Assessment of whole-body occupational radiation exposures in nuclear medicine practices of Bangladesh during 2010-2014

Original Article

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ABSTRACT

Introduction: Occupational exposure to ionizing radiation due to medical activities (both diagnostic and therapeutic procedures) has increased sharply in recent years. Among the occupationally exposed workers in these fields, those most affected by this increased exposure to ionizing radiation are nuclear medicine workers. In this study, annual average effective dose, annual collective effective dose, the individual dose distribution ratio, collective dose distribution ratio, frequency of dose ranges of workers in nuclear medicine departments of Bangladesh during the period 2010-2014 are presented and discussed.

Methods: Annually about 300 workers of nuclear medicine departments were monitored using thermoluminescent dosimeters (TLDs). The TLDs were readout using Harshaw TLD readers (Model-4500 and Model 6600 plus) for quarterly basis to evaluate the whole-body doses of workers.

Results: The annual average effective doses of workers are well below the annual average dose limit prescribed by national regulations and international organizations. Majority (95%) of workers received doses less than 1 mSv and only 0.33% workers received doses higher than 10 mSv. The annual average effective dose of workers is three times lower than the worldwide average effective dose quoted by UNSCEAR. However, the annual average effective dose of monitored workers is comparable to dose received by workers in Turkey and France.

Conclusion: The status and trends in occupational doses show that radiation protection at the majority of the workplace is satisfactory. In spite of that, additional measures are required due to large variations observed in the maximum individual doses over the last 5 years.

Key words: Nuclear medicine; Ionizing radiation; Occupational exposure; TLD; effective dose

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INTRODUCTION

The medical use of ionizing radiation, while offering great benefit to patients, also contributes significantly to radiation exposure of workers and populations [1-3]. Occupational exposure to ionizing radiation due to medical activities (both diagnostic and therapeutic procedures) has increased sharply in recent years [4, 5]. Among the occupationally exposed workers in these fields, those most affected by this increased exposure to ionizing radiation are nuclear medicine workers. The term 'occupational radiation exposure' is usually taken to mean those exposures that are received at work that can reasonably be regarded as the responsibility of the operating management [6, 7]. Exposed worker refers to a worker who is subject to individual radiation dose assessment [8]. Nuclear medicine involves handling of unsealed radioactive materials that can give rise to external and internal exposure of workers. The amount of exposure depends on radionuclide, its activity and type of work within a department in which the person is involved. Relatively newer imaging modality that involves use of positron-emitting radionuclides for PET scanning has lead to the increased exposure of workers. The fact that the higher energy (511 keV) gamma rays used in PET imaging contribute higher radiation exposure for the workers compared to technicium-99m gamma rays of 140 keV commonly used in imaging procedures. Within the field of therapeutic application in nuclear medicine, new agents with beta emitters of higher therapeutic effectiveness have been used. In line with increasing number of medical procedures involving beta emitting radionuclides, extremity doses and possible skin contamination of nuclear medicine workers is of special concern. The amount of exposures while performing clinical nuclear medicine procedures depends on the precautions taken including the use of syringe shields when administering injections. Personnel must be close to the patient when giving injections and while positioning the patient under the camera. Usually the imaging process makes the largest contribution to the exposure of workers [9]. Internal exposures of personnel are usually much lower than external exposures and are controlled by monitoring work surfaces and airborne concentrations [10]. In nuclear medicine, because of the possibility of internal exposure, higher values of annual effective dose are expected for personnel involved in the preparation and assay of radiopharmaceuticals than for medical doctors and nurses. The monitoring which is meant to control the dose accumulation pattern of individual [11] includes a programme of measurements, evaluations and recording of workers exposure to radiation.

With regard to this fact and according to the Bangladesh Atomic Energy Regulatory (BAER) Act-2012 [12], any activity in this field shall be performed only after obtaining a proper licence. All applicants must submit the necessary documents to the Bangladesh Atomic Energy Regulatory Authority (BAERA) and ensure that they have the competence to carry out all activities with the proper administrative and technical measures.

Any individual radiation monitoring program has at least two main aims. The first aim is to provide information on the capability of protection measures which is a key input for operational decisions related to the optimization principle [13, 14]. Secondly, the individual monitoring programs aim is to demonstrate compliance with the relevant dose limits as required by the national regulations [15] and recommendations of International Organizations [13, 14, 16]. In this context, the annual effective dose to the occupationally exposed workers should not exceed 20 mSv averaged over five consecutive years (100 mSv in 5-years), with a provision that the individual dose does not exceed 50 mSv in any single year. Regular assessment of occupational radiation exposures and the analysis of related trends are essential to examine changes that have taken place over time due to regulatory operations or technological improvements. The objectives of this paper were to present the occupational radiation exposure of workers in nuclear medicine practices in Bangladesh and to evaluate the related trends over a period of 2010-2014.

METHODS

Description of TLDs and readout process

The thermoluminescent dosimeters (TLD) consists of LiF:Mg,Ti (TLD-100); phosphor has the effective atomic number of 8.2, approximately equivalent to that of the soft tissue of a human body. TLD chips 3 mm (1/8 inch) square encapsulated between two sheets of Teflon 0.003 inches (10 mg/cm^2) thick and mounted on an aluminum substrate. In this study, two-chip TLD cards kept in a holder are issued for quarterly (3 months) basis to the occupational workers working in nuclear medicine departments (NMD). The worker wears the TLD on torso at the working time. After using the cards of the stipulated time, NMD send back those used TLDs to the Health Physics Division (HPD), Atomic Energy Centre, Dhaka (AECD) under Bangladesh Atomic Energy Commission (BAEC). The doses of the received TLDs are measured in the TLD Reader by using hot nitrogen gas flow. The gas heating system uses a stream of hot nitrogen at precisely controlled, linearly ramped temperatures to a maximum of 300°C. The hot gas heating under closed loop feedback control and the superior electronic design produces consistent and repeatable glow curves.

The annealed TLD again issue along with the dose report to the relevant worker for use of next quarter cycle.

Equipments and dose evaluation procedures

The operational dose quantity used for the estimation of doses from external radiation is the personal dose equivalent $H_p(10)$. Monitoring of occupational workers by the HPD, AECD under BAEC using TLDs begin immediately after a facility is licensed to operate. HPD, AECD is the only institute that provides dosimetry service for facilities that employ the use of ionizing radiation in Bangladesh. LiF:Mg, Ti (TLD-100) dosimeters have been used throughout the period 2010-2014. In the same period, two thermoluminescent dosimetry systems have been employed to readout the TLDs. They are Harshaw Manual TLD Reader, Model 4500 [17] (from 2000 and still running) and Automatic TLD Reader, Model 6600 Plus [18] (from June 2014) with manual system of data transfer. Harshaw 6600 plus Automatic TLD Reader which is one of the most technically advanced dosimetry systems for whole body, extremity, neutron and environmental monitoring, is being used by the HPD, AECD. The system offers 'one dosimetry solution' by its ability to monitor whole body (beta, photon and neutron), extremity and environmental exposure with a single dosimeter. It can take up to 200 dosimeters per cycle and also saves significant time by virtue of its automatic calibration capabilities.

It has a flat panel display and touch-screen operation service and it exceeds International Electrotechnical Commission (IEC), International Organization for Standardization (ISO) and American National Standards Institute Performance requirements. The Harshaw TLD Readers are connected to an external personal computer (PC) and are operated through installed menu-driven WinREMS software.

The Secondary Standard Dosimetry Laboratory (SSDL) has been available at BAEC since 1991, which is traceable to the Primary Standard Dosimetry Laboratory (PSDL) of National Physical Laboratory (NPL), UK. Prior to use, each TLD is exposed with 2 mSv dose from SSDL of BAEC with respect to H_p (10), using a ^{137}Cs beam incident on a slab phantom of PMMA for measurement of elemental correction coefficient (ECC).The performance of BAEC SSDL is maintained according to the requirements of the International Atomic Energy Agency (IAEA)/World Health Organization (WHO) network of SSDLs. Therefore, the evaluated doses are traceable to the international measurement system. Furthermore, the personal monitoring laboratory regularly participates in inter-laboratory dose comparison programmes as organized by IAEA. In the latest comparison, adequate performance was achieved according to the standards trumpet curve criteria [19, 20].

Dose reporting is performed on a quarterly basis. For all individual doses, the minimum detection level (MDL) is 0.05 mSv for 3 months for two TLD systems after background subtraction. This value (MDL) is taken as dose recording level.

The workers who received doses less than MDL are regarded as non-exposed. All doses that exceed the level of 5 mSv in a monitoring period (3 months) are always investigated. The dose record is accordingly amended after receiving a written explanation with reasons of high dose received by the workers from the Radiation Protection Officer/Head of the Institution. The database, therefore, includes only actual doses received by the radiation workers.

Table 1 shows the number of monitored workers for the years 2010-2014.

Table 1: Number of monitored workers in nuclear medicine practices for the years 2010-2014 (enclosed in the brackets in the column are the number of institutions).

Category of worker/Year	2010	2011	2012	2013	2014
Physician	57	61	68	70	70
Physicist	19	26	24	21	21
Others*	188	217	226	202	205
Total	264 (18)	304 (18)	318 (18)	293 (18)	296 (18)

*Others include technologists, technicians, experimental officers, scientific assistants, lab attendants and auxiliary

Monitored and exposed workers

The dosimetry service at HPD uses a personal dosimeter system with a MDL of 0.05 mSv for a three month monitoring period after subtracting background radiation. Exposed workers are workers who may be exposed to doses exceeding 0.05 mSv. The workers who have effective doses less than MDL are considered as non-exposed. Therefore, the doses less than MDL are recorded as zero. All values of $H_p(10)$ are recorded and reported as the effective dose.

Data analysis

In this study, four quantities recommended by UNSCEAR [1] were used to analyze individual doses for the years 2010-2014. They include the annual collective effective dose, the average annual effective dose, the individual dose distribution ratio and the annual collective effective dose distribution ratio. In addition, the minimum and the maximum values of the annual individual effective doses were analyzed to complement the average annual effective doses.

Annual collective effective dose (S)

The annual collective effective dose (S) was obtained according to the following equation given by UNSCEAR [1]:

$$S = \sum_{i=1}^{N} E_i \qquad (1)$$

Where E_i is the annual effective dose received by the i^{th} worker and N is the total number of workers monitored. The parameter S, gives an estimate of the impact of particular practice on the population in given time frame.

Average annual effective dose

The average annual effective dose, $\bar{E}$ was obtained from the ratio S/N, where the meaning of symbols are the same as in equation (1).

The individual dose distribution ratio

The individual dose distribution ratio, NR_E was obtained according to the following equation [1]:

$$NR_E = \frac{N(>E)}{N} \qquad (2)$$

Where N(>E) is the number of workers receiving annual dose exceeding E mSv. In this study, NR_E was analysed for values of E of 15, 10, 5 and 1 mSv. The parameter NR_E provides an indication of the fraction of workers exposed to higher levels of individual doses.

The annual collective dose distribution ratio

The annual collective dose distribution ratio, SR_E was obtained according to the following equation [1]:

$$SR_E = \frac{S(>E)}{S} \qquad (3)$$

Where S (>E) is the annual collective dose delivered at an annual dose exceeding E mSv. In this study, SR_E was analysed for values of E of 15, 10, 5 and 1 mSv. The parameter SR_E, provides an indication of the fraction of the collective dose received by workers exposed to higher levels of individual doses.

RESULTS AND DISCUSSION

Annual average effective dose and collective effective dose

The annual average effective dose and annual collective effective dose did not follow a particular trend between the 5-year periods. The annual average effective doses of the monitored workers were ranged 0.13-0.27 mSv during the period 2010-2014 as shown in Figure 1. The average annual effective dose of monitored workers for the last 5-year period was 0.22 mSv which is three times lower than the worldwide average annual effective dose of 0.70 mSv during 2000-2002 periods [4]. The lowest annual average effective dose was 0.13 mSv in 2014. The observation may be due to decrease in workload or adherence to proper radiation protection protocols in 2014. The sudden rise in annual average effective dose in 2011, 2012 and 2013 could be due to improper radiation protection measures resulting in unintended over exposure of certain TLDs [21]. The decrease in average annual effective dose after 2013 is probably due to the formulation of independent regulatory Authority (BAERA) under the BAER Act-2012 [12] and proper regulatory control of the nuclear medicine facilities.

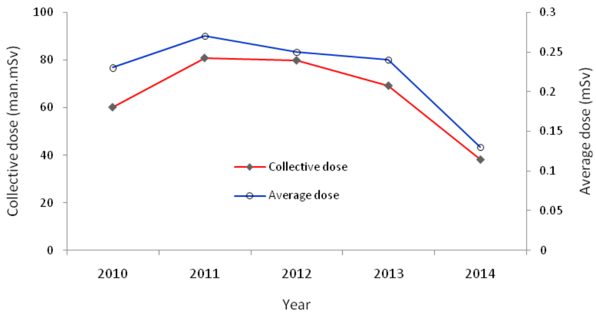

Fig 1. Trends of annual collective dose and average dose of the workers in nuclear medicine practices.

Figure 2 shows the annual average effective doses of physicians and physicists are lower than others, which comprising technologists, technicians, scientific assistants and so on.

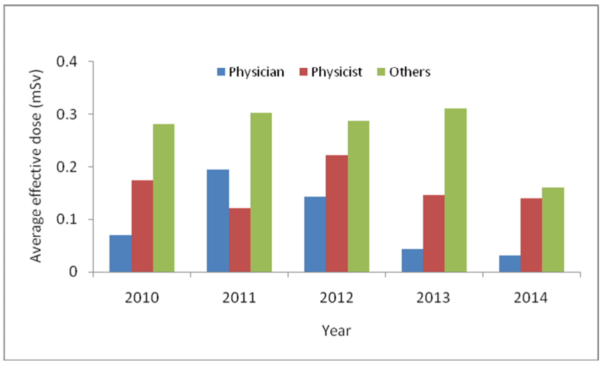

Fig 2. Annual average effective dose of physicians, physicists and others (technologists, technicians, experimental officers, scientific assistants, lab attendants and auxiliary) during the period 2010-2014.

This is the usual case and similar results were reported by Martins [22] and Piwowarska-Bilsk [23], because technicians and technologists are performing work in hot laboratories and those conducting in in-vitro tests with the RIA method. This group of workers was exposed to higher radiation doses and that was because of the fact that they prepared radiopharmaceuticals, performed examinations of the patients and controlled the scanners. Nuclear medicine technologists, nuclear medicine technicians and scientific assistants are the most exposed group of workers and consequently are the most important contributors to the total collective effective dose (Table 2).

Table 2: Collective dose (man.mSv) of the workers, organized by professions.

Category of worker/Year	2010	2011	2012	2013	2014
Physician	4.003	11.867	9.619	3.013	2.187
Physicist	3.314	3.157	5.305	3.054	2.957
Others*	52.847	65.664	64.786	63.059	33.162
Total	60.164	80.688	79.710	69.126	38.306

*Others include technologists, technicians, experimental officers, scientific assistants, lab attendants and auxiliary

This may be due to the fact that this group of workers is more directly involved with the patients in both the diagnosis and therapy conditions. The annual maximum individual effective doses of all monitored workers were 3.75, 10.74, 3.60, 7.82 and 1.94 mSv in 2010, 2011, 2012, 2013 and 2014 respectively as shown in Table 3.

It is the policy of HPD, BAEC dosimetry service to write to employers if any recorded dose exceeds 5 mSv for a monitoring period of 3 months. The employer is informed immediately of the dose and is requested to investigate the incident and to report the findings of such investigation to the HPD, BAEC. It is found that most of these exposures were due to prolonged working with radioactive sources or mistakes by radiation workers. Radioactive isotopes ^{99m}Tc and ^{131}I are widely used for nuclear medicine in Bangladesh. Some workers might not have proper training on radiation protection and their high exposure dose is thought to be the result of improper handling of the radioactive sources during their daily work. As can be seen from Figure 3, the majority of workers (95%) received doses less than 1 mSv during the entire study period. This means that the distributions are left skewed towards low doses in accordance with the distribution pattern described by UNSCEAR [11], the implication of which is that most occupationally exposed workers received very low doses with only a small number receiving high doses. During the period 2010-2014, no workers received doses higher than annual average dose limit 20 mSv. Although the workers received doses are well below the annual average dose limit prescribed by national regulation [15] and international organizations [13, 14], nuclear medicine workers should pay more attention to radiation protection procedures and guidelines to reduce the doses as low as reasonably achievable (ALARA). Based on this observation, as in most countries, nuclear medicine workers are the ones at risk (because of handling unsealed radioactive sources) and therefore rigorous surveillance has to be maintained in order to reduce the doses to this group of workers. The surveillance programme should include an analysis of worker dose records to determine whether the same set of workers always receives the higher doses.

Individual and collective dose distribution ratio

The individual dose distribution ratios for the period 2010-2014 were presented in Table 4. It is seen that very few individuals were exposed to doses exceeding 5 and 10 mSv. Furthermore, only 0.33 % of the monitored workers received doses above 10 mSv. Table 5 presents the results of the collective dose distribution ratio for the period 2010-2014.

The average annual effective dose of the workers in nuclear medicine departments in Bangladesh during the period 2010-2014 is three times lower than the worldwide average value during the period 2000-2002 quoted by UNSCEAR (Table 6).

Table 3: The maximum (max) and minimum (min) annual individual doses in mSv for the years 2010-2014, organized by professionals.

Type of worker/year	2010		2011		2012		2013		2014	
	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min
Physician	0.538	0	3.196	0	1.284	0	0.612	0	0.484	0
Physicist	1.650	0	0.818	0	2.694	0	1.521	0	0.745	0
Others*	3.754	0	10.744	0	3.603	0	7.824	0	1.944	0

* Others include technologists, technicians, experimental officers, scientific assistants, lab attendants and auxiliary

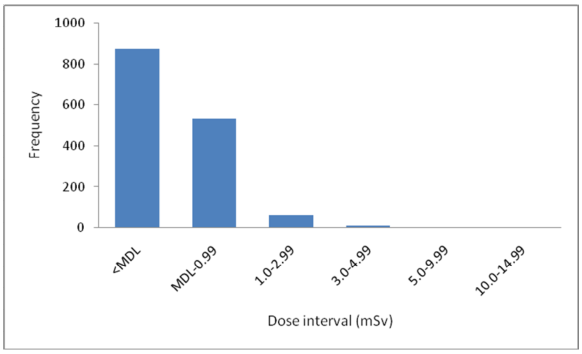

Fig 3. Frequency of observation of average annual effective doses interval of the workers in nuclear medicine practices during the period 2010-2014.

Table 4: The individual dose distribution ratio for the period 2010-2014

Annual individual dose exceeding (mSv)	Individual dose distribution ratio				
	2010	2011	2012	2013	2014
15	0.00	0.00	0.00	0.00	0.00
10	0.00	0.003	0.00	0.00	0.00
5	0.00	0.003	0.00	0.007	0.00
1	0.041	0.055	0.069	0.058	0.022

Table 5: Collective dose distribution ratio for the period 2010-2014.

Annual individual dose exceeding (mSv)	Collective dose distribution ratio				
	2010	2011	2012	2013	2014
15	0.00	0.00	0.00	0.00	0.00
10	0.00	0.156	0.00	0.00	0.00
5	0.00	0.156	0.00	0.202	0.00
1	0.350	0.518	0.420	0.623	0.285

The average effective doses of the monitored and exposed workers in Bangladesh (2010-2014) are six and four times lower than Portugal (1999-2003) [22] respectively and those are three and four times lower than Poland (1991-2009) [23] respectively. However, the annual average effective dose of nuclear medicine workers in Bangladesh is comparable to the dose received by workers in Turkey (2003) and in France (2005-2011).

The International Atomic Energy Agency recommends that the average annual dose for exposed workers in a nuclear medicine facility should range from 3 to 5 mSv [32]. According to the UNSCEAR report, the worldwide annual average dose for monitored and exposed workers during the years 2000-2002 was 0.70 and 1.4 mSv respectively [4].

Table 6: Comparison of annual average effective dose of monitored and exposed workers with other countries.

Country	Annual average effective dose (mSv)			
	Period	Monitored Worker	Exposed Worker	Reference
Poland	1991-2009	0.70	2.20	Piwowarska-Bilska et al [23]
Turkey	1995-1999	0.59	-	Gunduz et al [24]
	2003	0.29	-	Zeyrek et al [25]
Ghana	2000-2009	-	0.72	Hasford et al [26]
China	1986-1990	1.60	-	
	1991-1995	1.20	-	Weizhang et al [27]
	1996-2000	1.20	-	
France	2005-2011	0.31	0.83	Feuardent et al [28]
Greece	1994-1998	0.71	1.84	Kamenopoulou et al [29]
Portugal	1999-2003	1.42	2.36	Martins et al [22]
Brazil	2000-2003	2.30	5.40	Velasques de Oliveira et al [30]
Lithuania	1991-1995	2.13	-	
	1996-2000	1.42	-	Valuckas et al [31]
	2001-2003	1.47	-	
Bangladesh	2010-2014	0.22	0.55	This study
Worldwide average	2000-2002	0.70	1.40	UNSCEAR 2008 [4]

The annual average effective doses of the nuclear medicine workers are well below the average annual dose limit. The annual average effective dose and annual collective effective dose did not follow a particular trend between the 5-year periods. The average annual effective dose of the workers in nuclear medicine departments in Bangladesh during the period 2010-2014 is three times lower than the worldwide average value during the period 2000-2002 quoted by UNSCEAR. However, the annual average effective dose of nuclear medicine workers in Bangladesh is comparable to the dose received by workers in Turkey (2003) and in France (2005-2011). Nuclear medicine technologists, nuclear medicine technicians and scientific assistants are the most exposed group of workers and consequently are the most important contributors to the total collective effective dose. Even though majority of workers (95%) received very low doses, but only 0.33% workers received doses above 10 mSv. Therefore, a close monitoring and control of the activities of this group of workers must be ensured.

CONCLUSION

It can be concluded that courses in radiation protection particularly the safe operation and handling of unsealed radioactive sources are strongly recommended to those workers who have lack of proper training. Finally, workers should pay more attention to radiation protection procedures and guidelines in their daily work to keep the doses as low as reasonably achievable.

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REFERENCES

1. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources and effects of ionizing radiation. Report to the general assembly of the United Nations with scientific annexes, New York: United Nations sales publication. 2000; E.00.IX.3.
2. Council of the European Union. Council Directive 97/43/Euratom of 30 June 1997 on health protection of individuals against the dangers of ionizing radiation in relation to medical exposure, and repealing Directive 84/466/Euratom. Official J Eur Commun. 1997;L 180/22.
3. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources and effects of ionizing radiation. Report to the general assembly of the United Nations with scientific annexes, New York: United Nations sales publication. 1993; E.94.IX.2.
4. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources and effects of ionizing radiation. Report to the general assembly of the United Nations with scientific annexes, New York: United Nations sales publication. 2008; E.10.XI.3.
5. National Council on Radiation Protection and Measurements. Ionizing radiation exposure of the population of the United States. (NCRP Report No. 160). Bethesda, MD: 2009.
6. International Atomic Energy Agency. International Basic Safety Standards for protection against ionizing radiation and for the safety of radiation sources (Safety Series No. 115). Vienna: IAEA; 1996.
7. International Commission on Radiological Protection (ICRP). 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21 (1-3). Oxford: Pergamon Press;1990.
8. Colgan PA, Currivan L, Fenton D. An assessment of annual whole-body occupational radiation exposure in Ireland (1996-2005). Radiat Prot Dosimetry. 2008;128(1):12-20.
9. Barrall RC, Smith SI. Personnel radiation exposure and protection from 99mTc radiations. In: Kereiakes JG, Corey KR. Biophysical aspects of the medical use of technetium-99m. Monograph No. 1. New York: American Association of Physicists in Medicine; 1976. p. 77.
10. National Council on Radiation Protection and Measurements. Implementation of the principle of as low as reasonably achievable (ALARA) for medical and dental personnel. (NCRP Report No. 107). Bethesda, MD: 1990.
11. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Ionizing radiation: sources and biological effects. Report to the general assembly of the United Nations with scientific annexes, New York: United Nations sales publication. 1982; E82. IX.8.
12. Bangladesh Atomic Energy Regulatory (BAER) Act-2012 (Act No. 19 of 2012); 2012.
13. International Commission on Radiological Protection (ICRP). The 2007 Recommendations of International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2- 4). Oxford: Elsevier; 2007.
14. International Atomic Energy Agency. Radiation protection and safety of radiation sources: International basic safety standards. General safety requirements part-3. Vienna:IAEA; 2014.
15. The Nuclear Safety and Radiation Control (NSRC) Rules-1997 of Bangladesh (SRO No. 205-Law/97); 1997.
16. International Commission on Radiological Protection (ICRP). ICRP Statement on Tissue Reactions / Early and Late Effects of Radiation in Normal Tissues and Organs – Threshold Doses for Tissue Reactions in a Radiation Protection Context. ICRP Publication 118. Ann. ICRP 41(1/2); 2012.
17. Harshaw Model 4500, Manual TLD Workstation Operator's Manual (Cochran Road, Solon, Ohio) (Pub. No. 4500-0-O-0598-002, 6801); 1998.
18. Harshaw TLD Model 6600 Plus Automatic TLD reader user manual. Thermo Fisher Scientific Inc.; 2007. Available on: http://www.kortec.cz/files/thermo/TLDModel6600.pdf.
19. International Atomic Energy Agency. Assessment of occupational exposures due to external sources of radiation. Safety Guides Series No. RS-G-1.3. Vienna: IAEA; 1999.
20. International Commission on Radiological Protection (ICRP). General principles for the radiation protection of workers. Pergamon Press: Ann. ICRP 27 (1); 1997.
21. Hart D, Wall BF. Radiation exposure to the UK population from medical and dental x-ray examinations. National Radiological Protection Board, NRPB-W4; 2004.
22. Martins MB, Alves JG, Abrantes JN, Roda AR. Occupational exposure in nuclear medicine in Portugal in the 1999-2003 period. Radiat Prot Dosimetry. 2007;125(1-4):130-4.
23. Piwowarska-Bilska H, Birkenfeld B, Gwardyś A, Supińska A, Listewnik MH, Elbl B, Cichoń-Bańkowska K. Occupational exposure at the Department of Nuclear Medicine as a work environment: A 19-year follow-up. Pol J Radiol. 2011 Apr;76(2):18-21.
24. Gündüz H, Zeyrek CT, Aksu L, Işak S. Occupational exposure to ionising radiation in the region of Anatolia, Turkey for the period 1995-1999. Radiat Prot Dosimetry. 2004;108(4):293-301.
25. Zeyrek CT, Gündüz H. Occupational exposure to ionising radiation with thermoluminescence dosimetry system in Turkey, in 2003. Radiat Prot Dosimetry. 2005;113(4):374-80.
26. Hasford F, Owusu-Banahene J, Amoako JK, Otoo F, Darko EO, Emi-Reynolds G, Yeboah J, Arwui CC, Adu S. Assessment of annual whole-body occupational radiation exposure in medical practice in Ghana (2000-09). Radiat Prot Dosimetry. 2012 May;149(4):431-7.
27. Weizhang W, Wenyi Z, Ronglin C, Liang'an Z. Occupational exposures of Chinese medical radiation workers in 1986-2000. Radiat Prot Dosimetry. 2005;117(4):440-3.
28. Feuardent J, Scanff P, Crescini D, Rannou A. Occupational external exposure to ionising radiation in France (2005-2011). Radiat Prot Dosimetry. 2013 Dec;157(4):610-18.

29. Kamenopoulou V, Drikos G, Dimitriou P. Occupational exposure to ionizing radiation in Greece (1994-1998). Radiat Prot Dosimetry. 2000;91(4):385-9.

30. Velasques de Oliveira SM, Santos DS, Cunha PG. Occupational exposure in nuclear medicine in Brazil. World congress on medical physics and biomedical engineering 2006. IFMBE Proceedings. 2007;14(4):2114-17.

31. Valuckas KP, Atkocius V, Samerdokiene V. Occupational exposure of medical radiation workers in Lithuania, 1991-2003. Acta Medica Lithuanica. 2007;14(3):155-9.

32. International Atomic Energy Agency (IAEA) training material on radiation protection in nuclear medicine, part 5. Vienna: IAEA; December 2004.