Assessment of colorimetric reading out methods for radiochromic film and red radiation-sensitive poly-methylmethacrylate

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Abstract. This research is aimed to introduce and to compare 3 methods of reading out and analyzing light blue radiochromic film (BLF) dosimeter and red radiation-sensitive poly-methylmethacrylate (PMMA). The BLF and red radiation-sensitive PMMA act as a colour detector which its colour changes after being irradiated. These dosimeters are usually used in food irradiation for process control during irradiation process. The camera-based measurement in a constraint condition, scanner-based measurement with the Trichromatic Colour Analyser (TCA) software and spectrophotometer were used for obtaining colorimetric data of both dosimeters which were non-irradiated and irradiated in 5 doses: 5, 10, 15, 20 and 25 kGy. There were strong linear relationships between doses, given to BLF, and lightness (CIE L*), chroma (CIE C*) and yellowness-blueness (CIE b*) for 3 methods. For red radiation-sensitive PMMA, strong linear relationships were found between doses and redness-greenness (CIE a*) as well as CIE C* in both TCA and spectrophotometer methods. The doses and CIE L* gave strong relationship only in the spectrophotometric method.

1. Introduction
The purposes of food irradiation are to reduce certain pathogenic micro-organisms, to prolong shelf-life, to sterilize, to disinfect insects, to inhibit sprouting, to delay ripening and to quarantine. There are limitations of absorbed dose in different food classes, started from 0.1 kGy to 100 kGy. In the radiation processing of food, success depends on various factors, one of the important factor is ability to measure the absorbed dose delivered to the food product using reliable dosimetry [1]. The absorbed dose or dose, D, is the amount of energy absorbed per unit mass of irradiated matter at a point in the region of interest. The accurate dose, not over or under exposure, is required to obtain the right effect in specific food and to be legal and economic. The routine dosimeters, commonly radiochromic film and radiation sensitive PMMA, can be used for process monitoring and for food quality control. The radiation sensitive PMMA is useful for measuring absorbed dose in a hydrogenous food such as meat, vegetable or fruit. The absorbed dose of routine dosimeters is usually measured by spectrophotometer. In the previous research, the use of flat-bed scanner had been introduced to quantify the irradiated radiochromic films [2-10].

Our interest is in colour measurement methods and relationship of colorimetric data and doses for radiochromic BLF and radiation-sensitive PMMA dosimeters for medium and high dose levels. In this study, 3 methods for obtaining colorimetric data: 1) camera-based; 2) TCA scanner-based and 3) reflectance spectrophotometry are introduced. Dose ranges were limited to food application. The
camera-based and scanner-based color measurements were proposed for reading out of the radiochromic
dosimeter FWT 60-00 and the red radiation-sensitive PMMA. These techniques are alternatives for
quantifying the absorbance of both dosimeters. A colour wheel, comprising 24-colour and 6-gray
patches, as a calibrating tool for individual capturing image using a digital single-lens-reflex camera,
was developed. For the scanner-based method, the Trichromatic Colour Analyser system comprising our
own written software and a flatbed scanner with built-in xenon fluorescent lamp to obtain colorimetric
data was applied. The final method, a spectrophotometer, to obtain the reflectance spectrum and
subsequently CIELAB values was used. The objective of this research was to assess 3 colorimetric
reading out methods in terms of relationship between doses and colorimetric data of BLF and radiation-
sensitive PMMA.

2. Materials and methods

2.1. Radiochromic film and radiation-sensitive PMMA

Five pieces of light blue radiochromic film (BLF) dosimeter FWT 60-00, Batch number 1097, thickness
of 0.043 mm and 5 pieces of red radiation-sensitive poly-methylmethacrylate (PMMA), Harwell Red
Perspex Dosimeter, from Harwell UK, Batch NW, type 4034, Range 5-25 kGy were used. Irradiation
was carried out by Office of Atoms of Peace (OAP), Thailand, on 21-22 Nov 2016.

2.2. Irradiation

The BLF and red radiation-sensitive PMMA samples were irradiated by Gammacell 220 with dose rate
3.24 kGy/hr and absorbed dose 5-25 kGy, 5 kGy intervals. After irradiation, the samples were kept in
opaque metalized envelopes before measuring the absorption using UV-Visible Spectrophotometer
(Perkin Elmer) at 605 for BLF and at 640 nm for red radiation-sensitive PMMA samples. The measurements
were carried out at OAP. The colorimetric reading out then were performed at the
Department of Imaging and Printing Technology, Faculty of Science, Chulalongkorn University,
Thailand.

2.3. Digitization and quantification

2.3.1. Camera-based measurement. The Nikon D40x was used for capturing irradiated samples placed
on Munsell N9.5 which was in the center of a colour wheel (Figure 1(a)). The Munsell sheets used in
the colour wheel were: N2, N3.5, N5, N6.5, N8, N9.5, 7.5P 4/10, 10PB 4/6, 2.5GY 8/8, 7.5GY 7/10,
10R 6/8, 7.5RP 4/12, 10YR 7/4, 7.5B 8/4, 7.5PB 4/6, 5P 4/10, 5R 4/10, 10GY 7/8, 5YR 7/6, 7.5R 4/10,
5Y 8/4, 2.5BG 7/4, 2.5G 8/2, 5RP 4/12, 10BG 8/2, 5PB 4/2, 10Y 8/4, 2.5B 8/2, 7.5G 8/4 and 10P 6/4).
The captured image of the colour wheel taken by a camera is shown in Figure 1 (b). The nearby
environment would not be included in the scene and the position was fixed. The colour wheel was
developed for giving the similar CIELAB values regardless of light source changes. The process of
developing the colour wheel is described later in this section. The camera was 1 meter away from the
colour wheel at a shooting angle of 45°. A light box was constructed for the imaging work, equipped
with a light source, from light-weight materials painted in matt black. The light sources, Philips
ambience fluorescent cool 13W daylight 6500K Tornado E27/ES 650 lumen was fixed to the ceiling of
the box with an adjustable mechanical slider so that the illuminance at the bottom of the box could be
set to have values in the range of 600–650 lux. The light sources were attached to the power supply via
a stabilizer to reduce illuminance variations during the experiment. The light box and the camera were
placed in a dark room. Images were taken with a 135 mm lens, ISO 100, minimum aperture and flashlight
off, in sRGB mode, leaving all other settings in automatic mode. The digital image was obtained. These
settings were chosen to enable the system to use the slowest shutter speed, therefore obtaining longer
exposures of each camera’s sensor. The preset white balance versus the auto white balance mode was
tested and most tested cameras (Canon EOS X4, 600D and 6D; Nikon D40x and D70) gave better results
with the auto white balance under the controlled constrained conditions applied in this study. This is
possible because the white point of N9.5 is in the scene. The device-dependent RGB values read from the digital images of the irradiated sample were called \( R_d, G_d \) and \( B_d \) hereafter. Subsequently, they were transformed to CIEXYZ and CIELAB according to Figure 2.

\[
R_d, G_d, B_d
\]

\[
R_n, G_n, B_n
\]

\[
KR, KG, KB, gammaR, gammaG, gammaB
\]

\[
R_l, B_l, G_l
\]

\[
L^*a^*b^*
\]

The best-fit functions for the achromatic colours of the digital images were calculated as shown in the RGB linearization flowchart (Figure 2). The spectral reflectance factors of the Munsell neutral samples were invariant to wavelengths in the range of 430–700 nm. The linearization of the \( R, G \) and \( B \) values was performed using the reflectance factors of the six gray samples in the wheel at 640 nm, 530 nm and 480 nm \( (S(\lambda_{640}), S(\lambda_{530}) \text{ and } S(\lambda_{480}); i = \text{Munsell N2, N3.5, N5, N6.5, N8 and N9.5}) \) respectively, where DSLR digital cameras generally have a high sensitivity [11]. It was assumed that the RGB data obtained were the result of a power-function encoding and, therefore, the relationship between the average RGB values and the selected reflectance factors for the 6 neutral grays would fit inverse power functions.

In Figure 2, \( R_d, G_d \) and \( B_d \) are the device-dependent RGB values read from the digital images, \( R_n, G_n \) and \( B_n \) are the normalized RGB values. The terms \( KR, KG, KB, gammaR, gammaG \) and \( gammaB \) are the parameters of the best fit inverse power functions for the RGB channels, coefficients are noted with \( K \) and powers with gamma. The \( R_l, B_l \) and \( G_l \) are the linearized RGB values. The linearized RGB values were then converted to CIEXYZ values using the linear system of equation as shown in the bottom part of Figure 2. Since the pictures were taken after selecting the sRGB colour space from the camera’s menu settings, it was considered that the linearization done with neutrals should result in a corrected linear RGB within the sRGB colour space. Therefore, the coefficients of the sRGB linear transformation to the CIEXYZ values were used. Then the CIE (1976) \( L^*a^*b^* \) were calculated [12].

The initial idea of developing the colour wheel was to test the quality of light source, Colour Rendering Index (CRI) [11]. The process then was started from selecting 15 Munsell colour patches used in the Colour Quality Scale (CQS) which were developed by the National Institute of Standard and Technology (NIST) for testing new technology light source such as Light Emitting Diode (LED) lamp. Subsequently 8 standard Munsell colour patches used for determining CRI were added.

The colour wheel was constructed with this new set of colours (15+8) and with the six grays (neutrals): N3.5, N5, N6.5, N8, N9.5. The gray set was introduced to obtain the best fit power functions. The constructed colour wheel was captured using the imaging systems [13].

In the process of colour selection for the wheel, the CIEXYZ values were calculated for each digitized colour and then the CIE (1976) \( L^*a^*b^* \) or CIELAB values were calculated and compared with the measured spectrophotometric CIELAB (D65/2°, specular component excluded) values of the corresponding colours on the wheel. For this purpose, the CIEDE00 colour difference equation was used [14]. The X-Rite SP62 spectrophotometer was used to measure the colour patches of the wheels used in the preliminary study. The replacement colours of this wheel must cover all hue angles in order to offer meaningful colorimetric data. After each replacement, a new image was captured and the calculation process repeated. This was carried out until the minimum average \( \Delta E_{00} \) between the captured colours
and their corresponding measured colours from the colour wheels obtained in the scenes that gave an optimum linear response for the cameras. The aim of the iterative process, was to obtain a colour wheel with Munsell patches that had a minimum colour difference between the calculated and measured spectrophotometric CIELAB values. This target was reached following the experimental cycle described above of replacing or adding colours in the wheel.

Figure 2. RGB linearization flow chart.

Although the illuminance was maintained at a constant level throughout the experiment, each colour replacement modified the camera responses to the achromatic patches because of the camera’s automatic colour correction algorithms.

The Munsell sheets used in the final colour wheel were mentioned in section 2.3.1. The white dotted squares (Figure 1 (b)) mark the areas on which the obtained RGB values were averaged for each of the two exemplified colours. In a similar way, the RGB averages for the rest of the colours in the wheel were obtained. The colours in the wheel have a higher chroma than the CRI samples but a lower chroma than the CQS samples that were used as the starting point in this experiment.

The experiment was repeated using the same Nikon D40X and Canon EOS4 DSLR cameras and then the reproducibility of the results obtained with the final colour wheel was verified using the three additional DSLR cameras: Canon EOS X4, Canon 600D and Canon 6D. The RGB and CIELAB calculated from captured image and colour differences between colorimetric data obtained from camera-based captured image and measured CIELAB obtained from spectrophotometer under the same light source were recorded.

2.3.2. Trichromatic Colour Analyser (TCA). TCA obtains colorimetric data from colours scanned with GT20000 Epson flatbed scanner, from a very small sample of 0.07 mm², on the physical sample that is
scanned at 96 dpi, to a large sample of 10x10 cm² by using a scanner glass as a measurement port. It was initially developed for scanning large and non-uniform painted samples used in Thai Colour Naming project. The principle methods starting from acquiring colour to getting CIELAB values is explained in Katemake and Preda, 2014 [15]. The GT20000 Epson flatbed scanner has Xenon gas cold cathode fluorescent lamp, MatrixCCD® sensor and colour depth of 48 bits per pixel. The precision of the TCA system has been examined with short-term 50 repeated measurements on Munsell homogeneous gray N5 and it gave the Mean Colour Difference of the Mean (MCDM) of 0.008 as described in Katemake et al., 2016 [16].

After turning on the scanner for 10 minutes, the centre of the BLF sample was placed at the centre of scanning area, 7.5 cm from top and right edges. The centre of all samples were positioned here. The Munsell N9.5 was placed on top of the film sample as a background. The scanning area of 5x5 mm² was recorded as a bitmap image. The RGB then were extracted and transformed to average CIELAB as described in Katemake and Preda, 2014 and Katemake et al., 2013 [15,17]. The colorimetric data then were obtained from all irradiated samples and non-irradiated sample (control) used in this study.

2.3.3. Spectrophotometer. The irradiated blue radiochromic film and the red radiation-sensitive PMMA were measured by using the X-Rite spectrophotometer SP62, geometry d/8, illuminant/observer: D65/2°, measurement port of 6 mm. The average of reflectance spectrum and CIELAB were recorded, while measuring samples on N9.5 background.

3. Results and discussion

3.1. Radiochromic film (BLF)
The BLF changed its color after being irradiated with gamma ray in 5 different doses: 5, 10, 15, 20 and 25 kGy. The colour change could be expressed in terms of hue, chroma and lightness. The CIE \(L^*\) values were not much different among 3 methods of reading out. The camera-based and spectrophotometric methods showed more similarity of CIE \(a^*\) than TCA, whereas the camera-based and TCA showed more similarity of CIE \(b^*\) than spectrophotometer. The hue of BLF gradually changed from cyan-blue (CIE hue angle, \(h^o = 253.5\) degrees), without irradiation, toward magenta-blue (CIE \(h^o = 291.4\) degrees), with maximum dose, when measured with X-Rite SP62 spectrophotometer, D65/2°, and backing the BLF with Munsell N9.5. The \(h^o\) is the product of \(\frac{a^*b^*}{a^* + b^*}\). The negative CIE \(b^*\) changed from -14.18 to -61.37 showing the increase in blueness of the BLF. The chroma (CIE \(C^* = \sqrt{a^*+b^*}\)) increased from 14.8 to 65.9 and the lightness (CIE \(L^*\)) decreased from 72.3 to 38.7. The similar trend found when the reading out methods were camera-based and scanner-based. The dose responses of BLF in terms of the CIE \(L^*, b^*, C^*\) are plotted as shown in Figure 3. The fitting parameters are given in Table 1. The performances of 3 reading out methods were very similar when the degree of linear relationship between doses and colorimetric data was taken into account. The \(R^2\) of the relationship of predictor doses and CIE \(L^*,\) \(b^*\) and \(C^*\) were greater than 0.90 for all 3 reading out methods, except for CIE \(b^*\) obtained from camera-based method. The CIE \(C^*\) and doses gave the best response for 3 methods. The \(R^2\) of 0.94 tells us that 94.0% of the variance in CIE \(C^*\) could be accounted for by doses, leave only 6% unexplained. Values of “Prob > F” less than 0.05 suggesting that the model overall ‘significantly’ improved our ability to predict CIE \(L^*\) and \(C^*\). The statistical b-values indicate what degree each predictor affects the outcome if the effects of all other predictors are held constant. For CIE \(C^*\) obtained from camera-based, scanner-based and spectrophotometer, the \(b\) was 0.49, 0.41 and 0.47 which meant that as dose increased by one unit (kGy), CIE \(C^*\) would increase for an extra 0.49, 0.41 and 0.47 respectively. The same interpretation could be applied to CIE \(L^*\) but in the opposite way because the \(b\) was negative. The standardized \(b\) or \(\beta\) for dose told us that as dose increased by 1 standard deviation (SD), CIE \(C^*\) increased by 0.96, 0.97 and 0.97 for 3 methods. Again the same interpretation could be applied for CIE \(L^*\) and CIE \(b^*\) but in the opposite way because of the negative sign. The confidence intervals of the statistical \(b\) are shown in brackets.
It seemed that the linear model could be applied well for doses and CIE \(L^*\), CIE \(C^*\) and CIE \(b^*\) when all 3 methods were used except for CIE \(b^*\) obtained from camera-based method showing \(R^2\) of 0.81.

![Figure 3](image_url)

Figure 3. Relationship between doses and CIE \(L^*\), CIE \(C^*\) and \(b^*\) of blue radiochromic film, irradiated with gamma ray of 3.24 kGy per hour, colorimetric data obtained from camera-based (circle), scanner-based (triangle) and d/8 spectrophotometer (x).

| Table 1. Fitting parameters for the relationship between doses and CIE \(L^*\), CIE \(b^*\) and CIE \(C^*\) for BLF dosimeter. |
|---|---|---|---|---|
| **BLF_Camera** | \(b\) | SE | \(\beta\) | \(P\) |
| constant | -15.07 (-57.49,-7.16) | 3.42 | -0.916 | \(<0.05\) |
| CIE \(b^*\) | -0.50 (-2.01,1.01) | 0.54 | -0.916 | \(<0.05\) |
| constant | 47.57 (29.96,70.10) | 5.69 | 0.07 | \(<0.01\) |
| CIE \(L^*\) | -0.64 (-1.19,-0.39) | 0.10 | -0.953 | \(<0.05\) |
| constant | -15.69 (-36.15,-9.51) | 4.49 | 0.07 | \(<0.01\) |
| CIE \(C^*\) | 0.49 (0.32,0.78) | 0.07 | 0.96 | \(<0.01\) |

| **BLF_TCA** | \(b\) | SE | \(\beta\) | \(P\) |
|---|---|---|---|---|
| constant | -12.10 (-36.99,-7.05) | 4.07 | \(<0.05\) |
| CIE \(b^*\) | -0.49 (-0.86,-0.32) | 0.08 | -0.954 | \(<0.01\) |
| constant | 54.73 (36.27,76.49) | 5.47 | 0.05 | \(<0.001\) |
| CIE \(L^*\) | -0.74 (-1.18,-0.47) | 0.09 | -0.97 | \(<0.01\) |
| constant | -10.48 (-26.69,-6.38) | 3.14 | 0.05 | \(<0.05\) |
| CIE \(C^*\) | 0.41 (0.28,0.61) | 0.05 | 0.97 | \(<0.01\) |

| **BLF_Spectrophotometer** | \(b\) | SE | \(\beta\) | \(P\) |
|---|---|---|---|---|
| constant | -9.61 (-29.29,-5.34) | 3.76 | \(<0.05\) |
| CIE \(b^*\) | -0.50 (-0.85,-0.35) | 0.08 | -0.95 | \(<0.01\) |
| constant | 48.39 (34.67,65.31) | 5.70 | 0.05 | \(<0.01\) |
| CIE \(L^*\) | -0.70 (-1.08,-0.49) | 0.11 | -0.96 | \(<0.01\) |
| constant | -9.24 (-22.32,-5.46) | 2.92 | 0.05 | \(<0.05\) |
| CIE \(C^*\) | 0.47 (0.35,0.70) | 0.05 | 0.97 | \(<0.01\) |

3.2. Radiation-sensitive PMMA

The red radiation-sensitive PMMA were irradiated with the same dose levels as BLF. The hue of red radiation-sensitive PMMA slightly changed compared to BLF. Spectrophotometrically, it changed from yellowish red, without irradiation, (CIE \(h^* = 29.6\) degrees) to red, 25 kGy irradiated, (CIE \(h^* = 16.7\) degrees). The chroma (CIE \(C^*\)) decreased from 70.0 to 46.1 and the lightness (CIE \(L^*\)) decreased from 22.4 to 11.2. The relationship between doses and CIE \(L^*\), CIE \(C^*\) and CIE \(a^*\) gave fitting parameters as shown in Table 2. The most linear relationship was found in the spectrophotometric reading out and then TCA. The \(R^2\) of the relationship of predictor doses and CIE \(L^*\), \(a^*\) and \(C^*\) are greater than 0.90 when red radiation-sensitive PMMAs were measured with spectrophotometer. The doses and CIE \(a^*\) gave the best response for spectrophotometer and then TCA. The CIE \(a^*\) was used for red radiation-sensitive PMMA instead of CIE \(b^*\) as it was used in BLF because high amount of positive \(a^*\) (showing red) was found in the measurement. Increasing dose would decrease CIE \(L^*\) (lightness), \(a^*\) (redness) and \(C^*\) (chroma). For CIE \(L^*\), \(a^*\) and \(C^*\) (PMMA_Spec), \(b\) was -1.83, -1.26 and -0.88 indicating that as dose increased by one unit (kGy), CIE \(L^*\), \(a^*\) and \(C^*\) would decrease for an extra 1.83, 1.26 and 0.88 respectively.
The area of measurement was about the same for 3 methods which was limited by the size of the dosimeter itself. The BLF size gave the maximum area of measurement of 28.3 mm². The average of measured values then was from the same area with repeated measurements. The data points of the CIE L* against CIE C* were formed as a small cluster for smaller dose. It was obviously found that at 25 kGy, some of the BLF data points were away from the cluster. The data points of 20 and 25 kGy of red radiation-sensitive PMMA were scattered more than the smaller doses. Butson et al., [18] investigated the effect of film orientation on the optical density (OD) and also showed the variation of OD with the doses. They found that the orientation of the Gafchromic EBT film (high sensitive radiochromic film) gave 3 times higher effect compared to other films. In our case, when the TCA scanner-based was used, the orientation and the scanning position were fixed according to the locator tool and our TCA software. They also stated that the smaller dose gave high variation of optical density to the EBT film. However, in our results, it was found that the homogeneity of the BLF and the red radiation-sensitive PMMA decreased with higher dose indicated by higher scattering of data points found at highest dose.

In terms of cost, among the methods used in this research, the DSLR camera-based with the colour wheel is the lowest with a basic DSLR camera, the colour wheel and materials for setting up constraint environment comprised of light source and a black box. The medium cost is the TCA-scanner based, with high-end flatbed scanner and our own developed software, TCA. The highest cost is the portable spectrophotometer. In terms of ease of operation, the camera-based needs setting up the constraint condition and it must be the same for all shooting. After the initial setting, the condition is applicable for the next shooting. Subsequently the RGB data of sample and that of 6 gray patches will be used to obtain CIELAB values. Both of the scanner-based and the spectrophotometer are the most convenient.

One of the advantages of using CIELAB colorimetric data of dosimeter with various doses is that the data can be used for generating “dose colour chart” for matching with exposed dosimeter that may be attached to food or other objects that are needed to exposed with gamma ray. This way the dose could be visually controlled.

| Table 2. Fitting parameters for the relationship between doses and CIE L*, CIE a* and CIE C* for PMMA dosimeter. |
|---|---|---|---|---|
| PMMA_Camera | Constant | 23.00 (16.69,31.06) | 2.53 | <.001 |
| CIE a* | -0.66 (-1.55,-0.41) | 0.13 | -0.934 | <.01 |
| Constant | 31.09 (18.99,44.39) | 4.86 | <.01 |
| CIE L* | -1.40 (-4.92,-0.81) | 0.34 | -0.900 | <.01 |
| constant | 21.84 (15.59,30.04) | 2.63 | <.01 |
| CIE C* | -0.49 (-1.39,-0.29) | 0.11 | -0.92 | <.01 |
| PMMA_TCA | constant | 42.87 (33.20,61.96) | 4.41 | <.001 |
| CIE a* | -0.81 (-1.52,-0.61) | 0.11 | -0.963 | <.01 |
| constant | 48.02 (35.20,77.68) | 6.42 | <.01 |
| CIE L* | -1.40 (-2.79,-0.98) | 0.25 | -0.94 | <.01 |
| constant | 40.07 (31.34,59.14) | 4.11 | <.001 |
| CIE C* | -0.65 (-1.18,-0.49) | 0.09 | -0.96 | <.01 |
| PMMA_Spectrophotometer | constant | 77.22 (63.89,103.67) | 7.33 | <.001 |
| CIE a* | -1.26 (-1.80,-1.01) | 0.14 | -0.98 | <.01 |
| constant | 41.58 (34.10,59.41) | 4.18 | <.001 |
| CIE L* | -1.83 (-2.99,-1.41) | 0.25 | 0.96 | <.01 |
| constant | 61.97 (47.85,74.68) | 6.05 | <.001 |
| CIE C* | -0.88 (-1.12,-0.65) | 0.11 | -0.97 | <.01 |

4. Conclusions

The camera-based, scanner-based and spectrophotometer could relatively give similar colorimetric data for both BLF and red radiation-sensitive PMMA. The linear relationship between doses and CIELAB values is found better in BLF for all three methods. The linear models gave excellent performance with $R^2$ greater than 0.90. This confirmed that the CIELAB values, especially CIE L* and CIE C*, could be
used to predict the dose ranged from 5 to 25 kGy. However, for red radiation-sensitive PMMA, the spectrophotometer and TCA scanner-based methods gave better linear relationship between doses of 5 to 25 kGy and CIE $a^*$ and CIE $C^*$ whereas the camera-based method gave good linear relationship between doses of 5 to 10 kGy.

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References
[1] Technical reports series no.409, Dosimetry for Food Irradiation, International Atomic Energy Agency, Vienna 2002 ISSN 0074-1914
[2] Alva H, Mercado-Uribe H, Rodriguez-Villafuerte M and Brandon M.E. 2002 The use of a reflective scanner to study radiographic film response Phys. Med. Biol. 47(16), 2925.
[3] Devic S, Seuntjens J, Hegyi G, Podgorsak E B, Soares C G, Kirov A S, Ali I, Williamson J F and Elizondo A. 2004 Dosimetric properties of improved GafChromic films for seven different digitizers Med. Phys. 31 2392–2401
[4] Devic S, Seuntjens J, Sham E, Podgorsak E B, Schmidtlein C R, Kirov A S and Soares C G 2005 Precise radiochromic film dosimetry using a flat-bed document scanner Med. Phys. 32 2245–53
[5] Lynch B D, Kozelka J, Ranada M K, Li J G, Simon W E and Dempsey J F 2006 Important considerations for radiochromic film dosimetry with flatbed CCD scanners and EBT GAFCHROMIC® film Med. Phys. 33 4551–56
[6] Paelinck L, Neve De W and Wagter De C 2007 Precautions and strategies in using a commercial flatbed scanner for radiochromic film dosimetry Med. Biol. 52 231
[7] Soares, C G. Radiochromic film dosimetry. Radiat. Meas. 41, S100–S116 (2007)
[8] Matney J E, Parker B C, Neck D W, Henkelmann G and Rosen I I 2010 Evaluation of a commercial flatbed document scanner and radiographic film scanner for radiochromic EBT film dosimetry J. Appl. Clin. Med. Phys. 11 198–208
[9] Papaconstadopoulos P, Hegyi G, Seuntjens J and Sllobodan D 2014 A protocol for EBT3 radiochromic film dosimetry using reflection scanning. Med. Phys. 41 122101
[10] Lewis D and Chan M F 2015 Correcting lateral response artifacts from flatbed scanners for radiochromic film dosimetry Med. Phys. 42 416–429
[11] Cheung V, Westland S and Thomson M 2004 Accurate estimation of the nonlinearity of input/output response for color cameras, Color research and application 29 406-412
[12] Hunt G R W 1995 Measuring colour Ellis Horwood
[13] Varapaskul T, Katemake P and Preda R I 2013 Creating colour compositions that allow calculating the CIELAB values of each component colour from pictures taken with a digital camera AIC2013 – 12th International AIC Congress Gateshead 8-12 July. 1105-08
[14] Ohta N and Robertson A R 2005 Colorimetry Fundamentals and Applications Wiley-IS&T series in imaging science and technology ISBN-13 978-0-470-09472-3
[15] Katemake P and Preda R I 2014 Complete study of traditional Thai colors used in mural paintings: traditional Thai color name dictionary. Color Research and Application 6 616-629
[16] Katemake P, Preda R I and Duangmal K 2016 Automatic Monitoring Method of Apple Browning for Determining Optimal Inhibitor Mixtures International Food Research Journal 23 1100-06
[17] Katemake P, Preda R I and Hoontarakul D 2013 Identification of traditional Thai colours used for mural paintings and Khon masks Color Research & Application 38 229-234
[18] Butson M J, Cheung T and Yu P K N 2006 Scanning orientation effects on Gafchromic EBT film dosimetry, Australasian Physical & Engineering Sciences in Medicine 29 281-284