FIFTEEN YEARS OF OCCUPATIONAL EXPOSURE MONITORING IN THE FEDERATION OF BOSNIA AND HERZEGOVINA

by

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The personal dosimetry in Bosnia and Herzegovina started in 1960. After a brief interruption in 1990s, the dosimetry service resumed in 1999. Until 2013, the Radiation Protection Centre of the Institute of Public Health of Federation of Bosnia and Herzegovina has been the only institution in the country that could provide this service. In 2013, this Center covered more than 70 % (1,485) of all radiation workers in the country. They mostly worked in medical institutions (1,417 or 95.4 %), while others are exposed to radiation sources in industry and veterinary radiology. From 1999 to 2013, the majority of annual doses were less than 1 mSv (96.2 %). There are no registered cases of exceeding the annual dose limit (20 mSv). The results analysis shows the reduction of individual doses in last five years. Newly adopted practices in medicine, such as the positron emission tomography, could cause the increase of doses in the years to come.

Key words: occupational exposure, dosimetry, thermoluminescence dosimetry

INTRODUCTION

There is a wide variety of situations in which people at work are exposed to the ionising radiation. The conventional definition of occupational exposure to any hazardous agent includes all exposures incurred at work, regardless of the source [1]. However, to distinguish the exposure that should be subject to control by the operating management from the exposure arising from the general radiation environment, the term 'occupational radiation exposure' is taken to mean that those exposures were received or committed during the period of work and that can reasonably be regarded as the responsibility of the operating management [2, 3]. In most of the cases, such exposures are subject to the regulatory control.

The means of occupational dose monitoring are normally regulated by the responsible authority. Usually, the personal dosimeters are used for individual dose monitoring. The workers are issued with an appropriate individual dosimeter which provides periodical dose readouts in the chosen physical quantity recommended by the ICRU [4, 5]. The technology of individual dosimeters has been changing over the years. In general, a perfect individual dosimeter would be the tissue equivalent, able to measure all types of radiation, not depending on energy, with high precision and accuracy. Unfortunately, this is not possible for many reasons. The dosimeters used in this study are based on the property of certain crystalline materials to absorb the energy of ionising radiation and re-emit it as a visible light upon the exposure to high temperature. This property is called the thermoluminescence [6]. Historically, the radiographic film has been used as a method of choice in personal dosimetry for many years [7]. According to the European Radiation Dosimetry Group (EURADOS) Survey from 2012, the thermoluminescence dosimeters (TLD) and films make up more than 80 % of the issued dosimeters in Europe. According to the same survey, 15 out of 76 individual monitoring services worked with film dosimeters, which is less in comparison to the 2003 report [8, 9]. Although the radiographic films have a lot of advantages, their use in personal dosimetry is limited by their high energy dependence, poor sensitivity, possibility of accidental exposure to visible light, lack of

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compatibility with digital systems, *etc*. [10]. Other detectors commonly used in personal dosimetry are based on the radio photoluminescence (RPL), optically stimulated luminescence (OSL) *etc*. [11, 12]. In specific cases, the workers are issued the direct ion storage (DIS) dosimeters or active personal dosimeters (APD) [8].

Primarily, the individual monitoring is used to control the occupational exposure and ensure safe working conditions, as well as to demonstrate the compliance with the third radiation protection principle – dose limitation. Individual monitoring results provide the information on the adequacy of protection measures, which is the key input for operational decisions needed to address the second principle of radiation protection – optimisation. When low, the individual doses provide a reassurance to workers [13]. Hence, the individual monitoring of exposed workers is a requirement of the International Atomic Energy Agency (IAEA) International Basic Safety Standards and the national regulation of Bosnia and Herzegovina (BIH) [3, 14].

The personal dosimetry in BIH started in 1960. It was interrupted in 1990 and continued in 1999 after the IAEA donated a TLD reader and a set of appropriate dosimeters to the Radiation Protection Centre (RPC) of the Institute of Public Health of Federation of Bosnia and Herzegovina (FBIH). For many years, this has been the only institution in BIH that provided the personal dosimetry service, covering approximately 70 % of the exposed workers [15]. Now, the country has three institutions licenced by the State Regulatory Agency for the Radiation and Nuclear Safety (SRARNS) to provide such services. The SRARNS is responsible for the maintenance of the national register of individual exposures [16].

Several studies have been published with the results from FBIH. Most notably, a 10-year review from 2010 by Bašić *et al*, as well as the evaluation of occupational exposure in interventional cardiology in 2011 by Beganović *et al*., [15, 17]. This study evaluates additional five years of dose monitoring data, with the methodology matching the UNSCEAR 2008 Report, and makes the re-evaluation of previously published results using a different methodology [15, 18].

MATERIALS AND METHODS

In this paper, the individual monitoring results from 1999 to 2013, are summarized. The data is compiled to match the UNSCEAR 2008 Report [18]. During the analysed period, the RPC has been equipped with one thermoluminescent reader (Thermo Scientific™ Harshaw TLD Model 4500 Automatic Reader, Waltham, MA, USA). It used more than 3000 TLD, based on the Lithium Fluoride crystal doped with titanium and magnesium to increase the number of traps and luminescence centres (LiF:Mg,Ti). This material is known by its trademark name TLD-100™ and is used in personal dosimetry, as well as the patient dosimetry [19]. Each dosemeter is equipped with either two or four separate TLD-100 detectors, enclosed in a casing with appropriate filters. It is calibrated to measure the personal dose equivalent at the reference points of (10 and 0.07) mm, $H_P(10)$ and $H_P(0.07)$, respectively. Its minimum detectable limit (MDL) is approximately 50 μSv [20].

The dosimeters were calibrated in a secondary standard dosimetry laboratory (SSDL) in the radiation field of ^{137}Cs source. Their individual sensitivity and reproducibility was determined using an in-house ^{90}Sr/^{90}Y irradiator, specially designed for such purposes. All manufacturer's procedures for the dosimeter preparation and readout were followed, including the annealing recommendation from the IAEA safety guide [21].

As it is common in personal dosimetry, the TLD were issued to the users on a strict periodic schedule. Each user is subscribed to two dosimeters that are used interchangeably throughout the worker's professional life. They are replaced only when damaged beyond repair.

Until 2012, all dosimeters were changed once per month. Since 2013, some users have been classified as category "B" of professionally exposed workers, in accordance to the legislation promulgated by the SRANRS in 2011 [14]. This made workers eligible for the quarterly readout of dosimeters.

The majority of TLD users work in medical field, specifically, in diagnostic and interventional radiology. In some cases, medical professionals need to wear protective lead aprons. These workers were instructed to wear the dosimeters under the apron. In special circumstances, where the exposure to the non-uniform radiation field is expected, professionals were issued additional dosimeters. This relates to the medical staff in interventional radiology, cardiology, and gastroenterology, as well as cardiac surgery, whom the RPC issued two dosimeters, one to wear under and other above the apron, near the neckline.

The effective dose, E, received by a professionally exposed person is estimated using the available results of $H_P(10)$, which is an operational quantity used for the control of effective dose, designed for monitoring the strongly penetrating radiation (photons with energy above 12 keV) [22]. In special cases, when the worker is provided with two TLD that are worn under and above the lead apron, the effective dose is estimated using the measured values from both dosimeters, under and over the apron. There are different ways to make the estimation. The RPC uses a method described by Niklason *et al*. although other algorithms exist and are still being developed [23-26]. The Niklason's algorithm is not without flaws, mostly because it leads to the overestimation of the effective dose [27].

In order to measure the background dose, we used the unexposed control dosimeters located in the RPC. The value obtained was subtracted from the doses measured by the TLD issued to users. That value corresponds to the dose in two-month period of background radiation, or background dose during the time it takes for the dosimeters to be shipped, distributed, used, and shipped back to the RPC. A similar procedure was carried out for the dosimeters that were distributed quarterly. In cases when the reported background was higher, the dose measured on an "exposed" dosimeter was reported to be 0 μSv.

The final report to the customers has been sent via post in a *hard copy,* both to the customers, and to the SRARNS.

The analysis of the dosimetry data was performed to match the reports in UNSCEAR Report 2008. In order to assess the impact of high-dose records to the overall average, the UNSCEAR report introduced the 'number distribution ratio', NR_{E}, defined as

$$NR_{\mathrm{E}} \quad \frac{N(\quad E)}{N} \tag{1}$$

where N is the total number of persons, and N (> E) the number of users who received doses higher than E. In a similar fashion, the annual collective dose distribution ratio, SR_{E}, is defined as

$$SR_{\mathrm{E}} \quad \frac{S(\quad E)}{S} \tag{2}$$

where S is the collective dose of all workers, and S (> E) the collective dose of individuals who received the effective dose above E [18].

The workers are classified according to their profession (practice): diagnostic radiology (DgR), interventional radiology (IR), nuclear medicine (NM), positron emission tomography (PET), radiotherapy (RT), dental radiology (DeR), veterinary radiology (VR), and workers in industry (IN).

RESULTS

The results are grouped in three 5-year periods (1999-2003, 2004-2008, and 2009-2013), classified according to the professions of exposed workers. Figure 1 shows the number of TLD users from 1999 to 2013. At the end of 2013, the RPC covered 1,485 users with personal dosimetry.

In total, the number of annual doses evaluated by the RPC is approximately 15,000. Figure 2 shows the annual dose distribution according to the three 5-year periods. The majority of the annual doses were less than 1 mSv (96.2 %). Some users received doses 1.00-1.99 mSv/a (3.0 %) and very few doses between 2.00 and 2.99 mSv/a (0.6 %). The doses above 3.00 mSv were recorded in 47 cases, with the maximum annual dose of 10.4 mSv in 2003 for a worker in industrial radiography.

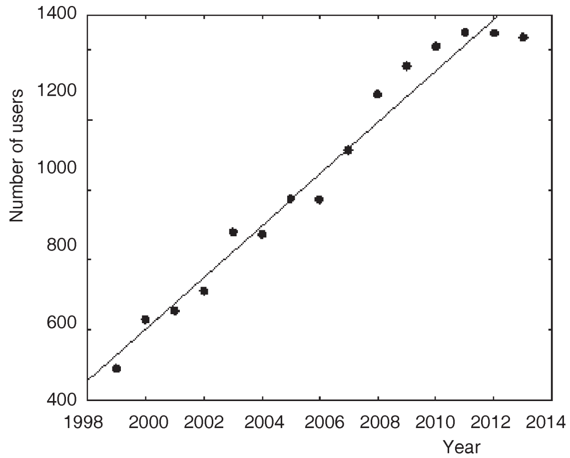

Figure 1. The increase of number of TLD users in the FB H from 1999 until 2013. The number of occupationally exposed workers covered by the TL dosimetry increased by 73 users per year (linear regression curve

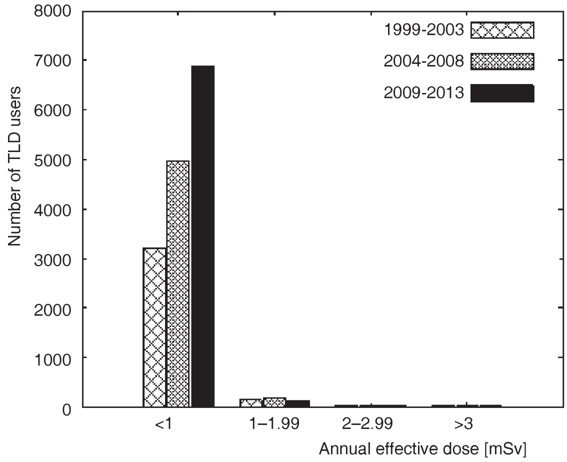

Figure 2. The total number of TLD users who received the doses below 1 mSv, 1-1.99 mSv, 2-2.99 mSv, and above 3 mSv in different time periods

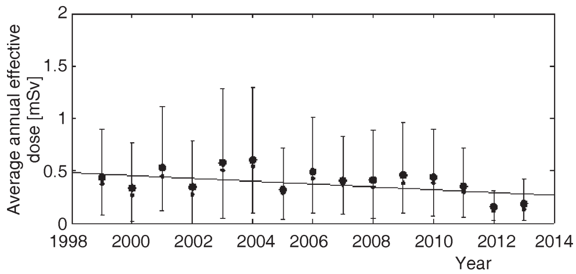

Figure 3. The average annual effective dose in the FB H from 1999 until 2013 with 5th and 95th percentile bars, and the median values represented with small dots. The negative correlation is significant (the Pearson's correlation test, $p < 0.001$). On average, the dose decreases by 0.018 mSv per year

Figure 3 illustrates how the average and median annual effective doses in FB H were changing from 1999 until 2013, with 5th and 95th percentile bars.

Table 1 shows the average number of workers covered by the personal dosimetry per year in an indicated

Table 1. The number of occupationally exposed persons in the FB H, *N*, covered by the personal dosimetry in different time periods, and the number distribution ratio, NR_E. The data from Croatia, Greece, Finland, and the World is from 2000-2002 period, as reported in the UNSCEAR Report 2008 [18]

Practice	Years	N^a	Number of workers[b]			Number distribution ratio		
			N_1	N_5	N_{10}	NR_1	NR_5	NR_{10}
Diagnostic radiology	1999-2003	527	17	0	0	0.032	0.000	0.000
	2004-2008	758	17	0	0	0.022	0.000	0.000
	2009-2013	973	3	0	0	0.003	0.000	0.000
	Croatia	2570				0.02	0.000	0.000
	Greece[c]	6430				0.07	0.03	0.01
	Finland	4360				0.05	0.01	0.00
	World[c]	6.67 10				0.19	0.02	0.01
Interventional radiology	1999-2003	51	7	0	0	0.137	0.000	0.000
	2004-2008	67	9	0	0	0.134	0.000	0.000
	2009-2013	96	16	0	0	0.167	0.000	0.000
	Croatia	340				0.14	0.03	0.01
	Finland	150				0.68	0.30	0.16
Nuclear medicine	1999-2003	39	2	0	0	0.051	0.000	0.000
	2004-2008	69	7	0	0	0.101	0.000	0.000
	2009-2013	89	6	0	0	0.067	0.000	0.000
PET-CT only	2014-2017	5[d]	3	0	0	0.600	0.000	0.000
	Croatia	270				0.22	0.06	0.01
	Greece	640				0.16	0.03	0.00
	Finland	450				0.08	0.00	0.00
	World	$120\ 10^3$				0.31	0.04	0.01
Radiotherapy	1999-2003	33	0	0	0	0.000	0.000	0.000
	2004-2008	47	0	0	0	0.000	0.000	0.000
	2009-2013	83	0	0	0	0.000	0.000	0.000
	Croatia	270				0.04	0.00	0.00
	Greece	370				0.02	0.00	0.00
	Finland	320				0.00	0.00	0.00
	World	$264\ 10^3$				0.11	0.02	0.01
Dental radiology	2003	23	2	0	0	0.087	0.000	0.000
	2004-2008	30	0	0	0	0.000	0.000	0.000
	2009-2013	54	0	0	0	0.000	0.000	0.000
	Croatia	330				0.00	0.00	0.00
	Greece	40				0.03	0.01	0.00
	Finland	100				0.00	0.00	0.00
	World	$404\ 10^3$				0.01	0.00	0.00
Veterinary radiology	2002-2003	2	0	0	0	0.000	0.000	0.000
	2004-2008	2	0	0	0	0.000	0.000	0.000
	2009-2013	5	0	0	0	0.000	0.000	0.000
	Croatia	50				0.04	0.00	0.00
	Greece	10				0.00	0.00	0.00
	Finland	290				0.06	0.01	0.00
	World	$119\ 10^3$				0.03	0.00	0.00
Industry	1999-2003	18	10	0	0	0.556	0.000	0.000
	2004-2008	68	8	0	0	0.118	0.000	0.000
	2009-2013	121	9	0	0	0.074	0.000	0.000
	Croatia[e]	90				0.18	0.07	0.04
	Greece[e]	250				0.17	0.04	0.01
	Finland[e]	360				0.10	0.00	0.00
	World	$113\ 10^3$				0.01	0.00	0.00
TOTAL	1999-2003	674	38	0	0	0.056	0.000	0.000
	2004-2008	1042	41	0	0	0.039	0.000	0.000
	2009-2013	1420	37	0	0	0.026	0.000	0.000

[a]Averaged total number of workers in the indicated time period, [b]N_1, N_5, and N_{10} is the average number of occupationally exposed workers who received annual doses higher than (1, 5, and 10) mSv in the indicated time period, [c]data includes both diagnostic and interventional radiology, [d]reportable level of 0.08 mSv applied when calculating the annual dose, and [e]data for industrial radiography

Table 2. The annual effective doses in different practices in the FBIH in different time periods, and the trends represented with the slope coefficient *b* and *p*-value of the Pearson's correlation test. The data from Croatia, Greece, Finland and the World is from 2000-2002 period, as reported in the UNSCEAR Report 2008 [18]

Practice	E^a [mSv]				Correlation	
	1999-2003	2004-2008	2009-2013	2014-2017	*b*	*p*
Diagnostic radiology	0.409	0.428	0.282	–	–0.017	<0.001
Croatia	0.11					
Greece^b	0.54					
Finland	0.22					
World^b	0.50					
Interventional radiology	0.753	0.555	0.528	–	–0.025	<0.001
Croatia	0.66					
Finland	4.95					
Nuclear medicine	0.553	0.546	0.428	–	–0.018	<0.001
PET-CT	–	–	–	1.58		
Croatia	0.92					
Greece	0.61					
Finland	0.21					
World	0.73					
Radiotherapy	0.324	0.349	0.233	–	–0.014	<0.001
Croatia	0.21					
Greece	0.19					
Finland	0.01					
World	0.47					
Dental radiology	0.335	0.322	0.309	–	–0.008	0.088
Croatia	0.06					
Greece	0.20					
Finland	0.00					
World	0.06					
Veterinary radiology	0.681	0.205	0.153	–	–0.043	<0.001
Croatia	0.13					
Greece	0.07					
Finland	0.23					
World	0.15					
Industry	0.989	0.498	0.411	–	–0.048	<0.001
Croatia	1.25					
Greece	0.73					
Finland	0.30					
World	1.48					
TOTAL	0.454	0.442	0.317		–0.018	<0.001

^{a}Annual effective dose averaged in a selected period, ^{b}data includes both diagnostic and interventional radiology

5-year period, *N*. The columns in tab. 1, titled N_1, N_5, and N_{10}, show the number of workers who received doses higher than (1, 5, and 10) mSv per year on a 5-year average, respectively. Similarly, the columns NR_1, NR_5, and NR_{10} show their number distribution ratio.

Table 2 shows the values of average annual effective dose, *E*, in the indicated time period. They are organized according to different professions. Figures 4 and 5 show how the average annual effective dose was changing from 1999 to 2013 in diagnostic and interventional radiology, nuclear medicine, radiotherapy, dental and veterinary radiology, as well as in industry.

Both tabs. 1 and 2 show the preliminary results of individual monitoring of workers in positron emission tomography.

Table 3 shows the values of average annual collective dose, *S*, for the indicated 5-year period, and collective dose distribution ratio, SR_E.

DISCUSSION

In 15-year period (1999-2013), the number of TLD users has been increasing steady, with the average of 73 users per year (fig. 1).

According to the national legislation, the recording level (RL) is set to 0.08 mSv per month, which is in accordance to the recommendations of the International Commission on Radiological Protection [14, 28]. Until 2013, however, no formal RL was defined, and therefore no data was excluded in reports. In special circumstances, the thermoluminescent dosimetry could provide the results below this value, but it is very close to the practical MDL of 0.05 mSv [20].

In the selected 15-year period of individual monitoring no doses above the limit (20 mSv per year) were reported. The majority of the professionals received doses less than 1 mSv/a (fig. 2).

On a 5-year average, none of the workers received the annual effective dose greater than 10 mSv per year. It is interesting to see that the number of those who received more than 1 mSv per year remained the same through the years (approx. 40), while the total number of TLD users doubled (tab. 1). This disproportional change affects the number distribution ratio NR1, that changes from 0.056 in 1999-2003 period to 0.026 in 2009-2013. In 2009-2013 the highest NR_1 among different professions was in interventional radiology (0.167). This, however, will most likely be

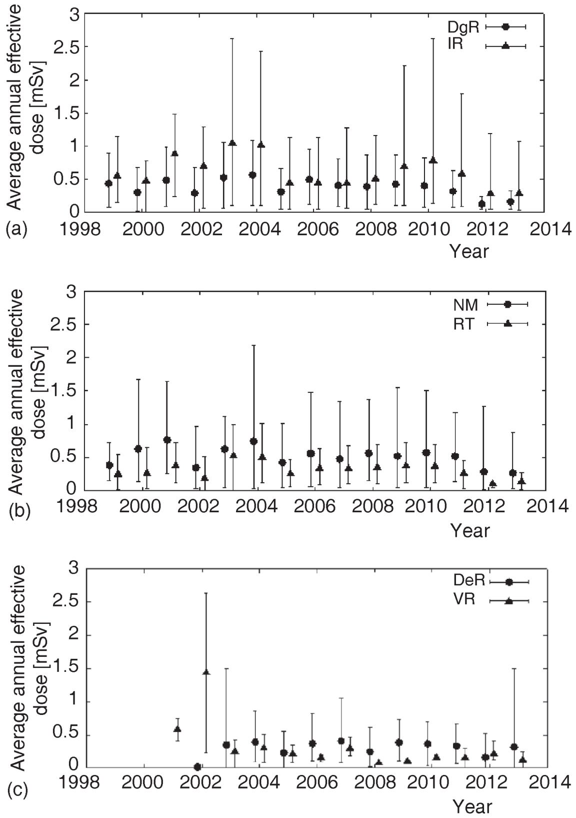

Figure 4. The average annual effective dose in (a) diagnostic and interventional radiology, (b) the nuclear medicine and the radiotherapy, and (c) the dental and veterinary radiology in the FBIH from 1999 until 2013 with 5th and 95th percentile bars

changed. The preliminary results, for period 2014-2017, showed that PET-CT procedures could give rise to the occupational doses in nuclear medicine. During the 3-year period, 3 out of 5 radiographers who work on a single PET-CT unit received doses above 1 mSv per year, so the NR_1 was 0.600 for these individuals only (tab. 1). Their average annual effective dose is 1.58 mSv (tab. 2), which is the highest number among all professions. The collective annual dose of PET-CT workers is 7.91 mSv. If we follow the trend of collective dose and the number of monitored workers increase in NM, the projected value of *S* in general NM in the 2014-2017 period would be 45.7 man mSv, and the number of monitored workers would increase to 112. Their average annual dose would be 0.408 mSv. If the dose reported for 5 PET-CT workers is added to the sum, the collective annual dose would be 53.7 man mSv. The doses received by PET-CT radiographers and nurses would account for 14.7% of *S* in NM and they would increase the average annual effective dose by 0.050 mSv, or 12.5%.

It should be noted that the dose highly depends on technical capabilities of PET-CT department (the existence and the type of automatic dispensing and injection system, available structural and mobile radiation shielding) and workflow (work organization, examination protocols, number of staff and procedures,

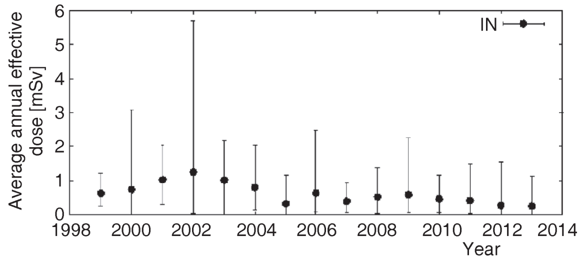

Figure 5. The average annual effective dose in the industry in the FBIH from 1999 until 2013 with 5th and 95th percentile bars. The negative correlation is significant (Pearson's correlation test, p = 0.004). On average, the dose decreases by 0.048 mSv per year

etc). A practice could be changed, perfected, or number of workers could fluctuate in a 5-year period. Therefore, a final conclusion on the influence of PET-CT procedures on occupational exposure in nuclear medicine could be given taking into account the doses for all nuclear medicine staff in the whole period between 2014-2018.

The results were compared to the data from 2000-2002 period from other countries, as reported in the UNSCEAR Report 2008 [18]. We have chosen Croatia, Greece, and Finland.

When compared to other countries in Europe, the NR_E values are in good agreement, but some discrepancies exist. The country discrepancies could be caused by different work practices, different total number of exposed workers and variations in dose monitoring methodology. The number distribution ratio, NR_E, for workers in diagnostic and interventional radiology is almost the same for the matching time period in the neighbouring Croatia which has a similar healthcare system (tab. 1). We observed a big decrease in number of radiologists/radiographers who received doses above 1 mSv in 2009-2013 period (from 17 to only 3). This is most likely due to the fact that the high dose procedures and technologies performed in diagnostic radiology (*i. e.*, barium enema), are replaced with computed tomography [29]. The staff is no longer required to work in the controlled area. On the other hand, the number of interventional radiologists/radiographers has been increasing.

The NR_E in nuclear medicine, radiotherapy and veterinary radiology are either similar or lower than the values reported by other countries. In dental radiology, however, there have been two individuals who received the doses above 1 mSv in 2003. This result is unusual, because they both worked with the low-dose intraoral X-ray units. One could conclude that the two dentists were not following all radiation safety protocols. The NR_E in industry had its maximum value in 1999-2003, when almost all exposed workers were involved in the industrial radiography and the non-destructive testing of metals. After other workers in the industry were issued dosimeters, the relative number of those receiving the dose above 1 mSv per year has decreased.

Table 3. The collective dose, *S*, and the collective dose distribution ratio, SRE, in the FBIH in different time periods. The data from Croatia, Greece, Finland, and the World is from 2000-2002 period, as reported in the UNSCEAR Report 2008 [18]

Practice	Years	S^a [man mSv]	Collective dose distrib. ratio		
			SR_1	SR_5	SR_{10}
Diagnostic radiology	1999-2003	215	0.067	0.000	0.000
	2004-2008	324	0.059	0.000	0.000
	2009-2013	275	0.008	0.000	0.000
	Croatia	280	0.41	0.16	0.04
	Greece[b]	3460	0.92	0.75	0.53
	Finland	940	0.00	0.00	0.00
	World[b]	3300000	0.79	0.48	0.36
Interventional radiology	1999-2003	38.1	0.310	0.000	0.000
	2004-2008	37.4	0.252	0.000	0.000
	2009-2013	50.7	0.376	0.000	0.000
	Croatia	220	0.79	0.42	0.13
	Finland	750	0.98	0.79	0.59
Nuclear medicine	1999-2003	21.5	0.181	0.000	0.000
	2004-2008	37.8	0.258	0.000	0.000
	2009-2013	38.0	0.190	0.000	0.000
Positron emission tomography	2014-2017	7.91	0.881	0.000	0.000
	Croatia	250	0.87	0.48	0.12
	Greece	390	0.79	0.32	0.06
	Finland	90	0.65	0.00	0.00
	World	87000	0.73	0.19	0.07
Radiotherapy	1999-2003	10.8	0.000	0.000	0.000
	2004-2008	16.3	0.000	0.000	0.000
	2009-2013	19.3	0.000	0.000	0.000
	Croatia	60	0.53	0.15	0.00
	Greece	70	0.87	0.62	0.62
	Finland		0.11	0.00	0.00
	World	132000	0.70	0.34	0.23
Dental radiology	2003	8.03	0.376	0.000	0.000
	2004-2008	9.67	0.000	0.000	0.000
	2009-2013	16.5	0.000	0.000	0.000
	Croatia	20	0.10	0.00	0.00
	Greece		0.84	0.54	0.00
	Finland		0.00	0.00	0.00
	World	24000	0.48	0.26	0.25
Veterinary radiology	2001-2003	1.59	1.000	0.000	0.000
	2004-2008	0.49	0.000	0.000	0.000
	2009-2013	0.77	0.000	0.000	0.000
	Croatia	10	0.39	0.00	0.00
	Greece	0	0.00	0.00	0.00
	Finland	70	0.84	0.38	0.10
	World	18200	0.50	0.20	0.10
Industry	1999-2003	17.4	0.691	0.000	0.000
	2004-2008	34.1	0.386	0.000	0.000
	2009-2013	49.9	0.342	0.000	0.000
	Croatia	90	0.92	0.79	0.64
	Greece	180	0.94	0.49	0.20
	Finland	110	0.66	0.03	0.00
	World	168100	0.90	0.57	0.35

[a]Collective dose averaged per one year in selected period. [b]data includes both diagnostic and interventional radiology

Table 2 shows the values of average effective dose in different professions, as well as the trends represented with the slope coefficient b of the fitted linear curve and the *p*-value of the Pearson's correlation test. It is evident from tab. 2 that the highest doses are associated with the professionals in the interventional radiology, the nuclear medicine and the industry. Table 2 provides the average annual effective doses from three European countries and the World in 2000-2002 period, as reported in the UNSCEAR Report 2008 [18]. The reported values vary from one country to another, including the results from our study. In DgR, for example, the average annual effective dose in 1999-2003 period was found to be 0.409 mSv, which is almost two times higher than the dose reported in Finland, and almost four times higher than the dose in Croatia. On the other hand, the doses in NM are two times less than in FBIH when compared to the results in Croatia. Other professions follow the similar patterns. Because the practice is not so different, especially in DgR, RT, DeR, and VR, we can only conclude that the methods of individual dosimetry used in different countries have a great influence on the reported doses. The methodology does not only include the type of dosimeters used, MDL, RL, but also the treatment of missing or unexpectedly high doses, the protocol for categorization of radiation workers, the analysis of background doses, *etc*. This has been a conclusion of the UNSCEAR Reports 2000 and 2008 [18, 30]. In total, the average annual effective dose for all professions in FB H in 2009-2013 period was 0.317 mSv.

Figure 3 illustrates how the annual effective dose (average and median) in FB H changes from 1999 until 2013 with 5^{th} and 95^{th} percentile bars. The negative correlation is found to be significant (the Pearson's correlation test, $p < 0.001$). On average, the dose decreases by 0.018 mSv per year. The change is mainly caused by the increase in number of workers and the significant changes in radiological technologies.

Figure 4(a) shows how the doses of individuals working in diagnostic and interventional radiology have been changing over the years. As expected, the doses are significantly higher in the interventional radiology (Mann-Whitney U-test, $p < 0.001$). Although the radiologists/radiographers in the IR attribute to approximately 10 % of the workforce in the radiology departments (tab. 1), their contribution in 2009-2013 period to the overall collective dose in radiology is more than 15 % (tab. 3), with the average annual effective dose two times higher (tab. 2).

The reduction trend is significant in both practices. On average, the doses in DgR and IR have decreased by (0.017 and 0.025) mSv in the 1999-2013 period, respectively (tab. 2). The percentile bars indicate the differences in annual doses between the different individuals. When the data from the 15-year period is analysed, the range between 5^{th} and 95^{th} percentile was (0.785 and 1.650) mSv in DgR and IR, respectively, indicating that the doses between different workers in diagnostic radiology are somewhat similar, while the individuals in the interventional radiology receive a wider range of doses. The larger dose range in the interventional radiology can be explained when the practice itself is closely investigated. In medicine, there are different image-guided procedures that are labelled as interventional, not only in radiology, but also in cardiology, gastroenterology *etc*. [31]. They are all associated with different exposure conditions, mainly caused by the procedure complexity, distance from the radiation source, and the possibility to use the radiation protection devices. In turn, the top 5 % of reported annual doses are above 1.72 mSv, which is more than four times larger than the median value in the observed 15-year period. In the diagnostic radiology, however, working conditions tend to be similar between the different individuals. Most of the exposed individuals work in the supervised area, behind the protective structural shielding, designed to have similar dose constraint level, usually set to 0.3 mSv per year, recommended by the International Commission on Radiological Protection for the members of the public [32]. Hence, the range between 5^{th} and 95^{th} is not as wide as in IR.

Furthermore, we have seen a significant improvement of imaging technology in the diagnostic radiology. In the 2000, slow calcium tungstate intensifying screens were replaced with faster rare-earth ones [33]. Later, during the next two decades, some of the X-ray units were digitized by the computed or the direct digital radiography. We have to bear in mind that the great majority X-ray equipment in B H has not been renewed in the 90 [34]. The technological improvement coincides with the increase in number of workers. Thus, both factors lead to the reduction of average annual doses.

Figure 4(b) shows the dose data in nuclear medicine and radiotherapy. In FB H, there are five hospitals with nuclear medicine department and four that provide the radiotherapy services. In 2009-2013 period, less than 90 individuals were associated with each of these two practices (tab. 1). The RT utilizes the medical linear accelerators and the radioactive sources to deliver high doses to a carefully selected tissue volume. While doing so, no worker is allowed in the controlled area, as the occupational doses could easily go above the threshold levels [35]. Thus, the workers in radiotherapy receive the doses lower in comparison to those received in other medical branches. Apart from the ionizing radiation transmitted through the structural shielding, the workers (usually RT technologists) are exposed to the radiation emitted by the radioactive elements induced in the treatment room by an 18 MV accelerators [36, 37]. Over the 15-year period there has been a significant trend of the average annual dose reduction amongst the radiation therapists, most likely because of the increase in number of workers (Table 1), but also because the lower number of procedures performed at telecobalt machines, which allow a certain amount of leakage radiation in 'off' position [38]. In the following years, it will be interesting to see whether the introduction of new RT techniques, such as the intensity modulated radiation therapy (IMRT) and the volumetric arc therapy (VMAT), that utilize lower photon energy, will affect the occupational dose [39].

Unlike in diagnostic radiology and radiotherapy, the workers in nuclear medicine might be exposed to the unsealed sources of ionizing radiation, which are usually in liquid form. This puts them in a risk of radioactive contamination [40]. The technetium-99m is used in 80 % of all NM procedures worldwide [41]. In 1999-2013, this percent was even higher in FB H, where no NM department owned a PET or PET-CT unit, or worked with the high activity (~3.7 GBq) of iodine-131 used in the ablation treatment of the thyroid cancer. The effective doses received by the NM workers can range widely between the different individuals, just like in the case of the IR. The highest doses are received by the staff performing the daily elution of Mo-99/Tc-99m generator. The range between 5^{th} and 95^{th} percentile was found to be 1.27 mSv during the observed 15-year period. Although the calculated average effective dose is lower in NM compared to the IR, there is no significant difference in the dose distribution between two practices over the 15-year period (Mann-Whitney *U*-test, $p = 0.071$).

Figure 4(c) provides the results of dose survey in dental and veterinary radiology from 2001 to 2013. Overall, the doses in dental radiology are slightly, but significantly, lower than the doses in general diagnostic radiology (Mann-Whitney *U*-test, $p < 0.001$), with the average of 0.315 mSv in the 15-year period compared to 0.361 mSv in DgR. However, in the latest observed period this has not been the case. While the doses in DgR decreased, the situation in DeR has not changed much. This is the only profession with no significant decrease in the individual doses in 1999-2013 period. The majority of professionally exposed dentists are self-employed and use the intraoral X-ray units that they themselves operate. Over the 15-year period no major changes happened. It will be interesting to see whether the introduction of cone beam computed tomography (CBCT) in dental practice will make significant changes in the occupational exposure in the years to come [42].

The lowest doses in FB H are associated with the veterinary radiology (tab. 2), with the average of 0.251 mSv in the observed 15-year period. This is significantly lower than the doses in the radiotherapy in the same period ($p = 0.008$).

The doses in the industry have decreased over the years, on average by 0.048 mSv per year (fig. 5). There are two possible reasons. One of them is the decline in the demand for the industrial radiography in the years after the post-war reconstruction in B H, and the other, which is more plausible – more individuals are categorized as the exposed workers and issued the dosimeters, while their doses are below 0.5 mSv per year. In 1999-2003, the number of recorded annual doses that were below 0.5 mSv in industry, was 40 or 46 %, while in 2009-2013, that number increased to 475 or 78% of the total number of annual doses evaluated in that period. Their number reached a maximum in 2011 when 138 persons were issued a dosimeter, while in 1999 only 11 had been classified as the professionally exposed persons. This trend could be seen in tab. 1, where the number N_1 is not changing over the years (approx. 10 workers with annual doses above 1 mSv), while the average annual number of individuals in industry has increased from 18 in 1999-2003 period to 121 in 2009-2013. This affects the average annual effective dose, the number distribution ratio, and the collective dose distribution ratio.

Table 3 shows how the collective dose and the collective dose distribution ratio compare to the selected countries. In 2009-2013 period, the collective dose in diagnostic radiology was 275 man mSv, which is 7 times higher than the dose in nuclear medicine, or 14 times higher than the collective dose in radiotherapy.

The finger and eye dosimeters have not been introduced. Meanwhile, we have seen the new advancements in the diagnostic and the therapeutic use of the ionising radiation. At the end of 2013, the Clinical Centre of Sarajevo University began performing the PET diagnostic procedures and the ablative radioiodine therapy [43-45]. On the other hand, the number of procedures in the interventional cardiology has been increasing ever since – in the Clinical Centre of Sarajevo University, as well as in other hospitals in B H [17]. This emphasised the need for finger and eye lens dosimeters.

CONCLUSION

During 1999-2013, no exposed worker in the FB H received a dose above the professional exposure dose limit. The maximum reported dose was 10.4 mSv for a worker in the industrial radiography. In the 15-year period, the number of TLD users has been increasing steady, with the average of 73 users per year. In total, the average annual effective dose in 2009-2013 period for all professions in FB H is 0.317 mSv. The doses received by the workers in all professions have decreased by 0.018 mSv per year on average over the 15-year period. In 2009-2013 period, the highest collective dose was reported in the diagnostic radiology, where the majority of monitored individuals work. The number of radiologists/ radiographers who received the doses above 1 mSv in 2009-2013 period dropped from 17 to only 3. The preliminary results showed that the introduction of PET-CT could give the rise to the occupational doses in nuclear medicine. The licencing of new technical services for the individual dosimetry liberalized the market, while the SRARNS became responsible for the record keeping of the dose data. The subsequent analysis should be performed on the national level, either through the SRARNS, or in cooperation with other dosimetry services in the country.

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AUTHORS' CONTRIBUTIONS

Begzada Bašić, while working for the Institute of Public Health of Federation of Bosnia and Herzegovina, performed the measurements, collected data, and maintained the database of the individual doses. A. Beganović performed the analysis of the data, created the tables and figures, and drafted the paper. A. Skopljak-Beganović and M. Gazdić-Šantić collected the doses and maintained the database of individual doses for workers in the Clinical Centre of Sarajevo University, as well as provided necessary information regarding the practices in the Nuclear medicine department. D. Damek provided the scientific support for the introductory part of the paper.

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ПЕТНАЕСТ ГОДИНА НАДЗОРА ПРОФЕСИОНАЛНЕ ИЗЛОЖЕНОСТИ ЈОНИЗУЈУЋЕМ ЗРАЧЕЊУ У ФЕДЕРАЦИЈИ БОСНЕ И ХЕРЦЕГОВИНЕ

Лична дозиметрија у Босни и Херцеговини почела је у шездесетим годинама. Након кратког прекида у деведесетим, услуге дозиметрије су се наставиле 1999. године. До 2013. године Центар за заштиту од зрачења Института за јавно здравство Федерације Босне и Херцеговине био је једина установа у држави која је пружала ову врсту услуга. У 2013. години овај Центар покривао је више од 70 % (1485) професионално изложених лица у земљи. У медицинским установама ради 95,4 % (1417), док су други изложени јонизујућем зрачењу у индустрији и ветеринарској радиологији. Од 1999. до 2013. године већина годишњих доза била је мања од 1 mSv (96,2 %), а нити један радник није примио дозу већу од 5 mSv. Нема регистрованих случаја прекорачења годишњег лимита (20 mSv). Анализа резултата показује смањење личних доза у последњих 5 година. Новоуведене технике у медицини, каква је позитронска емисиона томографија, могу довести до повећања доза у наредним годинама.

Кључне речи: професионална експозиција, дозиметрија, термолуминисцентна дозиметрија