0.34	0.3	50	135
52	0.15	1	3.2	50	123	52	0.02	0.15	0.38	50	123

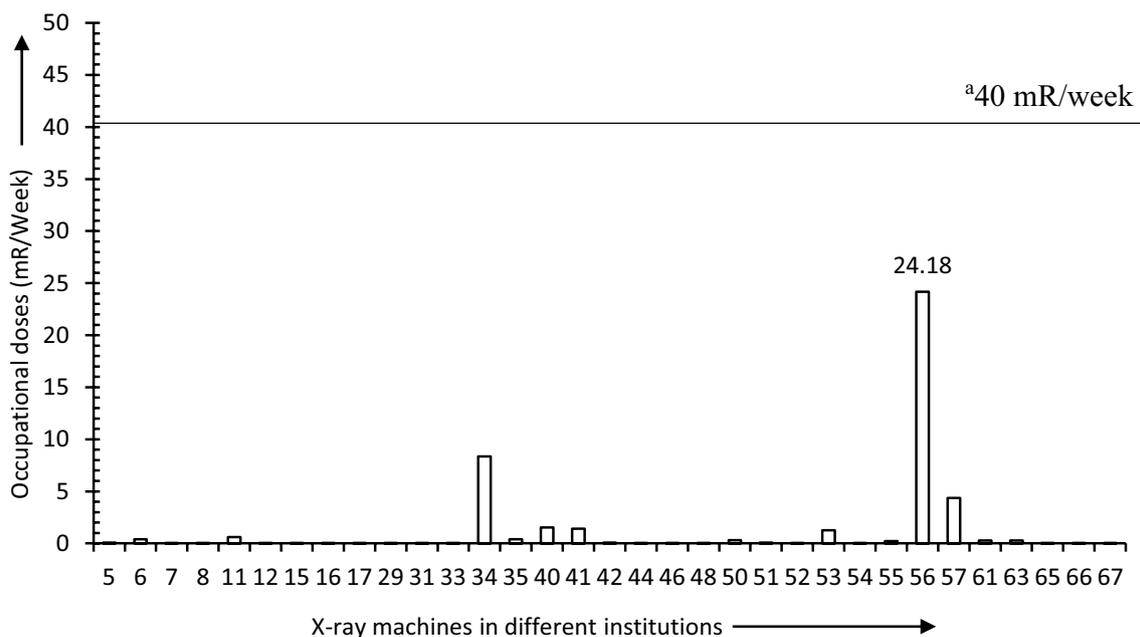


Fig. 12 Doses at the CPs (occupational dose) caused by stray radiation (^aAERB dose limit for radiation workers)

192.84 mA-min/week was high, compared with the mean workload of 72.3 mA-min/week (Table 4). Thus, the authors measured high exposure rates at the CP, all of which automatically generated relatively high doses compared with others. Further, the use of properly installed lead protective barriers (1.5–1.7 mmPb) was found to provide adequate

protection from stray radiation at CPs. However, less than 50% of the institutions covered their CPs properly.

Some marginal doses or overdoses were observed in public spaces outside the PED (Fig. 13), relative to the dose limit for the public: 2 mR/week [6]. The highest dose found was 7.11 mR/week, which is 3.55 times the public dose limit. High workload is the main reason for such high doses

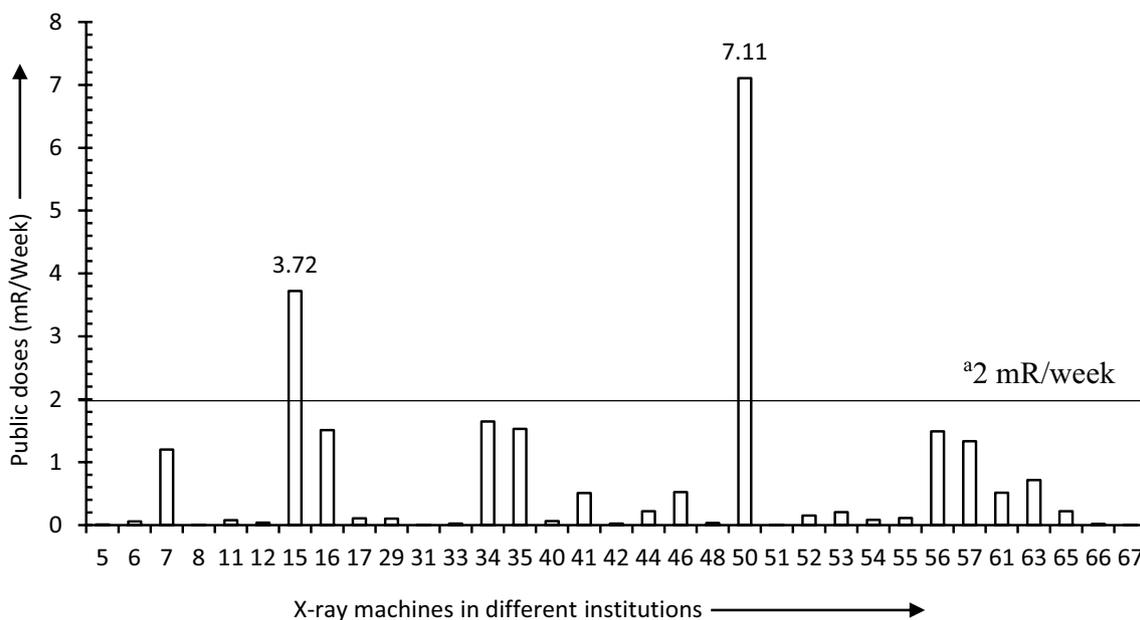


Fig. 13 Doses at the PEDs (public dose) owing to stray radiation (^aAERB dose limit for members of the public)

at unit 15 (Fig. 13), where the workload of 456 mA-min/week was 6.31 times the mean value. Although the PED was non-lead lined, the distance of the PED from the chest stand (i.e., 500 cm) and from the couch (i.e., 405 cm) results in average exposure rates (Table 4). Regarding unit 50, there was inadequate space between the PED and the chest stand (i.e., 230 cm) and the couch (i.e., 143 cm). These high exposure rates were measured outside a plywood PED having a thickness of 0.33 cm. High workloads, i.e., 2.72 times the mean value for couch mission and 5.21 times the mean value for chest mission were found (Table 4). These doses could be significantly reduced by following the standard installation layout and by employing lead-lined doors as recommended by the regulatory bodies [6, 25].

In the present study, radiation doses were found to depend on the input electrical parameters and installation layout. This is why quality assurance tests are mandatory for diagnosing and rectifying machine performance. Because repeated exposures were not included in this study, the doses reported appear underestimated. However, the study used maximum field sizes and longer exposure times than normal X-ray examinations. There was also high kV. Thus, the dose underestimation may have been compensated, falling on the safer side.

4 Conclusions

The authors did not find any excessive doses at the CP, as per the safety code. However, the absence of barriers and barriers not effectively covering CPs with respect to couch and chest missions should be rectified to decrease ancillary doses. The highest dose contributed by stray radiation from the couch and chest missions to the CP was 24.18 mR/week, which is 60.45% of the dose limit.

There were two installations where the dose outside the PED, a public space, exceeded the safety recommendations of 2 mR/week. The highest dose was found to be 7.11 mR/week, about 3.55 times the dose limit. The most often used materials (i.e., solid wood, plywood lined, and plane sheet lined) in the entrance doors attenuated radiation relatively less than did the lead-lined doors. The lead-lined doors appreciably reduced the radiation rate outside the PEDs. However, more than 90% of the institutions used traditional doors.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical approval This article does not contain any human studies. This article does not contain any animal studies.

References

1. Archer BR. History of the shielding of diagnostic X-ray facilities. *Health Phys.* 1995;69:750–8.
2. Bushong SC. Radiation protection. In: Ballinger PW, editor. Merrill's atlas of radiographic positions and radiologic procedures, vol. 1. 7th ed. St. Louis: Mosby Year Book; 1991. p. 17–33.
3. Sun Z, Inskip PD, Wang J, Kwon D, Zhao Y, Zhang L, et al. Solid cancer incidence among Chinese medical diagnostic X-ray workers, 1950–1995: estimation of radiation-related risks. *Int J Cancer.* 2016;138:2875–83.
4. González AB, Darby S. Risk of cancer from diagnostic X-rays: estimates for the UK and 14 other countries. *Lancet.* 2004;363:345–51.
5. Archer BR. Recent history of the shielding of medical X-ray imaging facilities. *Health Phys.* 2005;88:579–86.
6. Atomic Energy Regulatory Board. Safety Code No. AERB/SC/MED-2 (Rev. 1), 'Safety code for medical diagnostic X-ray equipment and installations' AERB, Mumbai, 2001.
7. Binks W. Some aspects of radiation hygiene. *Br J Radiol.* 1955;28:654–61.
8. Grover SB, Kumar J, Gupta A, Khanna L. Protection against hazards: regulatory bodies, safety norms, dose limits and protection devices. *Indian J Radiol Imaging.* 2002;12:157–67.
9. Bennett BG. Exposures from medical radiation world-wide. *Radiat Prot Dosimetry.* 1991;36:237–42.
10. Cunha P, Freire B, Drexler G. Occupational exposure in X-ray diagnosis in Brazil. *Radiat Prot Dosimetry.* 1992;43:55–8.
11. Bushong SC. Radiologic science for technologists: physics, biology, and protection. 10th ed. St. Louis: Elsevier Mosby; 2013. p. 578–9.
12. Osborn SB. Radiation doses received by the diagnostic X-ray workers. *Br J Radiol.* 1955;28:650–4.
13. Carlsson CA, Carlsson GA. Basic physics of X-ray imaging. 2nd ed. Sweden: Linköping University; 1996.
14. Johns HE, Cunningham JR. The physics of radiology. 4th ed. Springfield: Thomas CC, Publisher; 1983. p. 133–64.
15. IAEA. Diagnostic radiology physics; a handbook for teachers and students. Austria: IAEA; 2014.
16. Chen MYM, Swearingen FL, Mitchell R, Ott DJ. Radiation exposure during ERCP: effect of a protective shield. *Gastrointest Endosc.* 1996;43:1–5.
17. Cousins C, Sharp C. Medical interventional procedures—reducing the radiation risks. *Clin Radiol.* 2004;59:468–73.
18. Simkin DJ, Dixon RL. Secondary shielding barriers for diagnostic X-ray facilities: scatter and leakage. *Health Phys.* 1998;74:350–65.
19. Dixon RL. On the primary barrier in diagnostic X-ray shielding. *Med Phys.* 1994;21:1785–93.

20. Lee J, Cha ES, Jeong M, Lee WJ. A national survey of occupational radiation exposure among diagnostic radiologic technologists in South Korea. *Radiat Prot Dosimetry*. 2015;167(4):525–31.
21. Operator Manual 451P Ion Chamber Survey Meter. PN FBC-0059, Rev 1, Fluke Corporation, USA; 2013.
22. Sonawane AU, Singh M, Kumar SJVK, Kulkarni A, Shirva VK, Pradhan AS. Radiological safety status and quality assurance audit of medical X-ray diagnostic installations in India. *J Med Phys*. 2010;35:229–34.
23. Vlachos I, Tsantilas X, Kalyvas N, Delis H, Kandaraskis I, Panayiotakis G. Measuring scatter radiation in diagnostic X-rays for radiation protection purposes. *Radiat Prot Dosimetry*. 2015;165:382–5.
24. Tsalafoutas IA. Excessive leakage radiation measured on two mobile X-ray units due to the methodology used by the manufacturer to calculate and specify the required tube shielding. *Br J Radiol*. 2006;79:162–4.
25. NCRP. Report No. 147. Structural shielding design for medical X-ray imaging facilities; 2004.
26. Lalrinmawia J, Pau KS, Tiwari RC. Qualitative study of mechanical parameters of conventional diagnostic X-ray machines in Mizoram. *Radiol Phys Technol*. 2018;11:274–83.
27. Format for Quality Assurance test for diagnostic X-ray equipment. <https://www.aerb.gov.in/images/PDF/DiagnosticRadio/1-FORMAT-FOR-QUALITY-ASSURANCE-TEST-FOR-DIAGNOSTIC-X-RAY-EQUIPMENT.pdf>. Accessed 5 Feb 2019.
28. Lalrinmawia J, Pau KS, Tiwari RC. Investigations of public dose due to stray radiation in X-ray installations in Mizoram. Science and technology for shaping the future of Mizoram. New Delhi: Allied publishers Pvt. Ltd.; 2017. p. 305–9. ISBN 978-93-85926-49-5.
29. Operator Manual Victoreen 07-494. Manual No. 168001 Rev 4, Fluke Biomedical, Radiation Management Services, 6045 Cochran Road, Cleveland, Ohio 44139, USA; 2006.
30. Lalrinmawia J, Pau KS, Tiwari RC. Quality assurance assessment of conventional diagnostic X-ray installations in Mizoram. *J Med Phys*. 2017;42(Suppl S1):208–9 (ISSN: 0971-6203).
31. Lalrinmawia J, Pau KS, Tiwari RC. Investigations of workers dose due to stray radiation in X-ray installations in Mizoram. Recent advances in physics research and its relevance. New Delhi: Excel India Publishers; 2017. p. 258–63. ISBN 978-93-86256-85-0.

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