Abstract. A new method using imaging plates (IPs) to evaluate patient doses in interventional radiology (IR) procedures is developed. IPs are made of photostimulated luminescence (PSL) materials, are highly sensitive two-dimensional radiation sensors, and can be reused repeatedly. Mapping skin doses in complex fluoroscopy interventions helps determine the probability of a possible injury, helps find areas of overlapping irradiation fields, and can provide a permanent record of the most-exposed patient skin areas. Large films relatively insensitive to X-rays, such as Kodak EDR2, can be used for this mapping, but these films are not reusable and their linear range for accurate dose measurements only from 50 to 500 mGy. They are thus not adequate for indicating the likely onset of deterministic effects. The work reported in this paper explored the possibility of using IPs for estimating skin dose distributions in IR procedures with potentially higher doses. It was found that IPs could be used to obtain maps of patient skin doses up to 100 Gy and the linear range for accurate dose measurements is from 1 µGy to 10 Gy. Combining the sensitivity data measured using filters of three different metals showed that the PSL sensitivity of an IP to the dose equivalent (Hp(0.07)) is constant to within 8% for X-rays with effective energies from 30 to 120 eV. Irradiation, simulating actual fluoroscopy and radiography procedures showed that ratio of the weighted sum of the sensitivities obtained with three different metal filters to the sensitivities obtained values without filters was constant to within 5%.

1. Introduction

The use of interventional radiology (IR) in diagnostic and therapeutic procedures has seen a vast increase in recent years, primarily because of its numerous significant benefits. Associated with the high radiation doses resulting from the increasing complexity of IR procedures, prolonged fluoroscopy times, and large numbers of radiographs, however, there has also been an increase in the occurrence of deterministic effects in patients and hospital staff members [1-4]. The duration of an IR procedure usually ranges between 30 and 60 min and in some cases is even longer. Extended fluoroscopic times and increasing amounts of irradiation delivered to limited areas of the patient can cause deterministic effects ranging from transient erythema and dermatitis to skin necrosis. Radiation dose measurements in IR are very difficult, so patient doses are usually estimated after the IR procedure. A retrospective estimate, though, includes some degree of uncertainty because it is requires the individual who performed the procedure to remember such details as the tube current, tube potential, total screening time, the and number of images acquired. Thus, there is an apparent need for accurately measuring radiation doses during these procedures. Several methods for patient dosimetry are reported [5]:

1. measuring the dose-area product (DAP) (Gy.cm²) by placing a large-area ionization chamber on the head of the X-ray tube,
2. calculating the entrance skin dose (ESD), which can derived from the DAP if the field size and focus-to-skin distance are known,
3. using Monte Carlo theoretical calculations with mathematical phantoms,
4. directly measuring ESD by using thermoluminescence (TL) dosimeters.

The DAP alone is a poor indicator of the onset of deterministic effects since the projections vary during IR procedures, but the ESD is an important indicator. The easiest way to determine the ESD is by direct measurement with special detectors such as TL dosimeters that automatically correct for radiation backscattered from the patient. Incorrect positioning of dosimeters, however, can easily result in underestimation of the ESD. Mapping skin doses in complex fluoroscopy interventions is useful to determine the probability of a possible injury, to detect areas of overlapping irradiation fields, and to obtain a permanent register of the patient’s most exposed skin areas. Since most installations avoid high dose rates in the vicinity of the patient and staff by using fluoroscopy equipment configured with an over-couch image intensifier and an under-couch X-ray tube, the patient’s skin dose can be mapped by placing a large piece of film relatively insensitive to X-rays on the tabletop just under the patient. Guibelalde reported that Kodak EDR2 film could be used this way to estimate maximum skin doses up
to 1400 mGy but that the linear range for accurate dose measurements was only from 50 mGy to 500 mGy [6]. Furthermore, films like EDR2 cannot be reused.

The aim of the work reported in the present paper was to evaluate the possible use of imaging plates (IPs) for estimating skin dose distributions in IR with potentially higher doses. IPs are highly sensitive and easily handled two-dimensional radiation sensors and are widely used in computed radiography (CR), which is a technique for acquiring images in a digital format [7]. They have also been used as dosemeters in studies of environmental gamma rays [8]. An IP is made of europium-doped BaFBr, a photostimulated luminescence (PSL) material whose sensitivity to 12–120-keV X-rays is $10^3$ times that of X-ray emulsion films [9]. For the readout process, PSL is excited by light from a He-Ne laser and the blue emission from Eu$^{2+}$ is detected by a photomultiplier tube (PMT) in the image reader. The residual image on the IP can be erased by irradiation with visible light, allowing repeated use of the same IP. Deterministic effect occurs at exposures of several grays. The PSL of an IP irradiated by $^{60}$Co γ-rays is linearly related to doses from 1 µGy to 10 mGy [10], and for Cu K$_{\beta}$ and Mo K$_{\alpha}$ (17.4-keV) X-rays the dynamic range of the PSL of an IP has been reported to extend over five orders of magnitude: from less than 10 to more than $10^5$ X-ray photons/(100 µm)$^2$ [11]. The present upper limit of the measurable dose, however, is determined by the range of the output circuit of the image reader system rather than by the properties of the IP.

A simple technique that could be used to extend the upper limit of the measurable dose without adapting the readout system was therefore devised, and the degree to which this technique could extend the upper limit was investigated. The sensitivity of IPs to X-rays with effective energies of 30–120 keV, which covered the X-rays energies range used in IR procedures, was also investigated.

2. Experimental

2.1. Imaging plate (IP) and readout technique

Commercially available BAS-TR imaging plates, manufactured by Fuji Photo Film Co., Ltd. were used in this work. They have a 50-µm-thick photostimulable phosphor (BaBrF:Eu$^{2+}$) and have no protective surface layer. IPs of various sizes, cut from sheets of BAS-TR, were wrapped in black polyethylene to shield them from sunlight during irradiation. Just prior to each use, residual latent images caused by natural radiation or produced in previous experiments were erased by illumination with visible light. The IPs were scanned with a 200x200-µm BAS-1000 readout system (Fuji Photo Film Co., Ltd.). Ionizing radiation creates a large number of trapped centers in the sensitive phosphor layer of an IP, leaving a record of information about the amount and position of deposited energy. Stimulating the IP optically with a He-Ne laser (633 nm) in the image reader provides the energy necessary to release the trapped charges and causes photostimulated luminescence (390 nm) at the positions of the trapped centers. The luminescence is detected by a PMT in the image reader, and the PMT output is logarithmically amplified and converted to a 10-bit-depth digital image that can be processed by computer and displayed on a computer screen.

2.2. Experimental setup

2.2.1. Cellophane technique and annealing technique

Two X-ray units (MBR-1520R, Hitachi Medico Co. and KXO-15, Toshiba Medical Co.) were used to investigate IP responses to X-rays over a wide range of absorbed doses. Both of these units have a tungsten anode. The tube voltages used were 150 kV in the MBR-1520R and 100 kV in the KXO-15 the focus-IP distance was fixed at 450 mm for the MBR-1520R and at either 1388 or 2650 mm for the KXO-15. For the MBR-1520R, the absorbed dose was measured by an ionization chamber installed inside the X-ray unit. For the KXO-15, a separate ionization chamber (RAMTEC 1000plus, EXRADIN Inc.) was used. The upper limit of the measurable dose was extended without adapting the readout system by decreasing the intensity of the 633-nm laser light and PSL value of 390 nm by using commercially available 20-µm-thick sheets of red and blue cellophane placed over the IPs during the readout process. The transmittance (%) of each color of cellophane in the wavelength range of 300 to 800 nm was measured with 1.0-nm resolution by a spectrophotometer (Hitachi 330).
The use of an annealing process to decrease the PSL intensity was explored by investigating the effects of annealing temperature and time. After the IPs were irradiated with X-ray doses of approximately 67 mGy by the MBR-1520R, they were kept in an aluminum IP cassette inside an incubator before the latent images on them were read. The characteristics of the IPs were measured after periods ranging from 4 to 377 hours after irradiation and at temperatures of 80°C, 100°C, and 120°C.

2.2.2. PSL responses to X-rays of various effective energies

IP sensitivity depends on the photon energy, particularly when the energy is low [9]. The relation between sensitivity and X-ray energy was investigated by putting the IP, which was in contact with various metal filters, on an acrylic phantom and exposing it to X-rays with effective energies of 30, 40, 60, 80, and 120 keV. The acrylic phantom was 15 cm thick and had a 40 x 40-cm front face. The IPs were placed 2 m from the X-ray target in the X-ray generator at Japan Quality Assurance Organization. The set of filters used in these experiments were made of 0.3-, 0.5-, and 1.0-mm-thick aluminum, 0.1- and 0.3-mm-thick copper, and 0.5- and 1.0-mm-thick cadmium. The filter set was attached to both IP surfaces. The exposure doses on the IP attached to the phantom were fixed at 60 µGy (air kerma). PSL data from IPs were read out 24 h after exposure.

To generate the data needed to compare the PSL values obtained with the three different metals with the PSL values obtained without filters, IPs were placed on the tabletop just under an acrylic phantom and the X-ray beam was provided from under the table, simulating actual medical practice in fluoroscopy and radiography. The acrylic phantom was 20 cm thick and had a 33 x 33-cm front face. Two typical IR procedures were performed by using X-ray beams from the X-rays generator (KX0-2050, Toshiba Medical Co.) at Yamagata University Hospital, varying tube potential between 60 kV and 120 kV and varying tube current between 1.6 mA and 3.2 mA for fluoroscopy and 250 mA and 400 mA for radiography. To know the dose on a real-time during the procedure, a Skin Dose Monitor (SDM104-101, McMahon Medical Co.) was placed beside IPs.

3. Results and discussion

3.1. Linearity of the relation between PSL density and irradiated dose

When IPs are scanned in the conventional way, there is a good linear relationship between PSL density (PSL/mm²) and the absorbed dose in the range from 1 µGy to 600 µGy. The upper limit of PSL density is less than 4000. That is, the limit of the output circuit of the image reader system corresponds to about 600 µGy. The results obtained when covering the IPs with sheets of colored cellophane during the readout are shown in FIG. 1. The effect of cellophane on PSL density was investigated in combinations of two colors of cellophane—red-blue, blue-blue, and red-red—as well as in combinations of three colors: red-red-blue and red-blue-blue. With the combinations of two colors, the relation between PSL intensity and irradiated dose was linear for doses from $10^{-1}$ to $10^4$ mGy. With the combinations of three colors, a dynamic range was up to $10^5$ mGy, indicating that this upper limit is the property of the IP itself. When IPs are scanned in the conventional way, approximately 30% of a latent image is read out with a single laser-beam irradiation. When the IPs are scanned using the cellophane technique, only a few percent of a latent image is read out by several successive laser-beam irradiations, since the cellophane sheets decrease the intensity of the 633-nm laser light. Therefore, the use of this new cellophane scanning technique can, in combination with conventional scanning, extend the dynamic range from 1 µGy to $10^7$ mGy; that is, by eight orders of magnitude.

The transmittance of cellophane sheets of each color changed with the wavelength. The transmittance of the red cellophane was 81.47% at 633 nm and 2.46% at 390 nm, whereas that of the blue cellophane was 0.73% at 633 nm and 53.53% at 390 nm. Thus the red cellophane allows 633-nm laser light to pass through effectively but prevents the PMT from collecting the 390-nm PSL, whereas the blue cellophane blocks the laser light but allows the PSL to pass through it.
Although the IP has a number of advantages, the large fading effect of IPs becomes an obstacle for quantitative applications. That is, some charges stay trapped at localized defects but others recombine with holes over time after irradiation, and this recombination is temperature dependent. Thus, for accurate dose measurements, the fading effect should be accounted for. We have continued to measure the fading characteristics and determined precise equations to express fading as a function of elapsed time t and absolute temperature K [12-14]. The equations consist of four or five exponentially decaying terms, each having several activation energies. Appropriate annealing procedures eliminate trapped charges with low activation energies, enabling the radiation dose to be estimated accurately. Annealing also decreases the effect of fading and decreases the intensity of the PSL signal. Thus, an annealing technique should also be effective in extending the range of X-ray irradiation doses that can be measured by using IPs.

The effect of annealing on the PSL value is just the same as that of the fading, so the temperature dependence of the annealing after X-ray irradiation can be expressed by the following equations:

\[
\frac{(PSL)_t}{(PSL)_0} = 9.96 \times 10^{-1} \exp(-1.99 \times 10^{12} t \exp(-1.05 \times 10^{9} / K)) + 3.98 \times 10^{-6} \exp(-4.96 \times 10^{10} t \exp(-1.05 \times 10^{9} / K)) + 3.98 \times 10^{-4} \exp(-1.56 \times 10^{9} t \exp(-1.02 \times 10^{9} / K))
\]

where

\((PSL)_0\) and \((PSL)_t\) are respectively the PSL at time 0 and the PSL t (hours) after irradiation, and K is the absolute temperature.

The PSL values calculated from Eq. (1) and those measured in experiments at 80°C, 100°C, and 120°C showed good agreement at all temperatures and over all time periods. Several IPs that were irradiated with X-ray doses from 7.7 mGy to more than 10^4 mGy were read out after the appropriate annealing conditions calculated from Eq. (1); that is, at 100°C for 70 hours. The plot of PSL density (PSL/mm²) against absorbed dose (mGy) show excellent linearity (FIG. 2). Annealing can extend the upper limit to over 10^4 mGy and can also decrease the effect of fading, but this process takes a few days. Annealing should therefore be use in combination with colored cellophane.
3.2. PSL responses to X-rays energy and energy dependence correction

The energy dependence of IP sensitivity (PSL· mm$^{-2}$· mSv$^{-1}$) measured in the experiments with and without aluminum, copper, and cadmium filters of various thicknesses is plotted against effective X-ray energy in FIG. 3. The conversion coefficients Hp(0.07) between air collision kerma and dose equivalent at depth 0.07 mm that were used in calculating these energy dependences are from a report by Grosswendt [15]. Each sensitivity measured without a filter has a peak at around 50 keV, which is caused by the K electron absorption of Ba, and gradually decreases towards both lower and higher energies. FIG 3(a) shows that the sensitivities to low-energy X-rays, below 50 keV, decrease with increasing thickness of the aluminum filter but that the sensitivities to X-rays with energies above 50 keV are almost the same with and without an aluminum filter. This indicates that even the thickest aluminum filter absorbed almost none of the higher-energy X-rays. FIGs 3(b) and 3(c) show the IP sensitivities measured with copper and cadmium filters decreased with increasing filter thickness over the entire range of effective X-ray energies. The greater decrease observed in the experiments with cadmium filters was greater than that observed in the experiments with copper filters because of the higher atomic number of cadmium.

If dose is to be accurately estimated from PSL, the PSL per dose equivalent should be independent of effective X-ray energy. As shown in FIG 3(d), a constant PSL per dose equivalent independent of effective X-ray energy can be obtained by taking the weighted sum expressed by

$$\text{Res}_{\text{sum}} = \text{Res}_{\text{Al}} - 0.92\text{Res}_{\text{Cu}} + 2.82\text{Res}_{\text{Cd}},$$  \hspace{1cm} (2)

where

$\text{Res}_{\text{Al}}, \text{Res}_{\text{Cu}}$, and $\text{Res}_{\text{Cd}}$ are respectively the IP sensitivities measured with 0.5-mm-thick aluminum, 0.1-mm-thick copper, and 1.0-mm-thick cadmium filters.

FIG. 3(d) shows that the IP sensitivity so obtained is constant to within 8% for X-rays with effective energies from 30 to 120 keV.

The integrating dose during two experiments with X-ray irradiation simulating actual medical practice for fluoroscopy and radiography were 1,000 mGy and 900 mGy, respectively, measured by using a Skin Dose Monitor. These experiments showed that ratio of the weighted sum calculated from Eq. (2) to values without filters remained constant to within 5% in two typical IR procedures. This indicates...
that metal filters are not necessary when IPs are used for estimating skin dose distributions in IR. $\text{Hp}(0.07)$ values can be easily obtained by multiplying PSL values measured without filters by a constant.

**FIG. 3.** PSL sensitivities measured with and without (a) aluminum, (b) copper, and (c) cadmium filters of different thicknesses. (d): weighted sum of three PSL sensitivities measured with different filters.

### 4. Conclusion

A new method using imaging plates to evaluate patient doses in interventional radiology (IR) procedures has been developed. The use of cellophane and annealing enables maximum skin doses ranging from 1 µGy to 100 Gy—that is, varying over eight orders of magnitude—to be estimated from the photostimulated luminescence (PSL) of imaging plates, and the linear range for accurate dose measurements is from 1 µGy to 10 Gy. Combining the sensitivity data measured with filters of three different metals showed that the sensitivity of an IP to the dose equivalent ($\text{Hp}(0.07)$) is constant to within 8% for X-rays with effective energies of 30 to 120 keV. Irradiation simulating actual medical practice for fluoroscopy and radiography showed that ratio of the weighted sum of the sensitivities measured with filters of three different metals to the sensitivities measured without filters was constant to within 5% in two typical IR procedures. This result indicates that $\text{Hp}(0.07)$ values can be easily obtained by multiplying PSL values measured without filters by a constant. This, along with the possibility of reusing IPs repeatedly by irradiating them with visible light between uses, supports the use of IPs for estimating and mapping skin dose distributions in high-dose IR procedures.