DOSE ASSESSMENT WITH PASSIVE PERSONAL DOSIMETERS EXPOSED TO X-RAY GENERATOR USING THE ^{241}Am CALIBRATION CURVE

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Abstract. Halide film and thermoluminiscent dosimeters were exposed to the X-ray generator at the following voltages 40 kV, 80 kV, 130 kV and at 0.8 mA and 0.5 mA current intensities. The conventional true dose values were 0.51 ± 0.02 mSv and 1.06 ± 0.06 mSv. Also, the halide film and TLD dosimeters were exposed to the ^{241}Am standard source within the 0.10÷10.00 mSv dose range, in order to establish the correction between doses given by X-ray generator and those calculated with the ^{241}Am calibration curve. The work pay attention to the halide film dosimeter because its response depends significantly of parameters applied on the X-ray generator. The greatest differences between dose equivalent conventional true values and those calculated by using ^{241}Am calibration curve were recorded at low voltage and higher doses and high voltage and lower doses. The ratios between the optical densities recorded on the halide film under plastic and metallic filters of the dosimeter badge show exactly which was the voltage applied during the investigation procedure. The Plastic/Cu 1mm optical density ratios are between 7÷10 at 40 kV, over 5 at 80 kV and a little over 3 for 130 kV.

Key words: radiation quality, dosimeter, X-ray exposure, dose assessment.

1. INTRODUCTION

The occupational exposed workers from the medical or industry areas use X-ray generators applying different voltages, current intensity and metallic filters in order to obtain radiation of quality and clear images, considering the investigation reason. The radiation conditions applied for medical or industrial investigations have to be well characterized.

The international standards establish the irradiation conditions used in X-ray equipment operation and tries to solve communication problems between manufactures, user, patients and health protection authorities and occupational protection.

The working parameters: voltages, current intensity and metallic filters used by medical operator staff or X-ray industrial technicians are not always those indicated in the radiological norms. The radiological medical investigations apply a large range of voltages in investigations for diagnostic. The CEC-IEC 61267: 2006 refers to medical diagnostic X-ray equipment [1] and other standard, ISO 4037-3:1999(E) present specific conditions for the characterization of the X-ray beams used for the testing and calibrating instruments [2].

The dosimeter survey services assure radiation monitoring for persons which are occupationally exposed at different sources that emit beta, gamma and X-ray radiation. Generally, the most radiation sources with a large low energy variety are used in medical investigation fields. The passive individual dosimeters are more or less dependent on the radiation source type, more exactly on the photon energy of the source. The radiation scattering effect arise to interaction of the low energy photons with materials characterized by high atomic number.

Regarding the thermoluminescence detectors (TLD) the atomic numbers of the component elements have relatively comparable atomic numbers with air. The LiF (Mg, Cu, P) TLD has Z(Li) = 3, Z(F) = 9, Z(Mg) = 12, Z(Cu) = 29, Z(P) = 15. The TLD due to small size, high dose gradients are one of the most used detector in medicine. On the other hand, the TLD is a newer detector than the halide film and there are new papers regarding to studies on the radiation energy effects on the TLD response [3–6].

The halide film dosimeter is considerably influenced by the radiation energy or the applied voltage to the X-ray generator. The dosimeter sensitivity variation with energy is determined by the photon coefficient variation with the dosimetry probe material. The ratios between interaction coefficients of the photon with (AgX) silver halide and air are 140 and approximately equal with the unit at 30 ÷ 40 keV and higher energies respectively [7–9]. A powerful interaction of the photons with silver halide is revealed at low energies, as in the case of elements with relative high atomic number, Z(Br) = 35 and Z(Ag) = 47, the photoelectric effect is predominant and the dosimetric film sensitivity variation is significant at low energies.

The gelatin and packaging materials of the dosimetric film reduces the AgX/air photon interaction coefficient ratio to 20÷50 for low energies.

The sensitivity of the halide film with low energy radiations was approached in different ways, namely by reducing the ratio between low and high energies response of the halide film using a plastic scintillator or testing a large variation of the energies in order to obtain information about the radiation quality [7]. The film introduced into a dozimetric badge with different metallic filter gives information not only about dose but also radiation quality. So, the sensitivity variation of the halide film with low energy radiations can be an advantage or disadvantage depending on the interest of application.

The influence of the X-ray radiation on the halide film and thermoluminescente dosimeter response is presented in this work. A special attention is paid to the photodosimeter response *versus* the voltage applied on the X-ray tube of the generator. Also, the data recorded by the dosimeters are reported to the ^{241}Am calibration curve in order to obtain the dose assessment for occupational exposures with work with X-ray generators when using different voltages, current intensities and metallic filters.

2. EXPERIMENTAL PART

2.1. MATERIALS AND METHODS

The personal dosimeters used in this study were the halide film dosimeter and the thermoluminescent dosimeter. The Agfa "personal monitoring" film, that consists of a low speed film (D2) and a very sensitive film (D10), is designed to record the X, γ and β radiations over the dose range 0.1 mSv–1 Sv. The dosimeter badge made of Nuclear & Vacuum, Romania, contains a set of metallic filters of different thicknesses and a window for recording β radiations. The metallic filters are: one Al filter of 1 mm thicknesses, three Cu filters of 0.1 mm, 0.5 mm and 1.00 mm, respectively, and one Pb filters of 0.4 mm. The badge from plastic (polystyrene, 0.23 g/cm^2 density) has a 1 cm^2 area that enters directly in contact with the film; the optical density measurement data are used to calculate the doses given by the low energy radiation. The optical density is measured with the Gretag D- 200 II densitometer (Switzeland) within a range of 0.10–6.40 *optical density units* (odu). The detection limits for the halide film dosimeter are 0.1 mSv for low energy (under 200 keV) and 0.2 mSv for high energy radiation.

The TL dosimeter is a GR-200A type with LiF: Mg, Cu, P detectors. The TLD badge made of Nuclear & Vaccum Romania has polystyrene plastic filters and 0.1 mm aluminum filter, designed to record gamma radiation, and an open window for β radiations. This kind of TLDs record doses over the (0.001–100) mSv range. The process of measurement consists in the thermal annealing of the TL detector and the information display in pulses by TL reader, RA'94 type. The dose equivalent is obtained taking into consideration the calibration factor F. F is defined as the ratio of number of pulses over the conventional true value of equivalent dose usually taken as equal with 10 mSv [10]. The energy range for both dosimeter types is 30 keV–3 MeV.

The generator used is type X-STRAHL, 30÷150 kV voltage range, 0÷30 mA current intensity and maximum time of exposure 100 minutes.

Three halide film dosimetrs and three TLD were exposed to the X-ray generator at the following voltages 40 kV, 80 kV, 130 kV. The current intensities were 0.8 mA at 40 kV and 0.5 mA at 80 kV and 130 kV, respectively. The exposure was realized with the dosimeters placed on the PAMP phantom at a distance of 1 m [11]. The flow of electrons was performed in order to obtain radiation of following quality RQR2, RQR6, RQR10.

Table 1 presents the measurement conditions used in the experiment. The conventional true values of the dose equivalent were measured with the Eberline FH 40 GL 10 dose ratemeter. The blank film of the experimental lot was 0.42 ± 0.02 odu. The conventional true dose values were 0.50÷0.53 mSv and 1.02 ÷ 1.14 mSv with < 3% uncertainty.

Also, the three or five halide film dosimeters and TLD were exposed to the ^{241}Am standard source at values of doses within the 0.10÷10.00 mSv range, in order to establish the difference between doses given by X-ray generator and those calculated with the ^{241}Am calibration curve.

The experimental data were performed at the secondary standard laboratory for radiation metrology, testing and dosimetry from Horia Hulubei, National Institute for R&D in Physics and Nuclear Engineering, IFIN-HH.

2.2. RESULTS AND DISCUSSIONS

The conventional true values of the doses and the data obtained by the measurements of the optical density on the film under badge filters are presented in Table 2. Each five optical density measurements were performed on each area drawn on the film by the filters. In case of low energies (low voltages) and low doses, the results measured under plastic filter are relevant. At 40 kV and 0.53 mSv the optical densities measured on the film under Cu 1mm and Pb 0.4 mm are with at most 0.03 optical density unites more than the blank film of the experimental lot. At 80 kV and more the measurements made on the film under Cu 1 mm and Pb 0.4 mm are relevant also for the low doses.

For a dose of 0.51 ± 0.02 mSv, at all three voltages, the optical density varies significantly between 3.17 ± 0.01 and 3.71 ± 0.01 in case of plastic filter. Regarding the D2 film, small variations of optical densities conduct to a high variation of doses, especially at the low limit of detection.

The maximum energy of the photon beam is considered to be the same with the voltage applied on the X-ray generator. A photon beam with the same energy is expected to be obtained by using metallic filters.

The relative standard deviations of the optical densities measured on the film under dosimeter filters were below ± 5.1 % and ± 0.31% under plastic filters.

Table 1

Experimental conditions considered in the irradiation process

Voltage [kV]	Radiation quality	Intensity [mA]	Hp(10)c.v [mSv], for Film	Hp(10)c.v [mSv], for TLD
40	RQR2	0.8	0.53	0.53
40	RQR2	0.8	0.53	0.51
40	RQR2	0.8	1.03	0.95
40	RQR2	0.8	1.02	0.96
80	RQR6	0.5	0.52	0.52
80	RQR6	0.5	0.52	0.5
80	RQR6	0.5	1.13	1.13
80	RQR6	0.5	1.13	1.14
130	RQR10	0.5	0.48	0.5
130	RQR10	0.5	0.49	0.5
130	RQR10	0.5	1.06	1.06
130	RQR10	0.5	1.07	1.06

Hp(10)c.v – tissue dose equivalent, conventional true value, uncertainty below 3%.

In case of halide film dosimetry the radiation energy have a significant contribution in the radiation dose assessment. As it can be seen in Table 2, the dose assessment is difficult only with the data about optical densities. The ratio between the optical densities recorded on the film under plastic and metallic filters give information about radiation energy or the voltage applied on X-ray generator, as presented in Table 3. The most relevant results are obtained by studying the optical density ratios: Plastic/Pb 0.4 mm and Plastic/Cu 1 mm. The optical density ratios are very distinct for those three voltages considered in the experiment. The highest values are recorded at low energy. The Plastic/Cu 1mm ratio shows exactly what kind of voltage was applied. The Plastic/Cu 1mm ratios are between 7÷10 at 40 kV, over 5 at 80 kV and a little over 3 for 130 kV.

Table 2

Halide film dosimeter response at different voltage of the photon beam

Emax (keV) U (kV)	*Hp(10)c.v (mSv)	Optical density													
		Plastic 1 mm		Window		Al 1 mm		Cu 0.1 mm		Cu 0.5 mm		Pb 0.4 mm		Cu 1 mm	
		D10	D2	D10	D2	D10	D2	D10	D2	D10	D2	D10	D2	D10	D2
40	0.53	3.2	0.18	3.16	0.18	2.36	0.18	1.55	0.15	0.57	0.14	0.45	0.14	0.43	0.14
40	0.53	3.17	0.18	3.11	0.18	2.44	0.18	1.48	0.15	0.56	0.14	0.44	0.14	0.43	0.14
80	0.52	3.71	0.21	3.65	0.22	2.56	0.19	2.77	0.16	1.25	0.14	0.57	0.14	0.71	0.14
80	0.52	3.69	0.19	3.73	0.2	3.01	0.19	2.48	0.17	1.19	0.14	0.57	0.14	0.64	0.14
130	0.48	3.53	0.19	3.51	0.2	2.92	0.19	2.59	0.16	1.65	0.17	0.73	0.14	1.09	0.14
130	0.49	3.59	0.25	3.53	0.25	2.88	0.24	2.56	0.21	1.91	0.16	0.82	0.14	1.11	0.15
40	1.03	4.68	0.21	4.65	0.23	3.53	0.21	2.32	0.17	0.78	0.14	0.48	0.14	0.46	0.14
40	1.02	4.67	0.22	4.58	0.23	3.2	0.2	2.49	0.17	0.68	0.14	0.44	0.14	0.44	0.14
80	1.13	5.3	0.26	5.2	0.27	4.26	0.25	4.04	0.21	1.85	0.17	0.71	0.14	1.06	0.14
80	1.13	5.4	0.26	5.2	0.27	3.59	0.24	3.69	0.2	1.98	0.17	0.74	0.14	0.95	0.14
130	1.06	5.4	0.25	5	0.26	3.6	0.24	4.12	0.21	2.64	0.17	1.06	0.14	1.56	0.15
130	1.07	5.1	0.25	5.2	0.25	3.4	0.24	4.2	0.21	2.77	0.17	1.08	0.14	1.62	0.15

Table 3

Optical density ratios for various filters, at different maximum energies of the photon beam

Emax (keV) U (kV)	Hp(10)c.v (mSv)	Optical densities ratio											
		Plastic/window		Plastic/ Al 1 mm		Plastic/ Cu 0.1 mm		Plastic/ Cu 0.5 mm		Plastic/ Pb 0.4 mm		Plastic/Cu 1 mm	
		D10	D2	D10	D2	D10	D2	D10	D2	D10	D2	D10	D2
40.00	0.53	1.01	1.00	1.36	1.00	2.06	1.20	5.61	1.29	7.11	1.29	7.44	1.29
40.00	0.53	1.02	1.00	1.30	1.00	2.14	1.20	5.66	1.29	7.20	1.29	7.37	1.29
40.00	1.03	1.01	0.91	1.33	1.00	2.02	1.24	6.00	1.50	9.75	1.50	10.17	1.50
40.00	1.02	1.02	0.96	1.46	1.10	1.88	1.29	6.87	1.57	10.61	1.57	10.61	1.57
80.00	0.52	1.02	0.95	1.45	1.11	1.34	1.31	2.97	1.50	6.51	1.50	5.23	1.50
80.00	0.52	0.99	0.95	1.23	1.00	1.49	1.12	3.10	1.36	6.47	1.36	5.77	1.36
80.00	1.13	1.02	0.96	1.24	1.04	1.31	1.24	2.86	1.53	7.46	1.86	5.00	1.86
80.00	1.13	1.04	0.96	1.50	1.08	1.46	1.30	2.73	1.53	7.30	1.86	5.68	1.86
130.00	0.48	1.01	0.95	1.21	1.00	1.36	1.19	2.14	1.12	4.84	1.36	3.24	1.36
130.00	0.49	1.02	1.00	1.25	1.04	1.40	1.19	1.88	1.56	4.38	1.79	3.23	1.67
130.00	1.06	1.08	0.96	1.50	1.04	1.31	1.19	2.05	1.47	5.09	1.79	3.46	1.67
130.00	1.07	0.98	1.00	1.50	1.04	1.21	1.19	1.84	1.47	4.72	1.79	3.15	1.67

The ^{241}Am standard source activity was 6.5×10^3 MBq with a dose rate at 1 m distance of 174 μSv/h without phantom and 187 μSv/h on phantom. In Table 4 there are presented the dose measured with TLD and halide film dosimeter exposed on the PAMP phantom to the same dose conventional true values, at various values of the $Hp(10)_{c.v}$ [mSv], obtained from the ^{241}Am standard source.

The optical densities measured on the D10 and D2 films under plastic were taken into account. The dose equivalent was calculated with sigmoidal and linear curves established for D10 and D2 films [12].

Table 4

The dose recorded with TLD and film dosimeter by exposure to ^{241}Am standard source

Hp(10)c.v [mSv]	Hp(10) Dose calculated ± SD [mSv]		
	TLD	Film	
		D10 Sigmoidal curve Plastic filter	D2 Linear curve Plastic filter
0.1	0.09 ± 0.003	0.10 ± 0.01	–
0.5	0.48 ± 0.02	0.48 ± 0.005	0.57 ± 0.07
1.0	0.97 ± 0.08	1.08 ± 0.02	0.92 ± 0.07
2.0	1.83 ± 0.03	1.39 ± 0.41	1.98 ± 0.005
5.0	4.6 ± 0.36	–	4.85 ± 0.20
7.5	6.24 ± 0.30	–	6.75 ± 0.42
8.73		–	7.96 ± 0.65
10.0		–	10.07 ± 0.13

$U_{sigmoidalfit}$ D10 = 5.8 %; $U_{linearfit}$ D2 = 2.3 %; $Hp(10)_{c.v}$ uncertainty below 3%.

The low doses are recorded with high accuracy by TLD dosimeter. The D10 high sensitive film can record doses under plastic filter until 1.00 mSv. After this dose, the optical density reaches saturation state of 5.2 ÷ 6.4 optical density units such us in the case 2.0 mSv the error of measurement is 30%. Due to physico-chemical structure, the filters of Cu 1mm and Pb 0.4 mm allow the measurement of higher doses even by the D10 film. The doses higher than 1.00 mSv can be calculated with good accuracy using the D2 linear curve.

In Table 5, the deviations of the measured from c.v. dose values are presented; the TLD doses where calculated with the calibration factors (F), F1 = 31600 imp/mSv obtained by TLD calibration to ^{137}Cs standard sources from standard secondary laboratory for radiation metrology, testing and dosimetry, IFIN – HH. The deviations, are under 17 % for TLD.

Also, in Table 5 are presented the doses calculated taking into account the optical densities measured on film under plastic filter and using the dose *versus* optical density mathematic equation which fits the ^{241}Am standard curve.

The standard deviations for doses calculated on D10 films by ^{241}Am standard curve are between ± 0.17% and ± 7.5 %. The doses assessment by the ^{241}Am standard curve and recorded by halide film dosimeter in different X-ray irradiation conditions have a maximum deviation of 21%.

At low voltage, 40 kV, and higher doses the calculated doses are under those assessed. At high voltage, 80 kV and 130 kV, the calculated doses are higher than conventional dose values.

The National and European Norms for personal dosimetry [13, 14] impose that the individual dosimeter response regarding the energy dependence has to follow the trumpet curve rule, where the R_u, upper limit and R_l, lower limit allowed for the ratio between measured or calculated dose and conventional true value of the dose were calculate with (1) and (2) equations.

Table 5

Dose assessment recorded by TLD and photodosimeter

Emax (keV) U [kV]	Hp(10) TLD, ^{137}Cs [mSv]			Hp(10) [mSv] Photodosimeter calculated by using the ^{241}Am standard curve		
	Hp(10)c.v [mSv]	Hp(10) m [mSv] ± SD%	[Hp(10) m-Hp(10)c.v]/ Hp(10)c.v %	Hp(10)c.v [mSv]	Hp(10) [mSv] ± SD%	[Hp(10) m-Hp(10)c.v]/ Hp(10)c.v %
40	0.53	0.55 ± 0.42	3.77	0.53	0.52 ± 0.39	–1.89
40	0.51	0.50 ± 0.52	–1.96	0.53	0.51 ± 0.35	–3.77
40	0.95	1.11 ± 0.75	16.84	1.03	0.85 ± 0.83	–17.48
40	0.96	1.07 ± 1.05	11.46	1.02	0.85 ± 0.28	–16.67
80	0.52	0.63 ± 1.06	15.38	0.52	0.62 ± 0.32	19.23
80	0.50	0.60 ± 2.32	10.00	0.52	0.62 ± 0.26	19.23
80	1.13	1.31 ± 0.85	15.93	1.13	1.07 ± 5.71	–5.31
80	1.14	1.28 ± 0.55	12.28	1.13	1.11 ± 7.48	–1.77
130	0.50	0.66 ± 1.02	16.00	0.48	0.58 ± 0.34	20.83
130	0.50	0.65 ± 1.22	14.00	0.49	0.59 ± 0.17	20.41
130	1.07	1.15 ± 3.20	7.48	1.06	1.10 ± 5.99	3.77
130	1.06	1.20 ± 1.02	13.21	1.07	1.00 ± 1.80	–6.54

$$R_u = 1.5\left(1 + \frac{H_0}{2H_0 + H_{c.v.}}\right) \quad (1)$$

$$R_l = \frac{1}{1.5}\left(1 - \frac{2H_0}{H_0 + H_{c.v.}}\right). \quad (2)$$

In equations (1, 2) H_0 is the smallest dose value that can be measured with individual dosimeter and $H_{c.v}$ is $Hp(10)_{c.v}$.

The (2) equation is used when the $Hp(10)_{c.v}$ is higher or equal with calculated dose. In case when the Hp(10)c.v is lower than the calculated dose, the R_l is considered zero.

In Tables 6a and 6b there are presented the ratios Hm/Hc.v ratio between upper and low limits for photodosimeter and TL dosimeter, respectively, calculated from data of Table 5, as compared with the allowed Ru and Rl limits.

The photodosimeter response regarding the dose calculated by ^{241}Am standard curve is situated between these two limits. The Hm/Hc.v ratio is closer of upper limit due to the over estimation of the dose measured at 80 kV and 130 kV *versus* the conventional true values at low doses exposure.

Table 6a

Photodosimeter response limits at low energies

Emax [keV] U [kV]	$Hp(10)_{c.v}$ [mSv]	Hp(10) [mSv] calculated D10 film ± SD %	Upper limit R_u	Low limit R_l	Hm/Hc.v
40	0.53	0.52 ± 0.39	1.71	0.45	0.98
40	0.53	0.51 ± 0.35	1.71	0.45	0.96
40	1.03	0.85 ± 0.83	1.62	0.55	0.83
40	1.02	0.85 ± 0.28	1.62	0.55	0.83
80	0.52	0.62 ± 0.32	1.71	0.00	1.19
80	0.52	0.62 ± 0.26	1.71	0.00	1.19
80	1.13	1.07 ± 5.71	1.61	0.56	0.95
80	1.13	1.11 ± 7.48	1.61	0.56	0.98
130	0.48	0.58 ± 0.34	1.72	0.00	1.21
130	0.49	0.59 ± 0.17	1.72	0.00	1.20
130	1.06	1.10 ± 5.99	1.62	0.00	1.04
130	1.07	1.00 ± 1.80	1.62	0.55	0.93

Table 6b

TLD response limits at low energies

Emax [keV] U [kV]	Hp(10)c.v [mSv]	Hp(10) [mSv] calculated TLD ± SD%	Upper limit R_u	Low limit R_l	Hm/Hc.v
40	0.53	0.55 ±0.42	1.53	0.00	1.04
40	0.51	0.50±0.52	1.53	0.64	0.98
40	0.95	1.11±0.75	1.52	0.00	1.17
40	0.96	1.07±1.05	1.52	0.00	1.11
80	0.52	0.63±1.06	1.53	0.00	1.15
80	0.50	0.60±2.32	1.53	0.00	1.10
80	1.13	1.31±0.85	1.51	0.00	1.16
80	1.14	1.28±0.55	1.51	0.00	1.12
130	0.50	0.66±1.02	1.53	0.00	1.16
130	0.50	0.65±1.22	1.53	0.00	1.14
130	1.07	1.15±3.20	1.51	0.00	1.07
130	1.06	1.20±1.02	1.51	0.00	1.13

The results obtained through measurement of the pulse release by TL detectors exposed at different voltage and using F calculated for the ^{137}Cs standard source are over estimated for all voltage values.

3. CONCLUSIONS

The photodosimeter and TL dosimeter responses to different voltage values applied on the X-ray generator were studied in this work. The halide film detector is significantly influenced by photons of low energies even if the doses of exposure are small. The optical density ratios, more exactly Plastic/Cu 1.00 mm ratios, can be used to assess the voltage applied on X-ray generator or the energy of the photons.

The calculated doses using ^{241}Am calibration curve are within the limits allowed by NSR 06 individual dosimetry rules and ICRU Report 47 but the information about the photon energy improve the dose assessment accuracy.

Comparing with TL dosimeter, the photodosimeter gives clear information about irradiation conditions, refer to voltage applied on X-ray generator or the energy of the photons.

Taking into consideration results obtained with LiF: Mg, Cu, P, GR-200A type, a more number of experimental data regarding TLD response dependence of low energy radiation would be necessary for the factor correction calculation.

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