Nuclear Engineering and Technology 50 (2018) 519–525

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Technical Note

An innovative idea for developing a new gamma-ray dosimetry system based on optical colorimetry techniques

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A R T I C L E I N F O

Article history:
Received 1 December 2016
Received in revised form
19 January 2017
Accepted 9 January 2018
Available online 3 February 2018

Keywords:
Absorbed Dose
Colorimetry
Color Standards
Gamma Rays
MATLAB
RGB

A B S T R A C T

Obtaining knowledge of the absorbed dose up-taken by a certain material when it is exposed to a specific ionizing radiation field is a very important task. Even though there are a plenitude of methods for determining the absorbed dose, each one has its own strong points and also drawbacks. In this article, an innovative idea for the development of a new gamma-ray dosimetry system is proposed. The method described in this article is based on optical colorimetry techniques. A color standard is fixed to the back of a BK-7 glass plate and then placed in a point in space where the absorbed dose needs to be determined. Gamma-ray–induced defects (color centers) in the glass plate start occurring, leading to a degree of saturation of the standard color, which is proportional, on a certain interval, to the absorbed dose. After the exposure, a high-quality digital image of the sample is taken, which is then processed (MATLAB), and its equivalent I_{RGB} intensity value is determined. After a prior corroboration between various well-known absorbed dose values and their corresponding I_{RGB} values, a calibration function is obtained. By using this calibration function, an "unknown" up-taken dose value can be determined.

1. Introduction

The absorbed dose induced to a material by ionizing radiation is one of the main quantities used to describe the cumulative effects of such interaction. Whether we are talking about the effects induced by the ionizing radiation to nonliving matter or we are talking about effects induced on biological tissue, the absorbed dose, including the phenomena producing it, is the starting point. Obtaining precise knowledge of the absorbed dose magnitude in cases in which a certain material is exposed to a specific ionizing radiation field, in a certain point in space and for a certain period of time, is a very important task [1–3]. There are even a plenitude of methods for determining the absorbed dose, each one having its own strong points and also drawbacks. In this article, an innovative idea for a new gamma-ray dosimetry system is proposed. The method described in this article is based on optical colorimetry techniques, light being an ideal information-transporting vehicle that can be used to highlight and quantify some of the effects induced on matter by ionizing radiation [4].

Transparent optical materials are affected by their interactions with strong ionizing radiation fields via the occurrence of supplementary defects (color centers) into their structure, besides the preexisting ones due to the manufacturing processes. These color centers show associated absorption color bands, mainly in the ultraviolet–visible–infrared spectral region, due to redistributions of the dislocated valence electrons on more stable states. The color center–producing phenomenon is also known as “glass browning”. Color center occurrence leads to variations of the exposed glass samples’ colors and, implicitly, their absorption proprieties. These variations are proportional, on certain intervals, to the absorbed doses [5–7]. These intervals are strongly related to the glass types used and to the glass thickness. Using glass samples from the same manufacturer and from the same batch is highly recommended [8,9]. Color center production is also influenced by the environmental temperature. Eventually, a slow natural reversing process can be also seen. This reversing process can be accelerated by applying heat treatment (high temperatures) to the irradiated glass samples [10,11]. The main benefit of the reversing process it is economical nature, meaning that the used samples can be reused.

The innovative idea for developing a new gamma-ray dosimetry system proposed in this article is based on optical colorimetry techniques, making use of color standards. The color standards are

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https://doi.org/10.1016/j.net.2018.01.007

officially recognized instruments, containing standardized colors (pure color and well-determined ratios of mixtures), used for comparison with other unknown tones of a specific color (determined in the same measuring conditions). A color standard is used to describe the colorimetric characteristics of a sample and also to assure a traceability chain.

First, a color standard is fixed to the back of a BK-7 glass plate; then, the sample is placed in a point in space where the absorbed dose needs to be determined. When the exposure time is over, a high-quality digital image of the sample is taken. After digitally processing the image (by using of a specific MATLAB-developed code), the individual I_R, I_G, and I_B and the equivalent (I_{RGB}) color intensities are determined. It is known that any digital color image is expressed by its red, green, and blue spectral components. Each pixel of the image is composed of these three components, with intensities in the 0–255 interval [12]. The RGB term comes from the three primary colors: red, green, and blue. In the RGB color space model, a color can be expressed by its equivalent intensity function (1) [13]:

$$I_{RGB}^2 = I_R^2 + I_G^2 + I_B^2 \tag{1}$$

The RGB color space model can be described as the color space interpreted and provided by a personal computer. Relation (1) is based on the Cartesian coordinates system, in which red, green, and blue colors are combined to obtain all the spectral colors. At the same time, the RGB model is the only additive color system that operates with the abstract values of an image, being unaffected by human eye limits. Basically, the relation (1) represents the Euclidean distance inside the RGB color space (RGB color space cube—Fig. 1), from the origin [(0, 0, 0) coordinates] to a certain point [(r, g, b) coordinates], and indicates the equivalent intensity associated with a certain color. In 8-bit–sized coordinates, a color space of 256*256*256 values, meaning more than 16 million color tones, can be obtained.

The point having (0, 0, 0) coordinates represents pure black color; the one having the (256, 256, 256) coordinates represents pure white color. The diagonal of the RGB color space cube (equal R, G, B intensities values) represents the gray tones. To numerically describe a certain color, it is sufficient to assign 8 bits to each of its three primary colors. This way, 256 intensity levels can be codified, starting from (00000000) (pure black—zero intensity) to (11111111) (pure white—maximum intensity).

In this article, using relation (1), a specific MATLAB code was developed to decompose the captured digital images and to obtain their corresponding equivalent RGB intensities (I_{RGB}).

In relation (1), the I_R, I_G, and I_B components associated with the images of the color standards, taken through BK-7 glass samples exposed to ionizing radiation, are influenced by the doses up-taken in the glass's volume. An increased absorbed dose leads to increased absorption of light in the glass volume (wavelength dependent).

After corroboration using various well-known absorbed dose values and their corresponding I_{RGB} values, a calibration function is obtained. Using this calibration function and determining the I_{RGB} value corresponding to the image of an arbitrary-exposed sample, its “unknown” up-taken dose value can be determined. Comparison of the I_{RGB} values obtained for the irradiated samples with the standard values (nonirradiated glass) was done for each pure color and also for the other tones (well-known ratios of mixtures between pure color and white/black).

The proposed method is a relative one, its precision resulting mainly from its calibration procedures. Therefore, in the calibration protocol, it is very important that all the parameters contributing to the resulted I_{RGB} values be taken into account. To obtain high-quality calibration curves, it is important to take into account all the phenomena involved in the interaction between the ionizing radiation and the chosen glass samples. In the calibration process, it is very important to use a gamma-ray source that provides a precisely known energy distribution and dose rate because these two parameters involve the specific response of the exposed glass samples. Different dose rates can lead to different color center occurrence rates. The effects of different gamma-ray energies on an exposed glass sample consist of different probabilities of occurrence of the involved interaction mechanisms: photoelectric effect, Compton effect, and electron–positron pair creation. In the calibration process, as many as possible absorbed dose points must be assured by using high-quality reference dosimeters. It is very important to perform precise measurements and calculations in the calibration procedure.

An important benefit of the proposed colorimetric method is the ease of obtaining different shapes and sizes of glass samples, mandatory conditions in some nuclear physics experiments and applications. The possibility of analyzing the exposed samples at the pixel level also allows mapping of the dose distributions in field homogeneity studies.

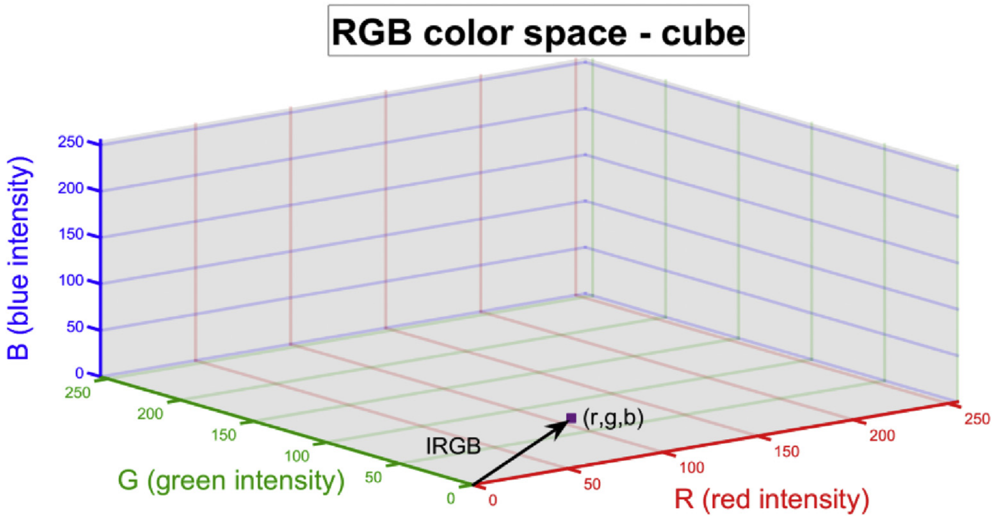

Fig. 1. Theoretical representation of RGB color space—cube.

In this article, 10-mm–thick glass samples were used, in a dose range between 0 kGy and 24 kGy. Following the Beer–Lambert Law, the dose range can be extended (by using thinner glass samples) or narrowed (by using thicker glass samples).

2. Methods and materials

Nine BK-7 glass samples (10-mm thickness) were exposed to a Co-60 gamma-ray source at the Horia Hulubei National Institute for Nuclear Physics and Engineering (IFIN-HH) irradiation facility and nine different absorbed doses were obtained. Using these results, the calibration curves, representing the dependencies of the I_{RGB} values on absorbed dose values, were determined. A maximum dose value of 24 kGy was reached, at a constant dose rate of 5.2 kGy/h (5% uncertainty, k = 2). The absorbed dose values were first calculated and then double checked using of Ethanol–-Chlorine–Benzene (ECB) dosimeters, with an average measurement uncertainty of 2.5% (k = 1). The achieved dose values were placed between 0 kGy and 24 kGy. Each one of the nine irradiated glass samples was placed in front of six color standards, and a Canon Power Shot G6-type (7.1 Mega Pixels) high-quality digital camera was used for taking the pictures. A stable Ne light source (40 W) was used to obtain proper illumination (150 lx). The illumination parameters were checked over the entire measuring time using a MOBILE-CASSY-524009 type luxmeter. The experimental setup [14–16] can be seen in Fig. 2.

One more BK-7 glass sample, from the same manufacturer, from the same batch, and having the same thickness as the ones used for the calibration, was exposed to the Co-60 gamma-ray source, in an arbitrary position. This one was an “unknown” dose sample and was used to validate the method proposed in this article.

In Fig. 3, pictures of the six color standards, taken through gamma-ray–exposed BK-7 glass samples (5.6 kGy, 10.7 kGy, and 23.2 kGy), can be seen.

3. Results and discussion

Because colorimetry measurements involve measuring the light reflected by the color standards and because the glass samples are placed in front of them before taking the pictures, some geometrical optics phenomena are involved. Therefore, the absorption coefficients of the irradiated BK-7 glass samples at 532 nm (Nd:YAG laser) and 633 nm (He-Ne laser) were determined using an optical power meter and the Beer–Lambert Law, in the form (2):

$$\alpha = \frac{1}{x} \times \ln \frac{P_0}{P_{tr.}} \tag{2}$$

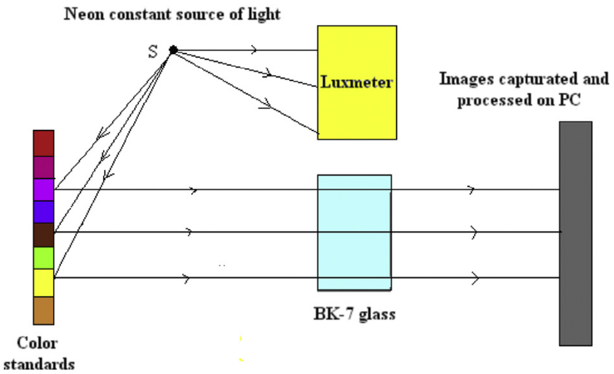

Fig. 2. Experimental setup.
PC, personal computer.

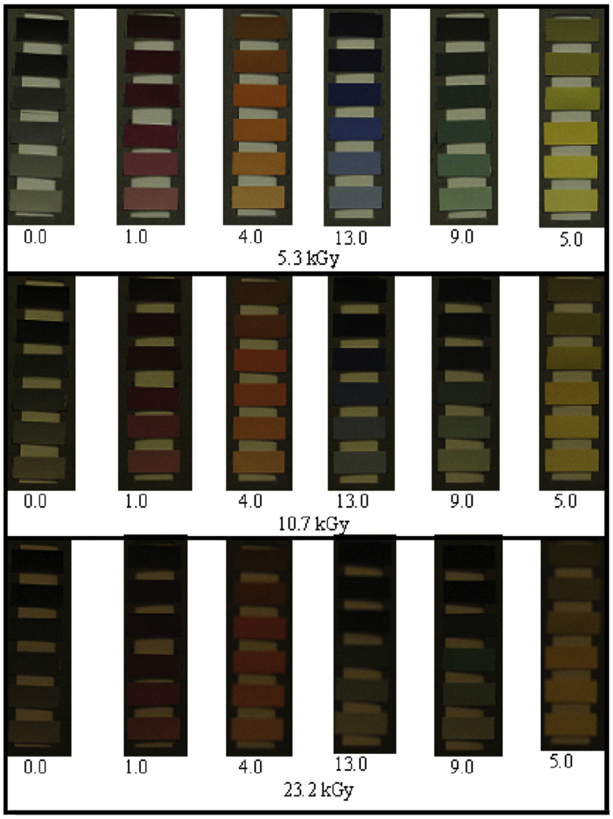

Fig. 3. Color standard pictures taken through gamma rays–exposed BK-7 glass samples.

where P_0 and $P_{tr.}$ are the initial and transmitted laser power, respectively;

x is the sample thickness (10 mm).

The variation of the absorption coefficient as a function of the absorbed dose can be seen in Fig. 4. The intensities of the transmitted and reflected light were also determined for each absorbed dose (Fig. 4). The optical measurements were performed at a distance of 10 mm from the surface of the samples. In both cases (transmission/reflection), a nonlinear response, with a strong decrease to a certain value, followed by saturation, is observed. This dependence of transmission/reflection as a function of the absorbed dose is caused by the significant increase of the absorption in the irradiated glass samples, leading to a strong decrease of transmission and reflection. A nonlinear variation of the absorption coefficient as a function of the absorbed dose, which begins saturating above a dose value of about 10 kGy, can be seen. A decrease of the absorption coefficient with the increase of the light wavelength can also be seen in Fig. 4. Values of the absorption coefficient ranging between 0.009 mm^{-1} and 0.080 mm^{-1} at 633 nm and between 0.008 mm^{-1} and 0.090 mm^{-1} at 533 nm were obtained.

The six color standards used in this article, each one containing a pure color and other five tones (pure color mixed with white/black, in well-known ratios), are presented in Fig. 5.

The calibration curves for each of the six color standards (pure and also their white/black mixtures), indicating the dependence of the I_{RGB} intensities on the absorbed doses, are presented in Fig. 6.

The fitting parameters of the calibration curves for each of the six color standards and for their white/black mixtures are presented in Table 1. Fig. 6 shows the measurements of equivalent color intensities for each of the nine irradiated glasses. For each color standard, an increase of the I_{RGB} values with the increase of

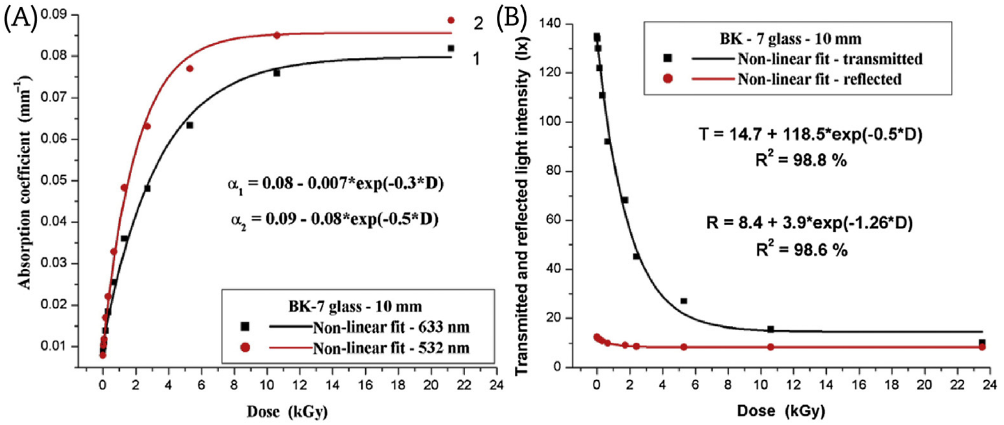

Fig. 4. Absorption coefficient and transmitted/reflected light intensity as a function of the absorbed dose. (A) Absorption coefficient. (B) Transmitted/reflected light intensity.

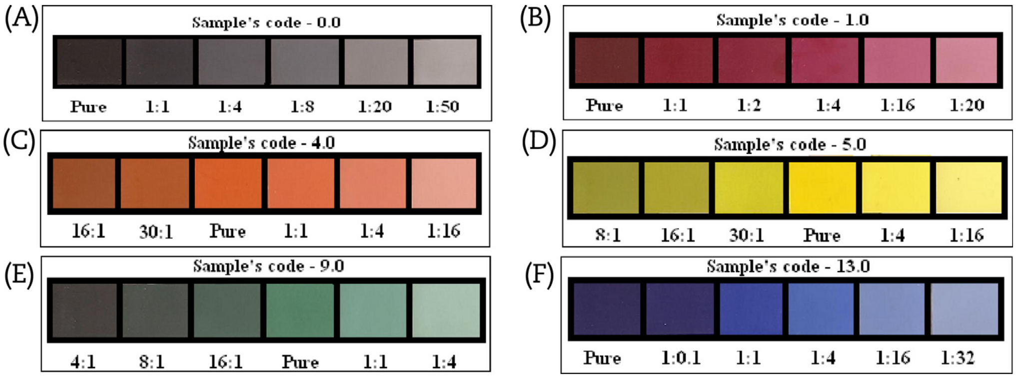

Fig. 5. Six color standards used in this article. (A) Color standard 0.0. (B) Color standard 1.0. (C) Color standard 4.0. (D) Color standard 5.0. (E) Color standard 9.0. (F) Color standard 13.0.

the white to pure ratio and a decrease of the I_{RGB} values with an increase of the black to pure ratio can be observed. When the absorbed dose is increasing, a depopulation of the whiter tones and a stronger population of the darker ones were observed.

An exponential decrease of the I_{RGB} values as a function of increasing absorbed dose can be seen in Table 1. The dependence of I_{RGB} on the absorbed dose is expressed, in a general form, as (3):

$$I_{RGB} = a + b \times \exp(-k \times D) \quad (3)$$

where a, b, and k are the fitting parameters and D is the absorbed dose. Using the fitting parameters obtained for each color standard in the calibration protocol, an "unknown" absorbed dose value can be determined for a certain I_{RGB} value (same glass type, same thickness, and same batch), using relation (4):

$$D = \frac{1}{k} \times \ln \frac{b}{I_{RGB} - a} \quad (4)$$

Using the colorimetric method proposed in this article, absorbed dose values can be determined in any types of activities involving the presence of gamma-ray fields. Certain values of I_{RGB} equivalent color intensities can serve as decision thresholds. For live-time measurements involving a high-quality digital camera focused on a colorimetry-based detector during exposure, an "*a priori*" I_{RGB} threshold value can be set to be compared with the real-time one, and as a result, an alarm can be triggered or an activity can be initiated/stopped.

Being a relative method, the method proposed in this article is based on indirect calculus of the absorbed dose according to relation (4), which relates the absorbed dose to other directly determinable quantities. All these quantities are affected by individual uncertainties. By applying the error propagation theory, the uncertainty associated with the proposed colorimetric method can be determined. Knowing the values of a, b, k, and I_{RGB} and their associated individual uncertainties ($\sqrt{Var(a)}$, $\sqrt{Var(b)}$, $\sqrt{Var(k)}$, and $\sqrt{Var(I_{RGB})}$), the variance associated with relation (4) can be calculated as follows (5):

$$Var(D) = \left(\frac{\partial D}{\partial a}\right)^2 \times Var(a) + \left(\frac{\partial D}{\partial b}\right)^2 \times Var(b) + \left(\frac{\partial D}{\partial k}\right) \times Var(k)^2 + \left(\frac{\partial D}{\partial I_{RGB}}\right)^2 \times Var(I_{RGB}) \quad (5)$$

obtaining (6)

$$Var(D) = \frac{1}{(I_{RGB} - a)^2 \times k^2} \times Var(a) + \frac{1}{k^2 \times b^2} \times Var(b) + \frac{1}{k^4} \times \ln^2 \frac{b}{I_{RGB} - a} \times Var(k) + \frac{1}{(I_{RGB} - a)^2 \times k^2} \times Var(I_{RGB}) \quad (6)$$

In relation (6), all the involved quantities are known. From variance (6), the uncertainty associated with the method is obtained as $\sqrt{Var(D)}$. The final result will be reported as (D $\pm\sqrt{Var(D)}$), expressed in Gy (Gray).

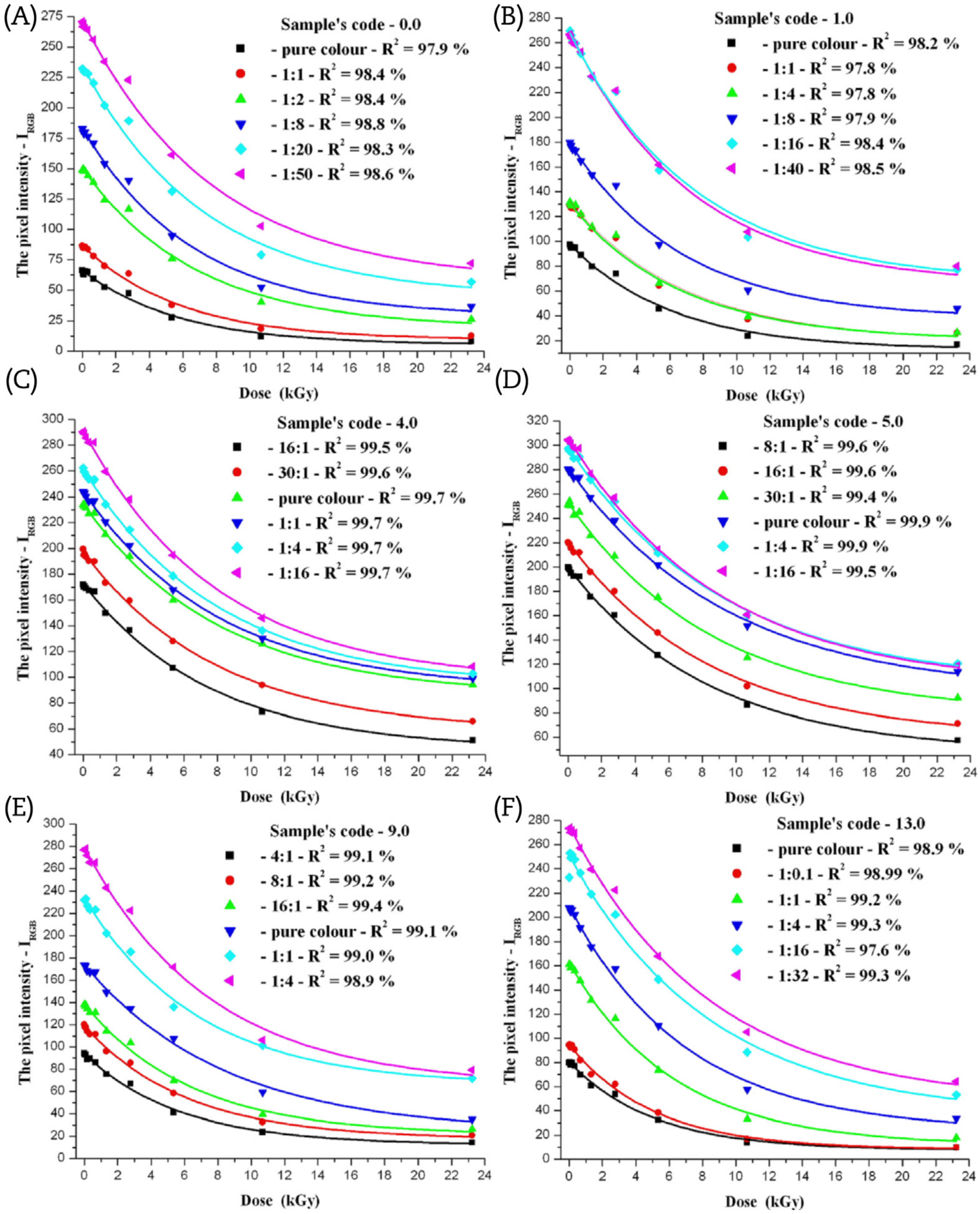

Fig. 6. Equivalent color intensity as a function of the absorbed dose (the calibration curves). (A) Color standard 0.0. (B) Color standard 1.0. (C) Color standard 4.0. (D) Color standard 5.0. (E) Color standard 9.0. (F) Color standard 13.0.

The absorbed dose value corresponding to the “unknown” BK-7 glass sample (from the same manufacturer, from the same batch, and having the same thickness as the ones used for the calibration), exposed to the Co-60 gamma-ray source at an arbitrary point in space, was (4.6 ± 0.36) kGy (determined by using the colorimetric method proposed in this article). The value determined using a classical ECB dosimeter was (4.8 ± 0.24) kGy. In both cases, the uncertainties were reported for a coverage factor k = 2.

The good agreement between the two results, as can be seen in Fig. 7, validates the method proposed in this article.

4. Conclusions

In this article, an innovative idea for developing a new gamma-ray dosimetry system was proposed. The proposed method is based on optical colorimetry techniques and was tested and validated by comparing its results with results obtained by the classical method (ECB dosimeter). The absorbed dose value obtained by the proposed colorimetric method for an “unknown” sample was (4.6 ± 0.36) kGy. The value determined by a classical ECB dosimeter was (4.8 ± 0.24) kGy. Uncertainties were reported for a coverage factor k = 2. The good agreement between the two results validates the method.

The proposed colorimetry-based dosimeters can be used “offline,” meaning the exposure of their glass component at a chosen arbitrary point in space (related to a gamma-ray source) where the absorbed dose value needs to be determined and, after that, their placement in front of the color standards in the experimental setup. The color standards can be part of each dosimeter or can be part of only the measuring setup. In this “offline” method of use, a high-quality digital camera is used to obtain the images.

The method can also be used in an “online” manner, meaning that the acquisition camera is used in live-time filming mode and the obtained I_{RGB} values (corresponding to certain absorbed doses)

Table 1
The calibration curves for each of the six color standards and the results obtained for the "unknown" test sample.

Color standard code	Color tone	$I_{RGB} = f(D)$ (calibration function)	I_{RGB} value	Dose value (kGy)	Mean dose value (kGy)	(Colorimetry) Reported dose value (kGy)	(ECB) Conv. dose value (kGy)	Relative difference (%)
0.0	1:50	$I_{RGB} = 57.1 + 215.0*\exp(-0.13*D)$	172.3	4.8	4.5	4.6	4.8	−4.2
	1:20	$I_{RGB} = 44.5 + 190.4*\exp(-0.14*D)$	145.9	4.5				
	1:8	$I_{RGB} = 28.4 + 155.3*\exp(-0.15*D)$	105.1	4.7				
	1:4	$I_{RGB} = 19.2 + 131.4*\exp(-0.15*D)$	89.2	4.2				
	1:1	$I_{RGB} = 9.6 + 77.4*\exp(-0.17*D)$	47.5	4.2				
	Pure color	$I_{RGB} = 5.4 + 60.8*\exp(-0.18*D)$	32.9	4.4				
1.0	Pure color	$I_{RGB} = 13.1 + 84.5*\exp(-0.17*D)$	51.8	4.6	4.7			
	1:1	$I_{RGB} = 20.5 + 109.8*\exp(-0.15*D)$	71.6	5.2				
	1:2	$I_{RGB} = 20.7 + 111*\exp(-0.15*D)$	74.8	4.7				
	1:4	$I_{RGB} = 37.6 + 141.9*\exp(-0.15*D)$	108.8	4.6				
	1:16	$I_{RGB} = 65.0 + 204.0*\exp(-0.14*D)$	178.3	4.2				
	1:20	$I_{RGB} = 67.0 + 200.7*\exp(-0.13*D)$	175.9	4.7				
4.0	16:1	$I_{RGB} = 44.2 + 128.4*\exp(-0.13*D)$	108.7	5.3	4.6			
	30:1	$I_{RGB} = 58.3 + 139.2*\exp(-0.13*D)$	132.9	4.8				
	Pure color	$I_{RGB} = 85.9 + 148.8*\exp(-0.13*D)$	167.7	4.6				
	1:1	$I_{RGB} = 90.2 + 154.4*\exp(-0.13*D)$	177.3	4.4				
	1:4	$I_{RGB} = 93.2 + 168.5*\exp(-0.13*D)$	189.5	4.3				
	1:16	$I_{RGB} = 97.0 + 194.4*\exp(-0.13*D)$	211.1	4.1				
5.0	8:1	$I_{RGB} = 47.3 + 152.7*\exp(-0.12*D)$	142.9	3.9	4.5			
	16:1	$I_{RGB} = 59.5 + 161.0*\exp(-0.12*D)$	152.2	4.6				
	30:1	$I_{RGB} = 78.8 + 174.3*\exp(-0.12*D)$	173.3	5.1				
	Pure color	$I_{RGB} = 96.9 + 184.7*\exp(-0.11*D)$	212.0	4.3				
	1:4	$I_{RGB} = 103.4 + 195.3*\exp(-0.11*D)$	218.6	4.8				
	1:16	$I_{RGB} = 101.7 + 204.5*\exp(-0.11*D)$	229.1	4.3				
9.0	4:1	$I_{RGB} = 12.3 + 81.6*\exp(-0.18*D)$	47.3	4.7	4.9			
	8:1	$I_{RGB} = 17.5 + 101.4*\exp(-0.17*D)$	61.6	4.9				
	16:1	$I_{RGB} = 21.3 + 117.3*\exp(-0.16*D)$	76.6	4.7				
	Pure colour	$I_{RGB} = 23.7 + 150.3*\exp(-0.12*D)$	103.3	5.3				
	1:1	$I_{RGB} = 71.9 + 161.7*\exp(-0.15*D)$	144.9	5.3				
	1:4	$I_{RGB} = 65.3 + 213.4*\exp(-0.13*D)$	187.3	4.3				
13.0	Pure colour	$I_{RGB} = 7.8 + 72.6*\exp(-0.2*D)$	38.5	4.3	4.5			
	1:0.1	$I_{RGB} = 8.3 + 84.4*\exp(-0.2*D)$	41.3	4.7				
	1:1	$I_{RGB} = 11.5 + 150.9*\exp(-0.16*D)$	87.3	4.3				
	1:4	$I_{RGB} = 23.5 + 185.6*\exp(-0.14*D)$	118.3	4.8				
	1:16	$I_{RGB} = 35.6 + 215.4*\exp(-0.12*D)$	165.7	4.2				
	1:32	$I_{RGB} = 46.9 + 228.5*\exp(-0.12*D)$	175.3	4.8				

ECB, Ethanol–Chlorine–Benzene.

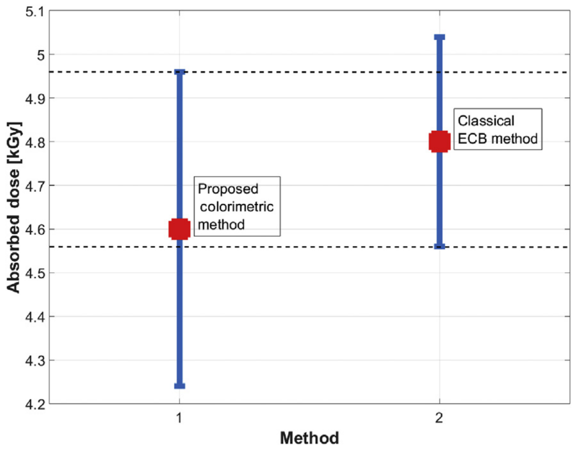

Fig. 7. Proposed colorimetric method compared with the classical ECB method. ECB, Ethanol–Chlorine–Benzene.

can be compared with certain prechosen values; as a result, an alarm can be triggered or an operation can be initiated/stopped.

The use of certified color standards gives traceability to the measurements. Only one color standard is sufficient to obtain a result, but using more of them and reporting the mean value give coherence to the method. The use of different tones of each pure color (mixtures with white or black in well-known proportions) and different types and thicknesses of glass improves the sensitivity of the method. This way, the usable dose interval can be also shifted/extended. The method can also provide field uniformity information with a resolution equal to the pixel size of the digital camera used.

The proposed colorimetric glass dosimeters are especially recommended for use as preliminary instruments in the case of strong gamma-ray fields, similar to the ones involved in state-of-the-art nuclear physics experiments such as the Extreme Light Infrastructure–Nuclear Physics. In these kinds of experiments, the presence of high-energy neutron fields can activate other types of expensive measuring systems. The colorimetric glass detectors show superior economic effectiveness and can be manufactured in various geometries and dimensions. By thermal resetting of gamma-ray–induced optical density, these detectors can be reused. The convenient economic impact of this absorbed dose–determining method makes it very practical.

Conflicts of interest

None.

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