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RADIOPROTECTION AND DOSIMETRY

EXPECTED PERFORMANCES AND PRACTICAL ASPECTES IN PERSONAL DOSES MEASURED BY HALIDE FILMS (PHOTODOSIMETERS)

F. MIHAI, A. STOCHIOIU

Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, IFIN-HH
POB MG–6, code: 077125, Bucharest, Romania
E-mail address: fmihai@nipne.ro

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Abstract. This work aims to point out the influence of the halide film background optical density growth on the radiation dose measurement and suggests some solutions to solve it. A high background optical density affects the image quality obtained on the film after radiation exposure and more than this influences both dose measurement accuracy and sensitivity of the detector. This work presents the dose response of the halide film with high background optical densities. In this respect, four film batches with the following background optical densities: 0.37 ± 0.07; 0.43 ± 0.09; 0.50 ± 0.01 and 0.78 ± 0.16, respectively, optical density, dimensionless, were irradiated at a ^{137}Cs calibration source, at different values of equivalent personal dose, from 0.1mSv - 100 mSv range. It was found that the sensitivity of the film is getting down with the growth of the background optical density. In order to fit the dosimeter film response, optical density function of dose, a new algorithm of data fitting has been tested and successfully applied in our laboratory. Using this calibration relationship, the calculated doses within the dose interval: 0.1 mSv to 100 mSv had differences (residual values) from the reference value of (–7.9% ÷ +10%) for the first batch of films and within 0.2 mSv to 40 mSv with differences (residuals) between –6% ÷ 10% for the fourth film batch.

Key words: photodosimeter, halide film, personal dose, radiation measurement, optical density, sensitivity.

1. INTRODUCTION

Radiation monitoring in for individual protection is performed by different dosimeter systems. For each type of dosimeter there are different problems regarding measurement accuracy of the radiation doses. Dose estimates are made by adjusting the exposure record of each facility using dosimeter characteristics and specific bias factors of the facility. The dosimetry with halide film continues to be one of the most used methods for estimation of doses from medical exposure, in many large diagnostic imaging departments for patients undergoing radiological medical procedure, for occupationally exposure monitoring [1–4] or used as comparing method with other new personal dosimeter types [5–7]. Many factors have been reported to influence film dosimeter accuracy and sensitivity: incident photon energy, different halide film type, dosimeter badge type, exposure geometry, calibration methods etc. [8–12], or errors due to the mode of use of film dosimeter [13–14]. Some papers report methods of data processing recorded by halide film dosimeter [2, 15]

The problems treated in this paper come from some practical aspects. Photodosimetry Survey Unit – USF, from IFIN-HH, performs personal monitoring with halide film made by Agfa Geveart, Belgium. Each lot of films has to be tested/ calibrated according to laboratory procedures and rules of quality and Romanian Radioprotection Survey Requirements [16-18] and this implies time and additional expenses. Generally a number of films were imported to cover needs over a period of 6–10 months, taking into consideration the fact that the halide film has a 12 months warranty period. The main limitation of the halide film is susceptibility to change the background optical density relatively fast. Optical density influences the dose measurement accuracy, dosimeter sensitivity (limit of detection) and image quality. There are three primary reasons for which film changes its background optical density: normal ageing, storage conditions (ambient conditions: temperature, humidity) and film chemical processing. Halide film dosimetry is a quantitative method of radiation dose calculation. AgX silver halide particles (generally, AgBr is used in dosimeter photoemulsion) which contain a certain numbers of Ag atoms, latent image centres, are progressively reduced by the developer solution. Without latent image centres due to film exposure to radiation, particular AgX particles could be grown from sensitivity centres to development centres by film ageing process. The AgX grain decreasing in the photographic emulsion is a solution to slow down the ageing process, but the method has a negative impact on the film sensitivity, mainly in the small dose range.

The dosimeter film is used to record occupational doses of radiation over one month. In this period the ambient conditions in nuclear laboratories are different to the standard storage conditions of the film: t of 20°C and $\leq$ 50% humidity. Environmental conditions hurry the background optical density increase, even if the films are kept in conditions specified by the manufacturer [19]. The optical density increase varies from a film batch to other. Also, it is possible that the film which is kept as control sample in the nuclear laboratory, used to record the ambient condition influence on the photographic emulsion, has sometimes a higher optical density than the control film from the dosimetry laboratory. Or, possibly, the monitored person works in difficult environmental conditions: high temperature, high humidity etc. Thus, the dosimeters could be exposed for prolonged periods at elevated temperature and low or high humidity without exposure to ionizing radiation. The pattern on the film due to metallic filters of the badge makes the difference between dose and an inexplicable increasing of the optical density.

The dose recorded by a film with high background optical density and its assessment on a calibration curve with low background optical density can be assessed with high errors. The diminution of the negative reasons which contribute to film optical density growth and the particular treatment of these are necessary. Calibration of the film batches at different time periods solves the problem of density growth due to natural ageing and film storage conditions. The drawbacks arise from the chemical processes of film development which could concur to the optical density increase and which cannot be eliminated by film batch calibration method. It is necessary to use an algorithm to determine with a good accuracy the effect of the optical density growth on the dose assessment. Calibration relationship is a quantitative expression between the optical density measured on the film and the radiation dose. In the current paper the influence of the background optical density on the small values of the equivalent personal dose, Hp(10), and the relationship between the dosimeter response and reference dose, were taken into consideration. In view of solving these aspects, the following studies have been performed: i) dosimeter film response fitting by mathematical equation used in the dosimetry laboratory USF – Photodosimetry Service Unit; ii) calculation of differences from reference (residual) values, R(%), and repeatability check and iii) correction of the background optical density growth due to the natural ageing, unwanted chemical reactions which might happen during the development process or to the ambient conditions, defined as the optical density measured on the film before processing of the dosimeter film calibration by exposure to radiation.

2. MATERIALS AND METHODS

2.1. DOSIMETER SYSTEM

The dosimeter film system used in the experiment consists in: FD–III–B plastic badge produced by Nuclear & Vacuum, Romania; Agfa personal monitoring film, Geveart, Belgium, and Gretag D200-II optical densitometer device. The Dosimeter badge has five Al, Cu, Pb metallic filters of different sizes and thicknesses, a polymer filter and an open window for β–rays. The filter pattern recorded on the film due to radiation exposure of the dosimeter film allows recognition of the type and energy of radiation: low or high energy. The Personal monitoring Agfa film consists of a double–coated, low speed, high contrast film (D2) and a double coated, very sensitive, high contrast film (D10). The optical density is read with the Gretag D200-II optical densitometer device. The dosimeter system is specifically designed to record X, gamma and beta radiations over the (0.1–1000) mSv dose range, with energy interval from 29 keV to 3 MeV. In the present work the experimental data measured on the D10 film under the Cu 1 mm filter and plastic filter of the FD–III–B badge was considered. Generally, occupationally exposed workers record small doses of radiation. The D10 film records low doses from 0.1 – 0.2 mSv to 10 mSv, up to maximum 100 mSv, depending on radiation energy, X or gamma rays.

2.2. HANDLING CONDITIONS

Four film batches, L1, L2, L3 and L4, have been used in this experiment. The films have been stored in the same conditions of temperature, humidity and environment radiation background: 19°–25°C, ≤ 50%, < 90 nGy/h. The film batches L1, L2, L3, L4 were exposed to radiation after four, six, eight and ten months of storage aiming to obtain batches of films with different background optical densities, reproducing approximately the real storage intervals. The film batches were irradiated and chemically developed in the same chemical and physical conditions.

The experimental data employed in this work were obtained by IFIN–HH, USF lab. The photodosimeters were exposed to a ^{137}Cs standard radiation source. The calibration procedure was carried out according to national and international standards (16, 18). Each five film dosimeters set, laying on a $40 \times 40 \times 40$ cm^3 solid water phantom, were exposed to radiation at different dose values from 0.1 mSv – 100 mSv range. The measurement uncertainty of Hp(10), conventional true value, certified by the secondary calibration laboratory from IFIN-HH, is ± < 3%.

The chemical processing of films was performed satisfying the Agfa manufacturer instructions and the procedures issued by the dosimetry lab (USF). The D10 film is more affected by the phenomenon of increasing of the optical density, so, the background optical density on D10 film was established. Ten films from each batch were randomly taken and developed in the same physical and chemical conditions. On each D10 film a number of 10 readings of the optical density were performed and for those four lots of films, L1, L2, L3 and L4, the following optical densities were established: 0.370 ± 0.007; 0.430 ± 0.009; 0.50 ± 0.01 and 0.78 ± 0.02 respectively, at 95% confidence level.

During the chemical processing of the irradiated films, reference films were used, in order to confirm that increases of the optical density due to unwanted chemical reactions from development baths were not recorded. The optical densities were performed with a maximum uncertainty of ± 0.02 density unit.

2.3. CALIBRATION RELATIONSHIP

The calibration relationship should be capable to adjust the dosimeter film response on a large dose range with very small residual values. The dosimeter film response *i.e.* optical density *vs*. dose can be graphically represented on a linear or semi-logarithmical scale and fitted with different mathematic relationships. In this work it was used for the first time a new equation for fitting of the photodosimeter response. So, the experimental data obtained on the L1–L4 lot D10 films were graphically represented on semi-logarithmical scale and fitted by Sigmoidal Weibull function, type 2, SWeibull, bellow presented and used to describe various behavioral phenomena (20).

$$y = a - \left(a - b\right) \cdot \exp\left(-\left(k \cdot x\right)^{d}\right), \tag{1}$$

where: y – are optical densities corresponding to x dose registered values, H_{m}; a – is the maximum value of the optical density recorded by the film; b – is the optical density recorded by the film for a traceable minimum dose value; k and d – are constants and particularly for each lot of films move the sigmodal curve to the right or to the left, depending of film speed and its background optical density.

Each film batch, L1–L4, was fitted by the equation presented above and the specifically constant parameters *a, b, k* and *d* were calculated. Dose residual value R(%) was calculated as follows:

$$R\left[\%\right] = 100 \cdot \frac{\left(H_m - H_r\right)}{H_r}, \tag{2}$$

where H_r is the conventional true value of Hp(10) dose and H_m is the measured dose, calculated by eq. (1).

The root-mean-square residual of the dose value, u_{fit}, arising from the calibration relationship was calculated for each batch by the mathematical relation:

$$u_{fit} = \left[\frac{\left(\sum R[\%]\right)^2}{n}\right]^{\frac{1}{2}}, \tag{3}$$

where n is the total number of data points in the calibration relationship. For each point of dose were used five dosimeters and on each film exposed to radiation three readings were made, such that n is greater than 100.

2.4. CALIBRATION RELATIONSHIP PLANNING VERIFICATION

Generally, this calibration relationship is valid for a specific batch of films. For verifying the repeatability of the calibration relationship, another film batch, L5, with (0.45±0,01) optical density (Agfa manufactured), was irradiated and chemically processed in the same conditions with the L1–L4 film batches. The repeatability of the film dosimeter response was tested in the low dose range, so the L5 films were irradiated at the following conventional dose true values, H_r: 0.1 mSv; 0.2 mSv; 0.5 mSv; 1.00 mSv; 1.97 mSv. The theoretical doses for the L5 films were calculated by the particular calibration relationship of the lot with the appropriate optical density, L2 respectively.

So, the dose value deviation measured in the routine test, H_m, related to the conventional dose true value – reference dose, H_r, should be between the low and upper limits, R_l and R_u, calculated by trumpet curves, relations (4) and (5), [18].

$$R_u = 1.5\left(1 + \frac{H_0}{2H_0 + H_r}\right), \tag{4}$$

$$R_l = \frac{1}{1.5}\left(1 - \frac{2H_0}{H_0 + H_r}\right), \text{ for } H_r \geq H_m, \tag{5}$$

where $R_l = 0$ for $H_r < H_m$; H_0 – the lowest dose that can be measured by the film.

3. RESULTS AND DISCUSSIONS

Equation (1) can be used to fit the optical density values measured on the film, after radiation exposure, on each pattern specific for each filter of the badge. The fitting of experimental data obtained by the measurement of the optical densities on all four batches of D10 films, under the Cu 1 mm metallic filter of the FD–III–B badge, is graphically presented in Fig. 1. To obtain a small residual value, the film batches were fitted on different dose ranges.

From a qualitative view point, higher differences among these three films batches with appropriate optical densities appear when recording low doses. Obviously, in higher dose range, over 3 mSv, the differences are more mitigated. The films with low background optical density are getting darker faster, so the optical density grows much faster in relation to dose than the lot of films with lower background optical density. The forth film batches had a special behavior in the range from 0.1 mSv to 100 mSv by comparison with the behavior of the other three batches with smaller background optical densities.

The mathematical calibration relationships (1) made possible the fitting of the four film batches which are used for the quantitative analysis of the film dosimeter dose response at different background optical densities, as presented in Fig. 1.

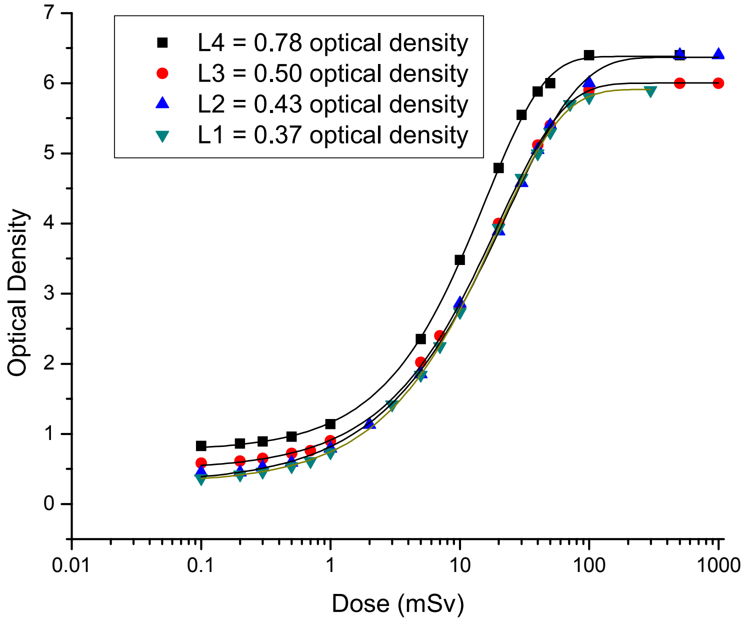

Fig. 1 – Data fitting recorded by passive detector with halide film limited of high background optical density.

The calibration relationship validity was analyzed. Table 1 presents the residual values between the conventional dose true value and the theoretical dose calculated by mathematic equations, (1), and the root-mean-square residual (u_{fit}) values for each lot L1–L4.

Table 1

Residual values calculated on each dose-response value of the dosimeter film

H_{r}	H_{m},L1	R%, L1	H_{m}, L2	R%, L2	H_{m}, L3	R%, L3	H_{m}, L4	R%, L4
0.10	0.11	10	0.19	90	0.16	59	0.15	50
0.20	0.21	5.0	0.19	-5.0	0.22	10	0.22	10
0.30	0.29	-3.3	0.32	6.0	0.31	3.3	0.30	-1.0
0.50	0.47	-6.0	0.46	-8.4	0.48	-4.0	0.47	-6.0
0.70	0.65	-7.9	-	-	0.69	-1.9	0.70	0
1.00	0.99	-1.4	0.93	-7.4	0.96	-4.0	0.95	-5.5
2.00	-	-	1.91	-4.5	-	-	-	-
3.00	3.22	7.3	-	-	-	-	-	-
5.00	4.96	-0.80	4.72	-5.6	5.22	4.4	4.90	-2.1
7.00	6.96	-0.60	-	-	7.17	2.4	-	-

Table 1 (continued)

10.00	9.81	-1.9	10.57	5.7	9.63	-3.7	10.12	1.2
20.00	20.12	0.60	20.01	0.05	19.94	-0.30	20.02	0.10
30.00	30.67	2.2	29.97	-0.10	-	-	31.04	3.5
40.00	38.75	-3.1	40.04	0.10	40.14	0.35	39.78	-0.55
50.00	49.04	-1.9	50.86	1.7	50.19	0.38	44.55	-11
71.20	78.01	9.6	-	-	-	-	-	-
100.00	96.38	-3.6	88.04	-12	100.51	0.51	-	-
u_{fit}		5.1		5.0		4.1		5.5
n		16		11		11		10

The calibration relationship fits the film dosimeter dose response with a good accuracy. The L1 film lot characterized by a low background optical density records doses over a large dose range: (0.1–100) mSv with residual values under 10%.

The highest residual values were obtained within the 0.1 mSv–0.2 mSv doses range and over 50 mSv, mostly in the case of high background optical density film batches. The range of dose measurements becomes narrower especially in case of L4 lot where one can observe that high variations in the optical density determine small dose variations. Table 2 presents the doses measured by equation (1) for two optical units, 2 and 3, on the curves from Figure 1, of each film batch corresponding to each dose response curve.

Table 2

Background optical density influence on dosimeter film sensitivity

Optical density	Dose (mSv) measured on each film lot ± standard error of the fitting equation			
	L1	L2	L3	L4
2	5.70 ± 0.45	5.43± 0.43	5.13± 0.20	3.61± 0.13
3	11.6 ± 0.23	11.6 ± 0.66	10.9± 0.40	7.66± 0.19

A background optical density increase by 35% (see L1 and L3 difference background optical density) leads to a dose assessment with less 10% (0.57 mSv) at 2 optical density units and of 5.6% (0.65 mSv) at 3 optical density units. High differences arise between L1–L3 and L4 doses. The background optical density of L3 lot is bigger with 0.13 optical density units than L1 lot. Simply, it is considered that the increase of optical density due to radiation exposure is overlapping the background optical density. In this respect the density value recorded by L3 high background optical density film at a special dose, was diminished artificially with 0.13 optical density units. Also, the optical densities recorded by L4 film at each doses are getting lower with 0.41 optical density units than the real value. Next, the doses recorded by L3 and L4 films are assessed on L1 dose response curve; the results are presented in Table 3, column 2 for L3 lot and in column 4 for L4 lot.

Table 3

Dose rate recorded by a high background density film and assessed, after the correction of optical density, on a low background density dose-response curve

H_r	H_m L3 corrected by L1	R%	H_m L4 corrected by L1	R%
0.1	0.27	170	0.21	110
0.2	0.33	65	0.27	35
0.3	0.428	43	0.337	12
0.5	0.595	19	0.498	-0.40
0.7	0.695	-0.71	0.72	2.9
1	1.06	6.00	0.959	-4.1
5	5.187	3.7	5.41	8.2
7	7.06	0.86	8.05	15
10	9.43	-5.70	12.08	21
20	19.33	-3.4	26.01	30
30	-	-	43	43
40	38.47	-3.8	57.7	44
50	47.78	-4.4	66.33	33
100	89.47	-11	-	-

After optical density correction, the doses measured by L3 film and assessed on L1 calibration curve are closer to H_r, on the 0.7–50 mSv dose range. In case of L4 film its response tends to the real dose, *i.e.* the R(%) is under 10% only on 0.5–5 mSv dose range. Above 5 mSv, the L4 film is recording the dose more and more slowly. At de same dose, L4 film records an optical density much greater than L3 film. It might have been expected that along with the dose increase the shape of L4 dose response curve is getting closer to L1–L3 set curves, because most of the AgX centers in photographic emulsion became latent image centers as a result of higher radiation exposure. Generally, the high background optical density influences especially the accuracy of low dose measurement as the case of L1–L3 film lots. A very high background optical density (L4 batch) influences not only low doses, but also high doses.

In order to check the equation (1) and to ensure that the dose measured by a film with a particular optical density can be measured again by another film with the same background optical density even if it belongs to different batches, the calibration relationships characteristic to the L2 lot for plastic filter were used to calculate the H_m recorded by L5 film lot. Taking into consideration the requirements regarding the condition of the routine measurements, the deviation of the dose value measured under routine condition, H_m, from the set point H_r must be within the limits fixed by the trumpet curves [18]. Table 4 presents the residual value for the doses recorded by L5 and the ratio H_m/H_r. One can see that the ratio H_m/H_r is the intended one. At each dose values, a number of 2–3 unscreened photodosimeters from L5 film lot were exposed, such as presented in Table 4.

Table 4

The ratio H_m/H_r values for D10 film L5 lot

Nr. Photo-dosimeter	H_r (mSv)	H_m (mSv)	R_l	R_u	H_m/ H_r	R (%)
1	0.1	0.11	0	2	1.1	- 10
2	0.1	0.07	0	2	0.7	30
3	0.1	0.11	0	2	1.1	- 10
4	0.2	0.23	0.22	1.87	1.15	- 15
5	0.2	0.206	0.22	1.87	1.03	- 3.0
6	0.2	0.206	0.22	1.87	1.03	- 3.0
7	0.3	0.28	0.33	1.8	0.93	6.7
8	0.3	0.28	0.33	1.8	0.93	6.7
9	0.5	0.52	0.44	1.7	1.04	- 4.0
10	0.5	0.55	0.44	1.7	1.10	- 10.
11	0.5	0.52	0.44	1.7	1.04	- 4.0
12	0.7	0.64	0	1.66	0.91	8.6
13	0.7	0.61	0	1.66	0.87	13
14	0.7	0.69	0	1.66	0.99	1.4
15	1	1.09	0.54	1.62	1.09	- 9.0
16	1	1.09	0.54	1.62	1.09	- 9.0
17	1	0.94	0	1.62	0.94	6.0
18	1.97	2.1	0.6	1.57	1.07	- 6.6
19	1.97	2.1	0.6	1.57	1.07	- 6.6

The H_m recorded by L5 lot is calculated with a good accuraty considering that the u_{fit} for L2 is 5.0% and the conventional true value is given by a 3% uncertainty. For film lots with the same optical density, the same calibration relationship may be used. However, in the low dose range, below 0.2 mSv, the R(%) is over 10%.

4. CONCLUSIONS

A high background optical density affects the dose assessment especially in low dose range. The consequence is that, unfortunately, for the dosimetry services, the film lots have to be taken in amounts so to be consumed in relatively short time, because a dose recorded by a film with high background optical density and assessed on a curve characterized by a low background optical density can be performed with high errors. If the workers, from various reasons (environmental conditions at workplace or storage conditions of the film dosimeter etc), have been monitored by films with high background optical density, it is necessary to use corrections in order to mitigate the errors of dose assessment.

The mathematic equation enables fitting of the dosimeter film response with a small residual value, under 10%, over the (0.1–100) mSv, or the (0.2–50) mSv dose range, depending on the background optical density values of the film. The optical density correction recorded by a film with a high background optical density and the dose assessment on the low optical density dose response curve gives very good results on (0.5–5) mSv dose range even if the background optical density difference between two lots of films is of a high degree (0.41 optical density units). The calibration relationship characteristic for a film batch can be used for another film batch, if they have the same background optical density. In very low dose range (below 1 mSv) the films should be often calibrated.

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