Determination of Sensitivity and saturation limit of phosphor imaging plates for photon energies up to 1.25MeV

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Abstract

Sensitivity calibration of imaging plates (IP) is important for quantitative measurements of intensity data obtained in various X-ray and gamma radiography experiments. To test the sensitivity of the IP (BAS2025) with the scanner (BAS5000) for higher photon energies, we have performed gamma exposure experimentsusing radionuclide (Co-57, Ba-133, Cs-137, Na-22 and Co-60). This provides useful information in assessing the intensities and dose received on IP in radiography especially with flash X-rays in the range 250keV to 1MeV.The IP was exposed for prolonged time to determine the saturation dose limit. The PSL intensity increases linearly up to $8x10^3$ with dose received. With further increase in dose the intensity goes nonlinear till it gets saturated at ~9070 PSL. The observed photon sensitivity was measured as 1.383 $x10^{-4}$ PSL/photon for 114 keV, 1.101 x 10^{-3} for 266 keV, 1.316 x 10^{-3} for 662 keV, 4.111 x 10^{-5} for 784 keV and 6.449 x 10^{-5} for 1250 keV.Both the sensitivity and the saturation dose are dependent on the photon energy.The calibration data of the SR2025 IP is used in assessing the dose in flash radiography experiments.

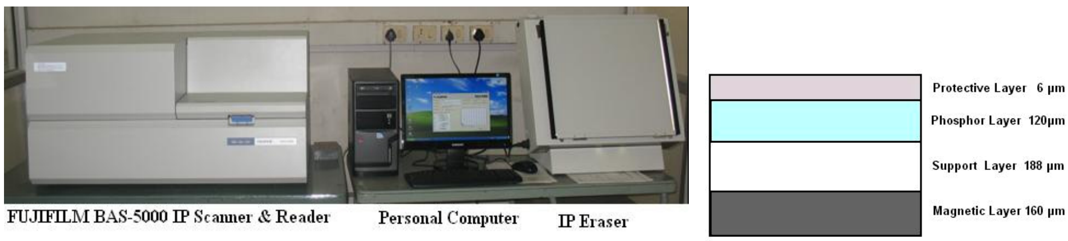
Key words: Photostimulated Luminescence, Phosphor imaging plate. SR2025, Radionuclide, Saturation dose, Sensitivity

Introduction

Image plates (IP) based on Photostimulable x-ray storage phosphor $BaFBr:Eu^{2+}$ are an alternative to conventional 2-dimensional detectors such as X-ray film[1,2]. The incident X-rays get absorbed in the phosphor and electron-hole pairs are generated. A fraction of the e-h pairs are trapped separately, holes at divalent Europium sites, electrons at F^+ and Br^+ vacancy sites. The concentration of trapped centers is proportional to the absorbed X-ray energy and forms the latent image. The latent image stored on the IP can be read out by irradiating the IP with He-Ne laser (λ=633 nm). The laser excites trapped electrons to recombine with Eu^{3+}. The decay of $Eu^{3+}$to Eu^{2+}causes the emission of photons λ=400 nm). The process is called photostimulated luminescence (PSL). A photomultiplier tube collects the PSL intensities. The resulting signal is converted and stored as a digital image and displayed on a monitor. After reading, the IP is exposed to strong visible light to erase the residual image and it can be reused. Variety of IPs and IP scanners are commercially available. The reading efficiency the PSL signal depends on the composition of the IP and design and performance of the readout system mainly laser power and spot size and scanning speed. Our laboratory is equipped with FUJIFILM scanner BAS5000 to use with BAS SR2025 IPs.Thesensitivity calibration of IPs is important for quantitative measurements of intensity data obtained in various X-ray and gamma radiography experiments. To test the sensitivity of the IP (BAS SR2025) with the scanner (BAS5000) for higher photon energies, we have performed gamma exposure experimentsusing radionuclides (Co-57, Ba-133, Cs-137, Na-22 and Co-60). The IP was exposed for prolonged time to determine the saturation dose limit. This provideduseful information in assessing the intensities and dose received on IP in our work with flash X-rays in the range 250keV to 1MeV.The details of the experiment for performing exposure, calibration and the results are given in this paper.

Experimental

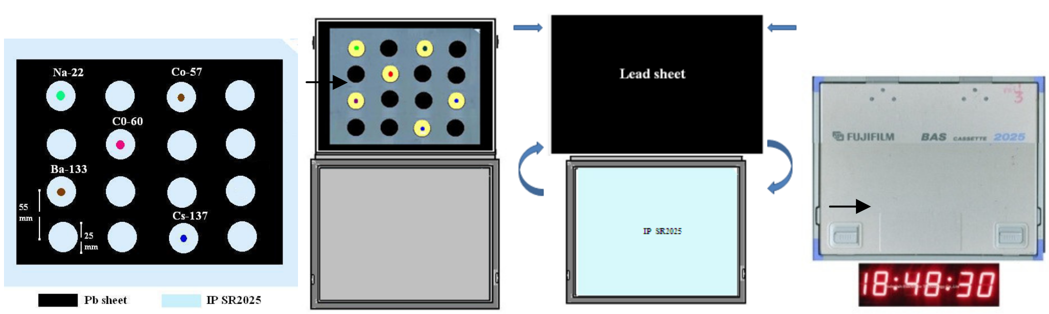
The image analysis setup consists of FUJIFILM make IP BAS SR2025 (size 20x25cm^2) and aPC controlled image analyzer BAS5000 and an IP eraseras shown in fig.1(a).The BAS-SR2025 IP is a four layer structure (fig.1(b)) with top layer of protective plastic layer of 6µm, the sensitive layer of 120µm made of BaFBr:Eu^{2+} phosphor crystals of size 5µm; followed by plastic support and magnetic layers. The magnetic layer keeps IP stuck on the reading stage while laser scanning. After exposure the IP was scanned with the analyzer set at 50µm pixel size, 4000 sensitivity at L5 level and image data stored in 8 bits gradation.The image plates were repeatedly used by erasing the residual image after the readout process. After every erasing the IP was read again to check any remains of residual or presence of ghost images.



(a) (b)

Fig.1 (a) BAS5000 image scanner system (b) Layer structure of IP

The gamma exposure to the IP was performed using radionuclide (Co-57, Ba-133, Cs-137, Na-22 and Co-60) point sources of known activity supplied by Atomic Energy regulatory Board, India. The details of these sources are given in table1. The sources were enclosed in a very thin walled circular box for ease of handling. For our experiment the sources were fixed on a lead sheet with circular holes of 25 mm diameter with pitch of 55 mm. The sheet holding the gamma sources was kept on IP for irradiation. In this arrangement the sources to IP distance remained constant to 2mm.The exposure procedure was performed in three steps as shown in fig.2. The Pb sheet with gamma sources was first fixed on the inner wall surface of the IP cassette cover. The sources were then covered with a lead sheet of 1mm. A pre-scanned erased IP was placed in the cassette with active area facing the sources. The lead sheet covering the sources was removed while closing the cassette cover in quick succession and exposure timer is switched on. It was previously ensured that the volume available in the closed cassette was enough to accommodate the IP and gamma sources template so that IP remained in contact with the sources. The IP was exposed for a required period of time. After the exposure the IP was removed from the cassette following the reverse of the procedure described above. Exposure experiments were carried out for time period of fraction of a minute to a few tens of hours.



1. 2. 3. 4

Fig.2. Steps involved in the exposing IP with various radionuclide sources

The latent images of the sources stored in the IP were then read out 5min after the exposure. The readout efficiency of the stored image depends on the scanner settings which was kept constant during scanning in all exposure experiments. Sensitivity of IP also depends on the time period between the exposure and reading; as the image fades due to thermal excitations of the trapped carrier and fading correction is needed for the data. Since the IPs were read 5 min after the exposure in all experiments; no fading correction was applied. The procedure of transferring the IP to the image reader was done in dark condition to avoid fading of latent image due to visible light. The details of the experiment are given in Table 1, which is self explanatory of the steps involved.

Results and Discussion

Fig.3 shows the IP images obtained for some of the exposure times. The images were corrected for noise reduction. It can be seen that as exposure time is increased there is corresponding increase in the PSL intensity and increase in spread of the regime of the source in contact with IP.

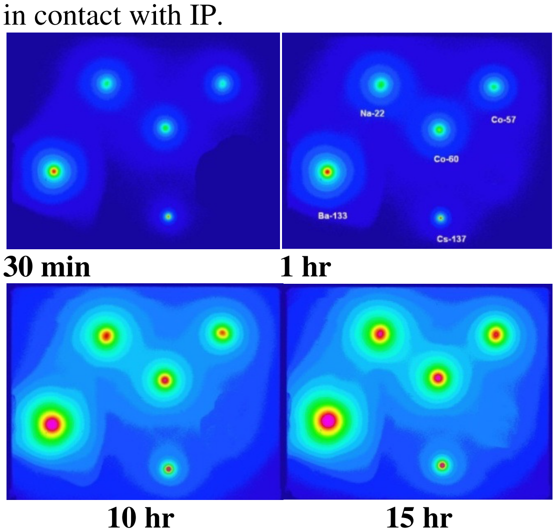


Fig.3. IP images of various gamma sources with exposures of 30min, 1hr, 10hr and 15hr

An intensity profile of individual spot was measured along with a 6mm strip (~120 50μm pixels) across the spot crossing the central intense portion. The intensity profiles for Co-60 source with typical exposure time are shown in fig.3. Fig.4 (a-c) gives intensity profiles of Co-60 source for exposure of 5, 15, 30 sec; 1, 2, 3, 5, 15, 30 min and 1, 2, 3, 5, 7, 10. 15, 17, 20 and 25hr duration. It shows increase in peak intensity with exposure time. The PSL intensity gets saturated at ~15 hr exposure and beyond giving a flat peak. The saturation in other sources occurs at exposures of ~17 hr (Na-22), ~25 hr (Co-57), >48 hr (Cs-137) and ~5hr (Ba-133) as shown in fig. 4(d).

This saturation limit depends on number of photons absorbed by IP which in turn depends on activity, half life time and photon energy emitted by individual source. These values are also given in table 1. The photon flux and dose received by IP were calculated using Rad Pro Calculator version 3.26 [ ]. Fig.5 shows plots of calculated Dose in mR vs. PSL intensity obtained by irradiating IP BAS2025. In case of Cs-137 the exposures up to 48 hr was necessary to reach the saturation limit.Fig.5 shows plots of dose received by the IP calculated at different exposure times vs. corresponding PSL values. The PSL intensity increases linearly with radiation dose received up to a certain value and then become nonlinear and saturates with further increase in dose. The saturation of PSL occurs at value of 9069.64 with set scanning parameters in our measurement.On the basis of dose and PSL values the radionuclides used in the experiment fall into two groups, one which saturates IP at lower value of dose and another at very high value of dose. These values are listed in table 2.The sources Co-57, Ba-133 and Cs-137 emit gamma photons of average energies of 0.114, 0.264 and 0.662 MeV respectively, whereas, that of Na-22 and Co-60 are 0.784 and 1.25 MeV. The PSL produced in the IP depends on absorption efficiency of the phosphor material which is highly dependent on incident photon energy. The incident photons interact with the phosphor material and generate a large number of low energy electron-hole pairs by photoelectric or Compton absorption. A small fraction of these pairs are trapped to form the image. When photon energy is more than 100 keV, the contribution of Compton recoil is more prominent. If the ranges of the electrons generated in the IP exceeds the thickness of the phosphor layer (~0.34mg/mm^2) they escape with depositing fraction of the energy in the phosphor. In case of Co-60 with average gamma photon energy of 1.25MeV the electrons produced have maximum range of 1800µm which larger than the pixel size (50µm) and thickness of the sensitive layer (~120µm).

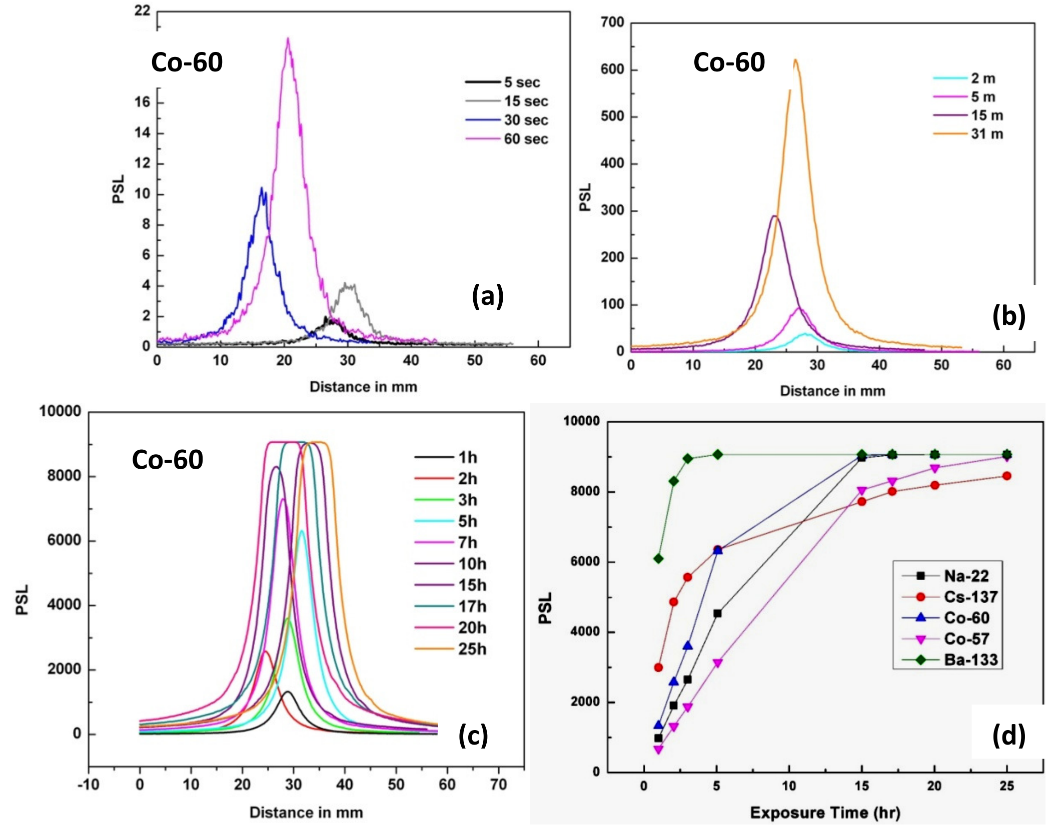


Fig4. Intensity profiles (a-b) of Co-60 source for all exposure times and (d) Exposure time vs PSL for all the sources used in the experiments

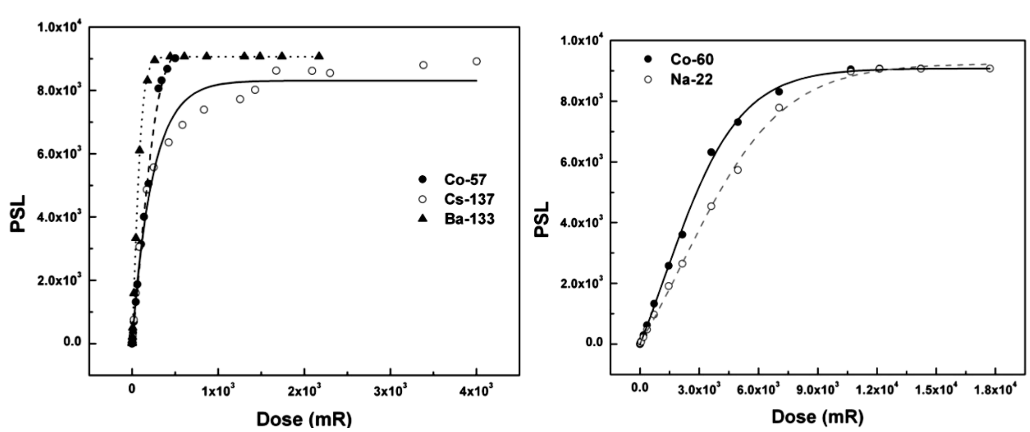


Fig.5. Dose vs PSL plot

In general about 3 PSL centers are created per absorbed keV. More irradiation time (more photon fluence) is required to produce sufficient amount PSL in IP. The PSL versus dose relation is linear up to the different values for different sources as given in table 2. The PSL intensity on average increases linearly up to $8x10^3$ with dose received. With further increase in dose the intensity goes nonlinear till it gets saturated at ~9070 PSL.

Sensitivity of imaging plate

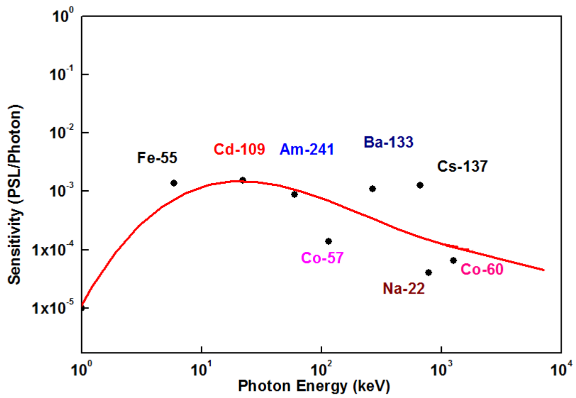


Fig.6 Sensitivity plot for IP BAS2025

The sensitivity of the imaging plate is defined as ratio of PSL/mm^2 to Photons/mm^2 or simply PSL/photon. It gives response of imaging plate to the incident photon fluence. It depends on the ratio of the detected to incident photons, mean number of PSL centers created in the phosphor per detected photon and number of photoelectrons created in the photomultiplier cathode per PSL center. The last parameter further depends on fraction of PSL centersreleased by laser light, itted by the light guide and the photocathode efficiency. Experimentally the PSL/mm^2 can be determined by quantifying the area of interest in the IP image. The calculations were performed using the quantification option in Multi Gauge Image processing software provided with the FUJI BAS5000 scanner by selecting circular region of interest (ROI) around the center of source image for every exposure. The diameter of ROI is selected by scanning each spot and fitting Gaussian to the intensity profile (as shown in fig.4 (a-c)) and taking the length of $\pm 2\sigma$ of the Gaussian curve as diameter of the ROI. The software gives the average value PSL/mm^{2}for the area of ROI.The photon fluence (photons/mm^2)incident on IP for various exposure times was calculated from decay per sec for source activity, number of photons released per decay and finally the no. of photons/mm^2 received on the IP at distance of 2mm. The PSL/mm^2 and photons/mm^2 values obtained for exposure of 3600 sec (typical) are given in table 1. The photon sensitivity of IP BAS2025 was calculated as 1.383 x10^{-4} PSL/photon for 114 keV, 1.101 x 10^{-3} for 266 keV, 1.316 x 10^{-3} for 662 keV, 4.111 x 10^{-5} for 784 keV and 6.449 x 10^{-5} for 1250 keV.The sensitivity decreases with increase in photon energy. N. Izumi et al [3]attributed this to the depth dependant readout efficiency of the laser scanner. Lower energy (a few keV) photons are absorbed in shallow depth at surface of the phosphor and higher energy photons (above 20keV) penetrate deeply and excite the entire volume of the phosphor. When the IP is scanned the readout efficiency of deep layer is lower than that on shallow surface. The diffuse transport of laser light and visible PSL signal is scattered by granular structure of the phosphor. Therefore sensitivity of high energy photons is reduced compared the for lower energy photons. They determined sensitivity values for X-ray energies 5.9, 24 and 59.541 keV using Fe-55, Cd-109 and Am-241 radioisotopes respectively and BAS2025 IP with BAS1800II scanner and performed the numerical modeling of the IP using MCNPX. The plot of sensitivity vs. photon energy is shown in fig.6 for exposures of 300sec (table 1). The sensitivity data of Izumi et al and present work are included in the plot for comparison. The observed photonsensitivities were found to be consistent with thesimulated model.The deviation of our sensitivity values from Izumi et al model may be due to different scanner used and its set parameters and thickness of IP. Our values lie in the band around the simulated curve to take account of depth effect.

Conclusions

The saturation dose limit and linearity region of dose vs. PSL is determined by exposing imaging plate SR2025 with various photon energies in the range 100 to 1250 keV. The

PSLintensity increases linearly up to $8x10^3$ with dose received. With further increase in dose the intensity goes nonlinear till it gets saturated at ~9070 PSL. Photon sensitivity of the imaging plate IP BAS SR2025 were measured .The observed photon sensitivity was measured as 1.383 $x10^{-4}$ PSL/photon for 114 keV, 1.101 x 10^{-3} for 266 keV, 1.316 x 10^{-3} for 662 keV, 4.111 x 10^{-5} for 784 keV and 6.449 x 10^{-5} for 1250 keV.

Table 1: Summary of the various radioisotopes used and sensitivity data calculated

Radioisotope Source	27-Co-57	56-Ba-133	55-Cs-137	11-Na-22	27-Co-60
Half Life (d)	271.80 ±0.05	3848.7 ±1.2	(1.099 ±0.004) 10^4	950.57 ±0.23	1925.23 ±0.27
Activity [kBq] as on25.05.2015	55.095	57.896	38.53	70.755	81.114
source to IP distance (mm)	2	2	2	2	2
Gamma energy (MeV)*	0.123	0.36	0.662	0.511 1.2745	1.172 1.332
Average gamma energy (MeV)	0.114	0.266	0.662	0.784	1.25
Photons per decay**	1.0537	1.3418	0.8499	2.7974	1.998326
Photons/mm^2/sec	1154.79	1545.291	651.389	3937.182	3224.304
Exposure time (sec)	3600	3600	3600	3600	3600
Photon fluence (photons/mm^2)	3.374 x 10^6	3.703 x 10^6	2.337 x 10^6	1.417 x 10^7	1.161 x 10^7
Average signal (PSL/mm^2)	423	4058	3076	636	881
Sensitivity (PSL/photon)	1.254 x 10^{-4}	1.096 x 10^{-3}	1.316 x 10^{-3}	4.487 x 10^{-5}	7.581 x 10^{-5}

Data for exposure time 300sec

Exposure time (sec)	300	300	300	300	300
Photon fluence (photons/mm^2)	2.603 x 10^6	3.069 x 10^5	1.943 x 10^5	1.155 x 10^5	9.579 x 10^5
Average signal (PSL/mm^2)	36	338	245	47.5	61.78
Sensitivity (PSL/photon)	1.383 x 10^{-3}	1.101 x 10^{-3}	1.26 x 10^{-3}	4.111 x 10^{-5}	6.449 x 10^{-5}

* Data taken from: Update of X-rays and gamma ray decay data standards for detector calibration and other applications, Vol. 1: Recommended decay data, high energy gamma ray standards and angular correlation coefficients, International Atomic Energy Agency, Vienna, 2007, ISBN 92-0-113606-4

Table 2. Dose (mR) vs. PSL intensity in linearity region and at saturation

Linearity region				Saturation level		
Radionuclide	Dose (mR)	PSL	Photon flux/cm^2	Dose(mR)	PSL	Photon flux/cm^2
Co-57	307	8054	4.8 x 10^9	>500	>9014	7.8 x 10^9
Ba-133	178	8311	4.3 x 10^8	442	9070	1.08 x 10^9
Cs-137	425	6358	6.9 x 10^8	>4002	8916	3.51 x 10^9
Na-22	5561.33	7780	2.9 x 10^9	11330	9067	5.87 x 10^9
Co-60	4955	7308	2.25 x 10^9	17720	9070	3.64 x 10^9

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