ISSN 2201-2796

Shielding calculation based on NCRP methodologies for some diagnostic x-ray facilities in Bangladesh.

Md.Mofazzal Haider
Bangladesh Atomic Energy Regulatory Authority
E-mail: mauntu2004@gamil.com
Fax: 88-02-8181015

Soma Shill
Bangladesh Atomic Energy Regulatory Authority
E-mail : soma.shill@gmail.com

Quazi Mohammad Rashed Nizam
Department of Physics
University of Chittagong
E-mail : rnizam_83@yahoo.com

Mir Akramuzzaman
Department of Physics
Jahangirnagar University, Savar, Dhaka
E-mail : akramuzzam50@ yahoo.com

Abstract- **When Wilhelm Konrad Roentgen accidentally discovered x-rays, he could have no idea what an enormous impact his discovery would have in future on medicine and industry. Today no hospital is complete without x-ray equipment although extensive use of this equipment gives rise to radiation doses that are usually well controlled, but in extreme cases, patients and occupationally exposed persons have been injured by this radiation. Therefore, only proper shielding design of an x-ray room can ascertain the safety of human health. The present study includes the shielding calculation of 13 diagnostic x-ray facilities of Mymensingh city in Bangladesh. In order to estimate the shielding for the diagnostic x-ray facilities, NCRP 49 & NCRP 147 methodologies have been followed. In the chosen facilities, a control panel barrier was commonly found inside the room to protect the occupational worker from the scattered radiation. The existing thickness of brick walls of the x-ray room are found 10 inch (2 mm lead equivalent). The calculated average thickness of lead for control panel (CP) barrier by NCRP 49 approach is 1.1 mm and 0.40 mm by NCRP 147 approach respectively. The present shielding condition of CP of the 85% facilities comply with the exposure limit of occupational worker (10µSv/h) as per national regulations. On the other hand, calculated shielding by NCRP 49 approach leads to 1.35 mm of lead for entrance door (ED) where as 0.64 mm of lead estimated by NCRP 147 for ED. The existing thicknesses of door shielding (lead) in the 70% of the facilities restrict the dose level within the permissible limit of public exposure (0.5µSv/h). In order to simplify calculation for the users, a computer program has been designed and implemented for shielding calculation of the x-ray facilities.**

Index Terms— **Shielding thickness, NCRP, radiation dose, permissible limit, Control Panel.**

I. INTRODUCTION

It is well known that diagnostic x-ray play a significant role to provide necessary diagnostic information for the patient treatment and hence save thousands of lives each year from the premature death throughout the word. However, use of x-rays for radiological examination is associated with a certain amount of risk to the patient, professionals and persons in the vicinity of the x-ray facilities, unless adequate protective systems are incorporated and used effectively (Haider et al.,2010, Martin & Harbison, 1979). In order to determine the shielding requirements for x-ray facility, shielding calculation is necessary. The most widely utilized concept for shielding calculation is the report of the National Council on Radiation Protection and Measurements (NCRP), report no. NCRP49 (1976). However, this methodology has obviously some deficiencies identified by many other studies (Petratonaki et al., 1999, Tsalafoutas et al., 2003 & Pesinian et al., 2009). Application of NCRP 49 in shielding calculation significantly overestimated the barrier thickness. The NCRP 49 methodology doesn't provide specific guidance for the estimation of radiation shielding of radiography room where multiple x-ray machines are in place (Petratonaki et al., 1999). However, Simpkin (1987) proposed a solution for the radiation shielding of multiple of sources of x-rays. Later on this solution was evaluated by the studies of Petrantonaki et al., 1999). The model developed by (Petratonaki et al., 1999) has described the attenuation caused by the building materials but in the NCRP 49 methodology this sort of attenuation was not considered. However, the overestimation of barrier thickness as per NCRP 49 approach results in wasting of financial resources (Farzaneh et al., 2011). The cost effective formulation of diagnostic x-ray shielding could reduce the shielding cost up to 50 % which has been evaluated in the earlier study (Costa & Caldas 2002). In the NCRP 147 approach the radiation attenuation caused by patient, image receptor etc are considered which were neglected through NCRP 49 approaches (NCRP report no. 147, 2004). The new guideline presented in the NCRP 147 approach make it more realistic than the NCRP 49 approach. In the current study, the calculated shielding by NCRP 147 approach found more practicable than the NCRP 49 approach with regard to radiation protection and cost effectiveness point of view. However, for properly determination of radiation shielding in the x-ray facilities radiation dose pass through the estimated shielding should be assessed. In this study, radiation dose rates were measured at different locations in and around the facilities across the existing barriers to verify shielding adequacy of the existing and calculated barriers.

II. MATERIALS AND METHODS

The present study was conducted over the 13 diagnostic x-ray facilities of Mymensingh city of Bangladesh. The facilities were randomly chosen. A data collection checklist was prepared before to collect the necessary data which are required to perform shielding calculation of the facilities. The checklist mainly includes the information machine specification, machine location, number of patients studied, thickness of aluminum filter, room size, distance from tube to patient bed, wall, door, control panel barriers status, wall thickness, status of entrance door, attenuated dose and unattenuated dose etc.. Radiation doses were recorded at different locations by radiation dose rate meter. Shielding calculations were done by using concepts of NCRP reports 49 and 147. Shielding calculations were done for primary and secondary barriers following NCRP 49 approach adopting the formulae:

Primary barrier, $$K_{\mu x} = \frac{pd_{pri}^{2}}{WUT} \qquad ...(1)$$

Transmission factor, $B = K_{\mu x}/K_0$ ....(2)

Secondary barrier, $$K_{\mu x} = \frac{\mathrm{Pd_{sec}}^{2}\mathrm{d_{sca}}^{2}\,400}{aWUTF} \qquad ...(3)$$

As per NCRP 49 method the quantity k_{ux}, is the exposure per week per mA-min, adjusted for occupancy factor (T) and use factor (U) respectively and P is the design dose used in the design or evaluation of barriers constructed for the protection of employees and members of the public.

The weekly design dose for a controlled area is a value of 1 mGy week^{-1} and for an uncontrolled area 0.1mGy week^{-1} as per NCRP 49 approach. On the other hand, 0.1 mGy week^{-1} for controlled area and 0.02 mGy week^{-1} for uncontrolled area as per NCRP 147 approach. The formulation contains terms like the distance from the x-ray tube to a primary barrier(d_{pri}) , the distance from the x-ray tube to a secondary barrier (d_{sec}) ,the weekly workload of the x-ray unit (W), the occupancy factor for an area is T defined as the average fraction of time that the maximally exposed individual is present while the x-ray beam is on. Assuming that an x-ray unit is randomly used during the week, the occupancy factor is the fraction of the working hours in the week that a given person would occupy the area, averaged over the year, k_0 is the relative radiation output with no attenuator, F is the actual field size in cm^2, and *a* is the ratio of scattered to incident intensity. Although *a* varies with scattering angle and kVp, a good approximation for *a* is 0.0015 for diagnostic x-ray energies.

To simplify the presentation of transmission data, a mathematical model was published (Archer et al., 1983). This model which allows parameterization of transmission data, B of any attenuating material, has the form:

Thickness of the material, $$x = \frac{1}{\alpha\gamma}\ln\left[\frac{B^{-\gamma}+\frac{\beta}{\alpha}}{1+\frac{\beta}{\alpha}}\right] \qquad ...(4)$$

where, B is the attenuation and α,β and γ are coefficients, specific for kVp, shielding material and application.

The following formulae were used for the calculation based on NCRP 147:

Primary barrier thickness:

$$x = \frac{1}{\alpha\gamma}\ln\left[\frac{\left(\frac{NTUK^{1}{}_{p}}{Pd_{pri}^{2}}\right)^{\gamma}+\frac{\beta}{\alpha}}{1+\frac{\beta}{\alpha}}\right] - X_{pre} \qquad ....(5)$$

Secondary barrier thickness,

$$x = \frac{1}{\alpha\gamma}\ln\left[\frac{\left(\frac{NTK^{1}{}_{\mathrm{sec}}}{Pd_{\mathrm{sec}}^{2}}\right)^{\gamma}+\frac{\beta}{\alpha}}{1+\frac{\beta}{\alpha}}\right] \qquad ....(6)$$

Here, K_p^1 is unshielded primary air kerma per patient at 1m for each of the workload distributions; K_{sec}^1 is unshielded secondary air kerma per patient at 1m for clinical workload distribution, the fitting parameters (α, β and γ) for primary and secondary radiations generated by the clinical workload distributions as per NCRP 147 report. For radiation dose rate measurements a gas filled radiation monitor was utilized during inspection of the facilities. This equipment was calibrated in Secondary Standard Dosimetry Laboratory of Atomic Energy Research Establishment, Savar, Dhaka.

The Computer Program

Different computer programmes such as FORTRAN, C, C^{++}, ORACLE, Visual Basic etc. are widely used to calculate the attenuation coefficient of neutron and gamma rays. Visual Basic is widely used, because it is one of the most popular high-level language programs. The program is easy to use in solving any mathematical equation. This has been used to solve the equations in order to extract relevant shielding information. The extracted information from the program is presented in a standard form. The basic information includes:

(i) Interface labeling,
(ii) Coding for the labeling program, and
(iii) Program running.

Based on the equation 1, 2, 3 & 4 the amount of primary & secondary shielding required for a given exposure is determined. A computer program has been written to calculate the shielding thickness, X as described in Eqn. 4.

III. RESULTS AND DISCUSSION

The calculated average thickness of lead for control panel (CP) barrier as per NCRP 49 and NCRP 147 approaches are 1.1 mm and 0.4 mm respectively. The average existing thickness of CP barrier is 0.5 mm. However, the national requirement is 2 mm of lead shielding for CP barrier. Table 1 shows the calculated and existing thickness of the CP barriers of 13 facilities of Mymensingh city. Facilities are identified by putting code MFC in the Tables.

TABLE I. CALCULATED THICKNESS OF SHIELDING MATERIAL (LEAD) AT CONTROL PANEL (CP)

Facilities Code	Distance from tube to CP(dsec) in m	Existing material thickness in CP barrier in mm(lead)	Average existing thickness in mm	Calculated material thickness in mm (lead) as per NCRP 49	Average calculated thickness in mm(lead)	Calculated material thickness in mm (lead) as per NCRP 147	Average calculated thickness in mm(lead)
MFC-01	1.6	1		0.71		0.12	
MFC-02	1.52	1		1.59		0.56	
MFC-03	1.19	0.5		1.22		0.46	
MFC-04	1.04	1		0.71		0.71	
MFC-05	1.24	1		1.20		0.53	
MFC-06	1.35	0.5		0.79		0.13	
MFC-07	1.22	0.5	0.5	0.88	1.1	0.16	0.4
MFC-08	1.52	1		0.89		0.5	
MFC-09	1.1	0.5		0.48		0.38	
MFC-10	1.14	0.5		1.42		0.53	
MFC-11	1.87	1		1.37		0.22	
MFC-12	1.62	1		1.55		0.47	
MFC-13	2.2	0.5		1.58		0.39	

The CP barrier is placed inside the x-ray room to protect occupational worker from the radiation hazard during operation of the x-ray machine. The value of calculated average thickness as per NCRP 49 is doubled than the value calculated by NCRP 147 approach. This variation may happen due to the use of some conservative values in NCRP 49 approach (NCRP report 49 & Farzaneh et al.,2011). The workload has been estimated in this study at single KVp i.e at 70 KVp. During investigation of shielding aspect in the facilities it has been found that most of the patient studies are being carried out at 70 KVp even though as per guideline different imaging required different KVp setting. To estimate the workload value, NCRP 147 utilizes the data of Task Group 13 by Simpkin (1996). In fact, the workload is distributed across the various tube potentials and considering a single potential as per NCRP 49 approach can lead to overestimation of barrier thickness. In shielding calculation, KVp is more important than the workload because the dose level across the barrier varied linearly with the workload where as the radiation level varies exponentially with the KVp (Pesinian at el., 2009). The radiation attenuation caused by patient, image receptor etc. has been considered in the shielding calculation by NCRP 147 approach which could reduce the value of barrier thickness (Tsalafoutas et al., & NCRP report 147). In the present study, the average calculated shielding thickness (1.1 mm) of lead for CP barrier (controlled area) as per NCRP 49 approach is consistent with the estimated value (1.48 mm) of the study of Tsafoutas et al., (2003) for secondary radiation. Tsafoutas et al., (2003) found the thickness of lead increased from 1.2 to 1.81mm by introducing new dose limit of 1 mSv/y i.e..02 mSv/week, (NCRP 147) in the NCRP 49 formulations where as the thickness of lead increased up to 2.29 mm for utilizing the dose constraint of 0.3 mSv/y for the protection of secondary radiation. In the present study, the lower value of dose constraint of 0.1 mGy/week has been considered for shielding thickness calculation of CP barrier by NCRP 147 approach; as a result, the smaller value of thickness (0.4 mm lead) have been calculated. As per national standard 2 mm lead/3mm stainless steel is requirement for CP barrier thickness (Obaidul Awal et al., 2002). This is obviously a overestimated value which has been verified by measuring the radiation doses across the barriers. The dose rate measured across the CP barrier in the 83 % of the facilities with the shielding thickness of 0.5 mm lead still found within acceptable limit of occupational exposure of 10 µSv/h (NSRC rule 1997), (Table 2). Therefore the calculated values by NCRP 147 approach are more realistic than that of calculated by NCRP 49 (Table1). However, the radiation safety of the occupational worker still requires significant improvement since the radiation levels observed in the 17% of the facilities are not within the permissible limit. Table 2 shows the radiation level in and around the facilities.

TABLE II. ASSESSMENT OF RADIATION LEVEL AT CONTROL PANEL AND ENTRANCE DOOR

Facilities Code	**Dose rate at ED in µSv/h**	**Percentage of facilities comply with acceptable limit of exposure for public**	**Dose rate at CP in µSv/h**	**Percentage of facilities comply with acceptable limit of exposure for occupational worker**	**Acceptable limit of exposure for public and occupational as per national regulations in µSv/h**
MFC-01	0.25		0.9		
MFC-02	120		1.2		
MFC-03	0.25		0.25		
MFC-04	0.25		80		
MFC-05	0.5		6		
MFC-06	0.25		0.25		
MFC-07	20	70%	0.25	85%	0.5 & 10
MFC-08	0.25		0.25		
MFC-09	0.5		0.25		
MFC-10	1.1		0.5		
MFC-11	20		0.25		
MFC-12	0.25		0.25		
MFC-13	0.25		0.8		

The calculated average thicknesses of lead for entrance door (ED) shielding are 1.35 and 0.64 mm of lead as per NCRP 49 and NCRP 147 approach respectively (Table 2). Again, the shielding thickness estimated by NCRP 49 approach showed significantly higher than that of NCRP 147 approach.

TABLE III. CALCULATED THICKNESS OF SHIELDING MATERIAL AT ENTRANCE DOOR(ED)

Facilities Code	**Distance from tube to ED(dsec) in m**	**Existing material thickness of ED(lead) in mm**	**Average existing thickness in mm**	**Calculated material thickness in mm (lead) as per**	**Average calculated thickness in mm(lead)**	**Calculated material thickness in mm (lead) as per**	**Average calculated thickness in mm(lead)**
MFC-01	2.13	1		1.96		0.83	
MFC-02	1.95	1	0.92	1.15	1.35	0.21	0.64
MFC-03	1.19	1		1.44		0.91	

MFC-04	2.54	1	1.35	0.66
MFC-05	1.24	1	1.39	1.02
MFC-06	1.22	0.5	1.09	0.44
MFC-07	2.13	1	1.32	0.27
MFC-08	1.52	1	1.37	0.61
MFC-09	1.27	1	1.3	0.52
MFC-10	1.52	1	1.1	0.98
MFC-11	2.13	0.5	0.98	0.44
MFC-12	1.63	1	1.65	0.78
MFC-13	1.78	1	1.47	0.67

Costa and Caldas (2002) calculated the shielding thickness of 1.49 mm of lead for secondary barrier adopting NCRP 49 methodology and using the findings of (Simpkin and Dixon's, 1998) study for workload of 294 mA min/week at 120 KVp. The estimated thickness of present study (1.35 mm of lead) as per NCRP 49 approach is in close agreement with the findings of Costa and Caldas study (1.49 mm). From Table 3, the assessment of dose rate across the ED of lead shielding of 0.5 mm thickness shows the 50% of the facilities still restrict the dose level within the permissible limit of public exposure (0.5μSv/h) (NSRC rules, 1997). Therefore, the estimation of entrance door shielding (lead) in the present study by NCRP 49 approach doesn't reflect the appropriate one. However, the present shielding condition of the ED in the 70% of the facilities are adequate to ensure the public safety with respect to dose level receiving by the public as per national requirements. On the other hand, the shielding condition of the CP in the 85% of the facilities complies with the national requirements (2 mm lead shielding) in order to ascertain safety of the occupational workers (Table 2). Oluwafisoye et al., (2009) measured the external dose rate in a CP of a Nigerian Hospital 4μSv/h which is found higher in comparison with the values of measured doses in the present study. The doses are recorded at background radiation level (0.25μSv/h) in most of the facilities. According to present study, the doses receiving by the occupational workers in the CP are found within permissible level (10μSv/h) i.e. the existing average shielding thickness (0.5 mm lead) of CP is sufficient to ensure the safety of the occupational workers. The calculated value (0.4 mm lead) for CP shielding by NCRP 147 approach is found more realistic than the value (1.1 mm) determined by NCRP 49 approach since the shielding thickness value estimated by NCRP 147 approach is very close to the existing thickness (average 0.5 mm).

The best Approach of Shielding Calculations for Diagnostic x-ray facilities:

In the present work, two shielding approaches have been applied for the estimation of shielding of x-ray facilities. The approach NCRP 49 results in over estimation for the shielding arrangements. In this methodology, the design dose is higher than that in NCRP 147 methodology. The definitions of occupancy factor, use factor, workload etc are more conservative in NCRP 49 than that in the NCRP 147 approach. Consequently, the shielding values calculated by the NCRP 49 methodology shows higher values than the required one. Dose levels across the NCRP 49 calculated value of shielding confirm this over estimation, because permissible level of radiation dose can be achieved for the occupational and the public even with less amount of shielding than the calculated values. This over estimation increases the cost of the shielding and waste the economical resources, thus it cannot be a realistic approach for shielding calculation (Farzaneh et al., 2011). Ignoring the ALARA concept of IAEA this approach only increases the value of shielding thickness. On the other hand, NCRP 147 approach is a more realistic one. It defines the workload reasonably, which in diagnostic radiology, extends over the ranges of the potentials. The results of the shielding calculations adopting NCRP 147 approach lead to the lower amount of shielding close to the existing one. These calculated values are also verified by measuring radiation doses across the existing shielding structures of the facilities. Among the two approaches of shielding calculation this one only accepts the more realistic concept of ALARA. Thus in order to design an x-ray facility or to improve the shielding conditions of the diagnostic x-ray facilities it is recommended to utilize the NCRP 147 approach in which case the local shielding aspects such as workload, room size, occupancy, use factor and shielding material should be considered.

Computer Program for Calculating Barrier Thickness

A user friendly computer programs for shielding calculation have been developed and implemented in this work. This sort of development will help the radiation user to calculate the required shielding thickness in a user friendly manner. Window presenting shielding thickness as per NCRP 49 methodology has been described in the figures 1 &2.

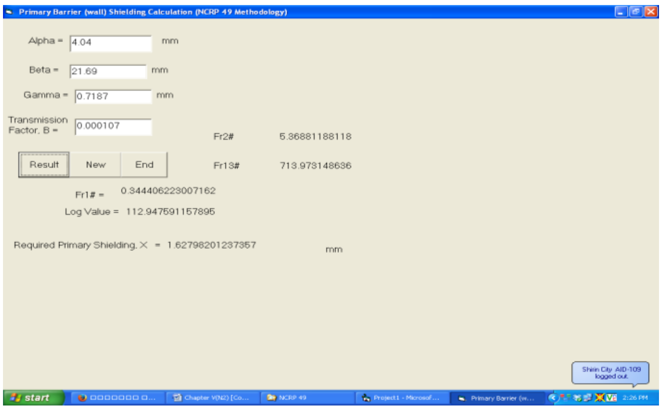

Fig.2 Calculated values for primary barrier shielding

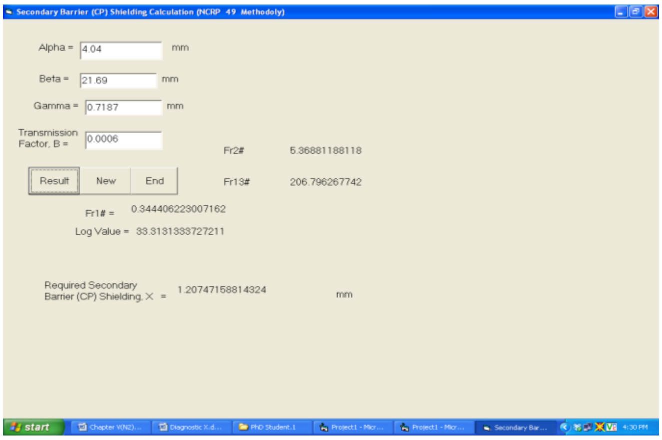

Fig. 3 Calculated values of secondary barrier shielding

IV. CONCLUSION

Each x-ray installation should be provided adequate shielding facilities as per national and international standards. Introduction of shielding in diagnostic radiological facilities plays vital role in order to ensure radiation safety of the occupational and the public staying in and around the facilities. However, the assumptions or approximations are utilized in shielding calculations in different approach may overestimate or underestimate the barrier thickness of the facility. The overestimation of the barrier thickness may increase the cost of the shielding and influence the user to loose their commitment about the radiation safety. Even though the dose rate measured around the facilities are found within the regulatory limit in most of the cases, it doesn't still make sense until 100% of facilities would become safe for the public and other concerned parties. However, if the dose rate is measured utilizing many other techniques such as using TLD, electronic pocket dosimeter more appropriate result could be achieved. Therefore, the barrier thicknesses are evaluated in this work by applying standard methods, for example NCRP's approach, still influencing the calculation to be done involving more realistic values of workload, KVp distribution considering other shielding model in order to estimate the shielding adequacy to ascertain the safety of the public and the professional as well.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of Bangladesh Atomic Energy Regulatory Authority for providing the necessary radiation measuring equipment for investigation of radiation level around the facility. The authors also wish to thank the owner of facilities for their great support during inspection of the radiation facilities.

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