INVESTIGATION OF THE EFFECT OF TEMPERATURE, DOSE RATE AND SHORT-TERM POST-IRRADIATION CHANGE ON THE RESPONSE OF VARIOUS TYPES OF DOSIMETERS TO COBALT-60 GAMMA RADIATION FOR QUALITY ASSURANCE IN THAILAND

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Abstract

The influences of combined effect of irradiation temperature from -80°C to 60°C and dose rate between 0.2 and 4 Gy/s on the gamma ray response of several commercial routine dosimeters (Harwell Red 4034, Gammachrome YR, FWT-60-00 radiochromic films, FWT-70-40 optical waveguides, GaFChromic films, and Fuji CTA-FTR-125 films) were investigated for quality assurance in radiation processes. Besides, the studies of short term post-irradiation stability for the period of 2 h to 7 days are also presented. The overall results indicate the need for a calibration protocol under conditions of use.

1. INTRODUCTION

In Thailand the use of gamma facilities for radiation processing is a growing industry and an active developing technology. Since 1984 the first commercial-scale gamma irradiation facility has been operating for the purpose of sterilization of medical products. In these facilities various types of commercial dosimeters have been used for absorbed dose measurement, which are first developed in laboratory, then transferred to an industrial application and finally to routine process control. The irradiation processes have occurred under the influences of external factors and specific condition due to the irradiation purpose. There are three different ways to calibrate commercial dosimeters used for gamma processing [1]. One way calls for the dosimeters to be irradiated in a calibration facility. The second way calls for the dosimeters to be irradiated in an in-house calibration facility that has an absorbed-dose rate measured by reference or transfer standard dosimeters. The third way calls for the dosimeters to be irradiated together with reference or transfer standard dosimeters in the production irradiator.

In practice the commercial dosimeters are irradiated at calibration facility using high dose rate irradiator at a different location and sending to the industrial irradiator site for analysis, whilst the dosimeters using in commercial facilities are irradiated in a poor defined radiation field over a period of several days and read out some hours after irradiation. This method has the advantage that the dosimeters are irradiated to accurately known absorbed doses under well-controlled and documented conditions and can reduce uncertainty introduced by the readout instrumentation. But in this case the sources of error due to dose rate effect and irradiation temperature include time-dependent instability in dosimeters response after irradiation have to be investigated. Many papers have been published about the environmental effects on the response of Harwell PMMA and FWT-60-00 radiochromic film dosimeters [2–9]. The collaborated work was set up between OAEP and JAERI for investigation the irradiation temperature effect from -190°C up to 45°C on the response of undyed and dyed PMMA dosimeters at specific dose of 2 and 25 kGy [10]. The present study is aimed to
investigate the combination of two effects of irradiation temperature from $-80^\circ C$ up to $60^\circ C$ and dose rate from 0.07 up to 4 Gy/s and short term post irradiation change on the response of several types of commercial dosimeters.

2. EXPERIMENTAL AND RESULTS

Various commercial types of dosimeters were used for this study. The characteristics of these dosimeter systems are listed in Table I.

**TABLE I. CHARACTERISTICS OF DOSIMETRY SYSTEMS**

<table>
<thead>
<tr>
<th>Dosimeters</th>
<th>Commercial name</th>
<th>Nominal size (mm)</th>
<th>Method of Analysis</th>
<th>Analysis wavelength (nm)</th>
<th>Useful dose range (kGy)</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymethylmethacrylate</td>
<td>Red 4034</td>
<td>30 x 11 x 3</td>
<td>vis. spectrophotometer</td>
<td>640</td>
<td>5-50</td>
<td>AEA Technology, United Kingdom</td>
</tr>
<tr>
<td>Gammachrome YR</td>
<td>30 x 11 x 1.5</td>
<td>vis. spectrophotometer</td>
<td>530</td>
<td>0.1-3</td>
<td>Harwell Laboratory, United Kingdom</td>
<td></td>
</tr>
<tr>
<td>PMMA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiochromic FWT-60-00</td>
<td>10 x 10 x 0.05</td>
<td>vis. spectrophotometer</td>
<td>510,605</td>
<td>1-50</td>
<td>Far West Technology, Inc., Goleta, USA</td>
<td></td>
</tr>
<tr>
<td>FWT-70-40m</td>
<td>3 dia x 50 long</td>
<td>photometry</td>
<td>600,656</td>
<td>0.01-1</td>
<td>Far West Technology, Inc., Goleta, USA</td>
<td></td>
</tr>
<tr>
<td>Optical Wave-guide</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Cellulose triacetate film(CTA)</td>
<td>0.125 thick</td>
<td>UV/vis spectrophotometer</td>
<td>280</td>
<td>5-300</td>
<td>Fuji Photo film, Minato-ku, Tokyo, Japan</td>
<td></td>
</tr>
</tbody>
</table>

2.1. Gammachrome YR polymethylmethacrylate dosimeter [15]

2.1.1. Combined effects of irradiation temperature and dose rate studies.

Harwell Gammachrome YR batch 5 are commercially available sealed in the puncture-resistance polyester/aluminium/polyethylene laminated individual sachets for protection against changing environmental condition specially humidity. The irradiations were carried out using two $^{60}$Co sources, gammacell 220 at absorbed dose rate of 2.7 Gy/s and Gammabeam 650 panoramic source at 0.18 Gy/s. The dosimeters were conditioned for 1 hour and irradiated at each temperature using a double-walled glass dewar flask and stored at room temperature immediately after the end of irradiation. The Gammachrome YR were irradiated for the dose range of 100 Gy up to 3 kGy at the following temperatures; $-78$, $-18$, 0, 25 and $60^\circ C$. Fluctuation of control of irradiation temperature was within $3^\circ C$. Table II shows the condition in dewar flask at each irradiation temperature. The irradiated dosimeters were kept at about $25^\circ C$ for 2 h before spectrophotometric (Shimadzu UV-3101PC) analysis.

**TABLE II. COOLANTS FOR LOW TEMPERATURE CONDITIONS**

<table>
<thead>
<tr>
<th>Condition in the dewar flask</th>
<th>Temperature($^\circ C$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol and dry ice</td>
<td>$-78$</td>
</tr>
<tr>
<td>Sodium chloride solution and ice</td>
<td>$-18$</td>
</tr>
<tr>
<td>Water and ice</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td>$+25$</td>
</tr>
</tbody>
</table>
FIG. 1. Temperature dependence, relative to that at 25°C, of gamma response of Gammachrome YR batch 5 at dose rate 2.7 and 0.18 Gy sec\(^{-1}\). Where the absorbance per unit thickness was measured at 530 nm.
FIG. 2. Combined effect on response of Gammachrome YR batch 5 at does rate of 2.7 and 0.18 Gy sec$^{-1}$ with the irradiation temperature: 60.25 and $-78^\circ$C.

FIG. 3. Post-irradiation studies of Gammachrome YR batch 5 at 1 kGy, analysis time 2.24 hour and 7 days after irradiation for the dose rate 2.7 Gy sec$^{-1}$.
2.1.2. Short term post-irradiation studies

In order to investigate post-irradiation effect nine dosimeters were irradiated at each irradiation temperature for absorbed dose of 1 kGy with the same previous conditions. The irradiated dosimeters were kept in seal before spectrophotometric analysis. The three dosimeters were opened and measured after 2 h whilst the others were measured at 24 h and 7 d after the end of the irradiation.

2.1.3. Results and conclusion

The temperature dependence, relative to that at 25°C of gamma response of GammaChrome YR at dose rate of 2.7 and 0.18 Gy/s for the absorbed dose of 0.1, 1 and 3 kGy are shown in Fig 1. Figure 2 shows the combined effect in term of ratio of response at 2.7 to 0.18 Gy/s at irradiation temperature of 60, 25 and −78°C. The result of the short term post-irradiation studies are shown in Fig 3.

The overall results show only slightly variations in the response of PMMA GammaChrome YR dosimeters for different gamma dose rates in the range from 0.18 to 2.7 Gy/s for irradiation temperatures from −80°C to 60°C.

2.2. Radiochromic optical waveguide FWT-70-40m [11]

Radiochromic optical waveguide is a specially prepared optical waveguide containing ingredients that undergo an ionizing radiation-induced change in photometric absorbance. This change in absorbance can be related to absorbed dose in water. FWT-70-40m are commercially supplied in 3 mm dia × 5 cm long by Far West Technology, Inc. for low dose radiation processing. The dosimeters use hexa(hydroxyethyl) aminotriphenylactonitril dye inside an optical waveguide. Readout of the dosimeter is by photometric means.

2.2.1. Combined effects of irradiation temperature and dose rate and short term post-irradiation studies

The irradiations were carried out using 60Co Gammabeam 650 panoramic source at dose rate of 3.96 and 0.26 Gy/s. The pre-irradiation absorbance for each dosimeter was read using Far West Opti-chromatic photometer reader at 600 and 656 nm. Three dosimeters in 3 mm thick polystyrene tube for electron equilibrium were conditioned for 2 h and irradiated at each temperature using a double-wall glass dewar flask and stored at room temperature immediately after the end of the irradiation. The dosimeters were irradiated for the dose range of 0.02, 0.10, 0.25, 0.5 and 1 kGy at the following temperature: −78, −18, 0, 25, 35 and 60°C using the coolants as shown in Table II. Fluctuation for control of irradiation temperature was within 3°C. The irradiated dosimeters were kept at 25°C for 2 h before absorbance reading and reread again at 24 h and 7 d after irradiation for short term post-irradiation studies.

2.2.2. Results and conclusion

The temperature dependence, relative to that at 25°C, of gamma response of FWT-70-40m batch 4-5 at irradiation temperature of 60, 35, 25, 0, −18, −78°C for two dose rate are shown in Fig 4. Where the absorbance were measured at 600 and 656 nm. The results show only slight variation in the response of dosimeter for different gamma dose rates in the range
FIG. 4. Temperature dependence, relative to that 25°C, of gamma response of FWT-70-40 m batch 4–5 were irradiated at dose rate 0.26 and 3.96 Gy sec⁻¹, measured at 656 and 600 nm (temperature during irradiation: −78, −18, 0, 25, 35, 60°C.
FIG. 5. Short term post-irradiation studies on the gamma response of FWT-70-40 m batch 4–5 at 1 kGy, analysis time 2.24 hr and 7 d after irradiation at dose rate 0.26 and 3.96 Gy sec⁻¹, measured at 656 and 600 nm (temperature during irradiation: −78, 25, 60°C).
from 0.26 to 3.96 Gy/s for irradiation temperature -18°C to 35°C. The response of irradiated dosimeters show stable over 7 day after irradiation as in Fig 5.

2.3. GafChromic™ dosimeter media DM-1260

The transparent radiochromic film, GafChromic dosimeter media, are commercially supplied by Far West Technology, Inc. The dosimeter consists of a 7 μm thick radiation sensitive layer coated on a 100 μm thick polyester base [12]. They are colourless, grainless and transparent before exposure to radiation and develop a deep blue colour after irradiation. GafChromic™ DM-1260 is available in a roll of film 10 mm wide.

2.3.1. Combined effects of irradiation temperature and dose rate and short term post-irradiation studies

The GafChromic film were cut into 10x10 mm for fitting to the standard 10-mm cuvette holder of spectrophotometer. Three films for each irradiation were held between two electron equilibrium layer of 3-mm thick acrylic and sealed at 60% r.h. in the polyethylene-aluminium foil laminate for protection against changing environmental condition specially humidity. The pre-irradiation absorbance for each dosimeter was read using Shimadzu UV-3101PC UV/vis spectrophotometer at 400, 500 and 580 nm. The irradiation were carried out using 60Co Gammabeam 650 panoramic source at 0.26 and 3.96 Gy/s for dose range 0.02 to 1 kGy. The dosimeters were conditioned for 2 h at each irradiation temperature before irradiation and then irradiated using a double-walled glass dewar flask for temperature control. The dosimeters were irradiated for the dose range of 0.02, 0.1, 0.35, 0.5 and 1 kGy at the following temperatures: -78, -18, 0, 25, 35 and 60°C using the coolants as shown in Table II. Fluctuation for control of irradiation temperature was within 3°C. The irradiated dosimeters were kept at 25°C for 2 h before absorbance reading and reread again at 24 h and 7 d after irradiation for short term post-irradiation studies.

2.3.2. Results and conclusion

The temperature dependence, relative to that at 25°C, of GafChromic DM-1260 at dose rate of 0.26 and 3.96 Gy/s for the dose range from 0.02 to 1 kGy over the irradiation temperature -78°C to 60°C are shown in Fig 6, where the absorbance per unit thickness were measured at 580 nm. The post-irradiation studies in Fig 8 show very slightly variation for irradiation temperature over -78°C. Figure 7 shows significant dose rate effects.

2.4. Cellulose acetate dosimeter(CTA) [13]

2.4.1 Combined effects of irradiation temperature and dose rate and short term post-irradiation studies

The untinted cellulose triacetate(CTA) FTR-125 film dosimeters are commercially supplied by Fuji Photo Film Co., Tokyo, Japan. The dosimeters were cut into 8 x 10 mm for fitting to the standard 10 mm cuvette holder of spectrophotometer. Three films for each irradiation were held between two electron equilibrium layer of 3-mm thick acrylic and sealed at 60% r.h. in the polyethylene-aluminium foil laminate for protection against changing environmental condition specially humidity. The pre-irradiation absorbance for each dosimeter was read using Shimadzu UV-3101PC UV/vis spectrophotometer at 280 nm. The
irradiations were carried out using $^{60}$Co gamma cell 220 at dose rate of 2.26 and 0.27 Gy/s. The dosimeters were irradiated at 5, 10, 15, 20 and 25 kGy at the following temperatures: −18, 0, 25, 35 and 60°C using TURBO-JET air compressor control. Fluctuation for control of irradiation temperature was within 1°C. The irradiated dosimeters were kept at 25°C for 2 h before absorbance reading and reread again at 24 h and 7 d after irradiation for short term post-irradiation studies.

FIG. 6. Temperature dependence, relative to that at 25°C, of gamma response of GafChromic at dose rate 3.96 and 0.26 Gy sec$^{-1}$. Where the absorbance per unit thickness was measured at 580 nm.
2.4.2. Results and conclusion

The effect of irradiation temperature on the gamma response of CTA over the range 18°C up to 60°C for the dose range of 5 to 25 kGy are shown in Fig 9. Figure 10 shows significant dose rate effect at 2.26 and 0.27 Gy/s for the irradiation temperature of 25 and 35°C. The post-irradiation behaviour of dosimeters cover the range from 2 h to 7 day after irradiation was found slightly variation in Fig 11.
FIG. 9. Temperature dependence, relative to that at 25 °C, of gamma response of CTA at dose rate 2.26 Gy sec\(^{-1}\) where the absorbance per unit thickness was measured at 280 nm.

FIG. 10. Combined effect on the response of cellulose acetate (CTA) at dose rate of 2.26 and 0.27 Gy sec\(^{-1}\) with the irradiation temperature of 25 and 35 °C.
FIG. 11. Short term post-irradiation studies of cellulose acetate (CTA) at 25 kGy, analysis time 2, 24 hours and 7 days after irradiation for the dose rate 2.26 Gy sec\(^{-1}\).

2.5. Radiochromic film FWT-60-00 dosimeter [14]

The transparent radiochromic film, FWT-60-00 batch 5E4 and 7F7, are commercially supplied in 10 mm x 10 mm x 40–50 μm by Far West Technology, Inc. They are thin colourless films that change to deep blue upon irradiation to nominal absorbed doses from 1 to 50 kGy.

2.5.1. Combined effects of irradiation temperature and dose rate and short term post-irradiation studies

Three films for each irradiation were held between two electron equilibrium layer of 3–mm thick acrylic and sealed at 60% r.h. in the polyethylene-aluminium foil laminate for protection against changing environmental condition specially humidity. The pre-irradiation absorbance for each dosimeter was read using Shimadzu UV-3101PC UV/vis spectrophotometer at 605 nm. The dosimeters were conditioned for 1 h at each irradiation temperature before irradiation and then irradiated using a double-walled glass dewar flask for temperature control. The irradiations were carried out using \(^{60}\)Co Gammabeam 650 panoramic source at dose rate of 4.04 Gy/s for the dose range from 5 up to 50 kGy at the irradiation temperatures of −18, 0, 35 and 50°C using the coolants as shown in Table II. Fluctuation of the irradiation temperature was within ±3°C. The irradiated dosimeters were kept at 25°C for 2 h before absorbance reading and reread again at 24 h and 7 d after irradiation for short term post-irradiation studies. For the combined effect studies, the irradiations were carried out using two \(^{60}\)Co sources, gammacell 220 at absorbed dose rate of 2.7 Gy/s and Gammabeam 650 panoramic source at 0.18 Gy/s for the absorbed dose of 5 kGy at the following temperatures: −78, −18, 0, 25 and 60°C using the same conditions as previous experiment.
2.5.2. Results and conclusion

Figure 12 shows temperature dependence of the response of FWT-60-00 batch 7F7 at dose rate 4.04 Gy/s for dose range 5 to 50 kGy over the irradiation temperature of -18 up to 50°C. The results of the dose rate effect in Fig. 13 indicate that the bias on a dose interpretation based on calibration at a high dose rate would be underestimated by another irradiation to an unknown dose at a lower dose rate. The effect of post-irradiation on the response of dosimeter in Fig. 14 shows insignificant.

**FIG. 12.** Temperature dependence, relative to that at 35°C, of gamma response of radiochromic film FWT-60-00 batch 7F7 at dose rate 4.04 Gy sec^{-1}. Where the absorbance per unit thickness was measured at 605 nm.

**FIG. 13.** Combined effect on the response of radiochromic film FWT-60-60 batch 5E4 (at 5 kGy) at dose rate 2.7 and 0.18 Gy sec^{-1} with the irradiation temperature from -78 to 60°C.
FIG. 14. Short term post-irradiation studies on gamma response of radiochromic film FWT-60-00 batch 7F7 at 35 kGy, analysis time 2.24 hours and 7 days after irradiation for the dose rate 4.04 Gy sec\(^{-1}\).

2.6. Red Perspex 4034 polymethylmethacrylate dosimeter [15]

Harwell Red 4034 batch DA is a dyed polymethylmethacrylate dosimeters which are commercially available in the puncture-resistance polyester/aluminium/polyethylene laminated sachets for protection against changing environmental condition.

2.6.1. Combined effects of irradiation temperature and dose rate and short term post-irradiation studies

The irradiations were carried out using \(^{60}\)Co Gammabeam 650 panoramic source at absorbed dose rate of 4.04 Gy/s. The dosimeters were conditioned for 1 h and irradiated at each temperature using a double-walled glass dewar flask and stored at room temperature immediately after the end of irradiation. The dosimeters were irradiated for the dose range of 5 up to 50 kGy at the following temperatures: -18, 0, 35 and 50°C. Fluctuation of the irradiation temperature was within ±3°C. Table II shows the conditions in the dewar flask. The irradiated dosimeters were kept at about 25°C for 2 h before spectrophotometric (Shimadzu UV-3101PC) analysis and reread again at 24 h and 7 d after irradiation for short term post-irradiation studies. For the combined effect studies, the irradiations were carried out using two \(^{60}\)Co sources, gammacell 220 at absorbed dose rate of 2.7 Gy/s and Gammabeam 650 panoramic source at 0.18 Gy/s for the absorbed dose of 5 kGy at the following temperatures: -78, -18, 0, 25 and 60°C using the same conditions as previous experiment.

2.6.2. Results and conclusion

The results in Figs 15 and 17 show only slight variation in response of the PMMA Red 4034 on post-irradiation behaviour over the irradiation temperature of -18 up to 50°C for the
period of 2 h to 7 day. The temperature dependence at 5 kGy shows similar behaviour for the two dose rates investigated, 0.18 and 2.7 Gy/s, between 0°C and 25°C, but outside of this temperature range the dose-rate dependence was found to be significant as shown in Fig. 16.

**FIG. 15.** Temperature dependence, relative to that at 35°C of gamma response of red perspex 4034 batch DA at dose rate 4.04 Gy sec⁻¹. Where the absorbance per unit thickness was measured at 640 nm.

**FIG. 16.** Combined effect on the response of red perspex 4034 batch DA (at 5 kGy) at dose rate of 2.7 and 0.18 Gy sec⁻¹ with the irradiation temperature from -78 to 60°C.
FIG. 17. Short term post-irradiation studies on gamma response of red perspex 4034 batch DA at 35 kGy, analysis time 2, 24 hours and 7 days after irradiation for the dose rate 4.04 Gy sec\(^{-1}\).

3. CONCLUSION

As the national calibration laboratory for high-dose dosimetry, this research work has helped us to appreciate the influence of various parameters on the performance of many types of commercial routine dosimeters. Assuring that the calibration conditions are as close to the conditions of use as possible will increase the dosimetry accuracy and reliability for quality assurance in radiation processes.

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REFERENCES


