Personal Dosimetry in Pulsed Photon Fields with the Dosepix Detector

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Abstract

First investigations regarding dosimetric properties of the hybrid, pixelated, photon-counting Dosepix detector in a pulsed photon field (RQR8) for the personal dose equivalent \(H_p(10)\) are presented. The influence quantities such as pulse duration and dose rate were varied, and their responses were compared to the legal limits provided in PTB-A 23.2. The variation of pulse duration at a nearly constant dose rate of 3.7 Sv/h shows a flat response around 1.0 from 3.6 s down to 2 ms. A response close to 1.0 is achieved for dose rates from 0.07 mSv/h to 35 Sv/h for both pixel sizes. Above this dose rate, the large pixels (220 \(\mu m\) edge length) are below the lower limit. The small pixels (55 \(\mu m\) edge length) stay within limits up to 704 Sv/h. The count rate linearity is compared to previous results, confirming the saturating count rate for high dose rates.

Index Terms— Pulsed photon fields, hybrid pixel detector, active personal dosimetry

1 Introduction

Dosimetry in pulsed photon fields with active electronic personal dosemeters (APDs) is an important topic of the last decade. A pulsed radiation field is defined as ionizing radiation with a pulse duration shorter than 10 s [1]. With this definition, most X-ray tubes in medical applications are classified as pulsed radiation emitters [2]. Tests performed in [3–6] showed an insufficient response of APDs in pulsed photon fields, with the main issue being high peak pulse dose rates and short radiation pulse durations. The EURADOS Report 2012-02 [7] confirmed these findings with only a hybrid dosemeter being able to determine the dose within \(\pm 30\%\) at high dose rates up to 55 Sv/h. This can be an issue, especially in interventional radiology and interventional cardiology (IR/IC), where staff would profit from an APD with the capability to detect low energies and pulsed radiation [8]. It was further found that APDs are almost entirely insensitive in the direct beam of medical diagnostic situations where a pulse duration smaller than 20 ms and a dose rate up to 400 Sv/h can be expected [9]. The Dosepix detector [9] was developed in order to circumvent such problems. In this work, the dose rate and pulse duration dependence of the normalized response for the personal dose equivalent \(H_p(10)\) were measured in a pulsed photon field with the Dosepix detector on an ISO (International Organization for Standardization) water slab phantom in accordance with ISO standards [9,10]. In the following, the corresponding results are presented.

2 The Dosepix detector

Dosepix is a hybrid, pixelated, photon-counting X-ray detector. The hybrid design consists of an application-specific integrated circuit (ASIC) and a semiconductor sensor layer connected pixelwise to the ASIC. As described in [11] and in this work, a 300 \(\mu m\) thick silicon sensor is used. The pixel layout comprises 16\(\times\)16 square pixels with 220 \(\mu m\) pixel pitch with a p-in-n doping profile. The upper two and lower two rows of the pixel matrix consist of small pixels
with an edge length of 55 µm, while the remaining 12 rows consist of larger pixels with an edge length of 220 µm. The smaller pixels detect fewer events than the larger pixels and therefore have a lower tendency for pile-up, which allows applications at high-flux conditions. The Dosepix can be operated in 3 different programmable modes: the photon-counting mode, the integration mode, and the energy-binning mode. Here, the Dosepix detector is used in the latter one, which is used for dosimetry applications. The energy-binning mode pixelwise counts events in one of 16 histogram bins according to the deposited energy of the event. The energy bin edges are individually programmed for each pixel. The Dosepix operates dead-time-free using the rolling-shutter principle. A single column is read out at a time while the rest of the matrix continues to process signals, which is a significant advantage in practical applications in pulsed photon fields, where radiation pulses are random in time. Information regarding the characterizations of Dosepix with X-rays and analog test-pulses can be found in [12], and measurements of the count rate linearity in dependence of the dose rate can be found in [13]. A dosimetry system consisting of 3 Dosepix detectors is utilized as described in [11], where the energy and angular dependence in continuous photon fields were already presented.

3 Methods

The tests in pulsed photon fields were performed in collaboration with and at the PTB (Physikalisch-Technische Bundesanstalt Braunschweig) using its X-ray unit for pulsed radiation GESA (GEpulste Strahlungs Anlage) presented in [4]. The chosen reference radiation field is the medical radiation quality RQR8 with a tube voltage of 100 kV filtered with 3.36 mm aluminum and a mean energy (fluence) of 51 keV [14]. Each measurement was repeated 2 or 3 times for statistical purposes. According to ISO standards [10], the dosemeter was irradiated on an ISO water slab phantom. However, to achieve very high dose rates up to 1080 Sv/h, the dosemeter had to be irradiated relatively close to the X-ray tube resulting in small field diameters down to 8.5 cm. In these cases the dosimetry system was irradiated without the ISO water slab phantom which has a 30 cm × 30 cm cross-section. Correction factors were determined for measurements with and without the phantom and measurements with a small (8.5 cm) and a large (42.0 cm) field diameter. The correction factors are stated in Table 1 and were used to correct all measurements to the equivalent of the dosemeter being placed on the ISO water slab phantom that is completely irradiated to guarantee $H_{p}(10)$ conditions. The quantity of interest is the change of the response $R_i$ relative to the response at reference conditions $R_0$, i.e., the normalized response. The response is defined by the ratio of the indication (calculated dose with Dosepix) and the reference dose determined by monitor ionization chambers which are practically independent of the dose rate and pulse duration. The change of the normalized response has to fulfill the following condition according to [15]

$$1 + f_{\text{min}} \leq R_i^{\text{Norm}} = \frac{R_i}{R_0} = \frac{H_{\text{DPX}}^i}{H_{\text{ref}}^i} \frac{H_{\text{DPX}}^0}{H_{\text{ref}}^0} \leq 1 + f_{\text{max}}$$

(1)

with $R_i$ being the response at measurement $i$, $H_{\text{DPX}}$ the dose measured by the Dosepix dosimetry system, $H_{\text{ref}}$ the reference dose, and $f_{\text{min}}$ and $f_{\text{max}}$ depending on the influence quantity (see Table 2). The statistical uncertainty of the normalized response is calculated via:

$$u(R_i^{\text{Norm}}) = R_i^{\text{Norm}} \sqrt{\left(\frac{u(H_{\text{DPX}}^i)}{H_{\text{DPX}}^i}\right)^2 + \left(\frac{u(H_{\text{ref}}^i)}{H_{\text{ref}}^i}\right)^2}.$$  

(2)

The minimum requirements for the dose rate and pulse duration for conformity assessment are shown in Table 2.

Table 1: Correction factors for the phantom influence and the field-diameter influence

| Pixel size | Presence of Phantom correction | Field diameter correction |
|------------|-------------------------------|--------------------------|
| 55 µm      | 1.148±0.004                   | 1.033±0.003              |
| 220 µm     | 1.168±0.002                   | 1.024±0.007              |
4 Results and Discussion

4.1 Dependence on the pulse duration

The pulse duration was varied between 2 ms and 3.6 s, while the dose rate was held nearly constant at 3.7 Sv/h. Due to the dead-time-free measurement of the Dosepix, no dependency on pulse duration is expected. Figure 1 shows the normalized response for both pixel sizes. The response value at 3.6 s was chosen as reference $R_0$. The normalized response is flat within the margin of the uncertainty bars. Overall, all data points are within limits.

4.2 Dependence on the dose rate

The measurements for the dependence on the dose rate were performed in the range from 0.07 mSv/h to 1080 Sv/h. To achieve such dose rates, both the reference dose and the pulse duration were varied. The response for both the small and large pixels was evaluated and is shown in Figure 2. Both pixel sizes have a nearly flat response up to about 35 Sv/h. The normalized response of the large pixels falls under the lower limit, slightly below 100 Sv/h, whereas for the small pixels, a dose rate up to about 704 Sv/h is achievable in the used reference field. The small pixels would allow an active warning in accident situations, e.g., if the person is exposed to the direct X-ray beam of a medical diagnostic X-ray tube where dose rates up to 400 Sv/h can occur.

Table 2: Minimum requirements for conformity assessment according to PTB-A 23.2 for $H_p(10)$ dosemeters

| Quantity               | Minimum rated range of use | Reference value | $f_{\text{min}}$, $f_{\text{max}}$ |
|------------------------|-----------------------------|-----------------|-----------------------------------|
| Dose rate              | 0.1 µSv/h to 1 Sv/h         | 1 mSv/h         | -0.13, 0.18                       |
| Radiation pulse duration | 1 ms to 10 s                 | Response at continuous radiation | -0.2, 0.2                          |
The measurements with the RQR8 spectrum when varying the dose rate are compared to previous measurements performed in [13]. For comparability, the abscissa is first re-scaled to Sv/s and then divided by the $H_p(10)/K_{air}$ conversion coefficient for the RQR8 spectrum (1.438 Sv/Gy). The results are shown in Figure 3 for each pixel size of the three detectors and are additionally labeled by their filter cap, i.e., aluminum cylinder with a thin aluminum foil on its top, which has a hole above the sensor (free), aluminum half-sphere (Al), and tin half-sphere (Sn). Similar behavior is observed as presented by Zang et al. [13], which means that the count rate saturates with high dose rates for unfiltered or weakly filtered detectors. The Dosepix filtered with tin shows for both pixel types no saturation and overall a low count rate. The explanation for the saturation is stated by Zang et al. in arguing that analog pile-up is increasing with an increasing dose rate which is equal to an increase of the flux. Therefore, an increase in the dose rate flattens the deposition spectrum in the detector, namely by converting several low-energy photons into a single high-energy event. For dosimetry, this implies that the dose determination is impacted. A correlation between the normalized response and count rate is observed. From the turning point at 35Sv/h onward, the response falls below the limit. The compensation of the larger values of the conversion factor in higher energy bins is not strong enough to counteract the loss of separate events. Even due to the count rate saturation and analog pile-up, a good normalized response is achieved. The reason for this is that one of the three detectors - namely the Dosepix filtered with the tin.

4.3 Count rate linearity

The measurements with the RQR8 spectrum when varying the dose rate are compared to previous measurements performed in [13]. For comparability, the abscissa is first re-scaled to Sv/s and then divided by the $H_p(10)/K_{air}$ conversion coefficient for the RQR8 spectrum (1.438 Sv/Gy). The results are shown in Figure 3 for each pixel size of the three detectors and are additionally labeled by their filter cap, i.e., aluminum cylinder with a thin aluminum foil on its top, which has a hole above the sensor (free), aluminum half-sphere (Al), and tin half-sphere (Sn). Similar behavior is observed as presented by Zang et al. [13], which means that the count rate saturates with high dose rates for unfiltered or weakly filtered detectors. The Dosepix filtered with tin shows for both pixel types no saturation and overall a low count rate. The explanation for the saturation is stated by Zang et al. in arguing that analog pile-up is increasing with an increasing dose rate which is equal to an increase of the flux. Therefore, an increase in the dose rate flattens the deposition spectrum in the detector, namely by converting several low-energy photons into a single high-energy event. For dosimetry, this implies that the dose determination is impacted. A correlation between the normalized response and count rate is observed. From the turning point at 35Sv/h onward, the response falls below the limit. The compensation of the larger values of the conversion factor in higher energy bins is not strong enough to counteract the loss of separate events. Even due to the count rate saturation and analog pile-up, a good normalized response is achieved. The reason for this is that one of the three detectors - namely the Dosepix filtered with the tin.
cap - is only in the beginning stage of its saturation. The latter statement implies that its 16 energy bins appropriately represent the energy deposition spectrum and that its partial dose is still correctly determined.

5 Conclusion

The Dosepix detector’s dependence of the normalized response in an RQR8 pulsed photon field (with a mean energy of 51 keV) was shown for the variation of the pulse duration and the variation of the dose rate. Both tests show promising results for applying the Dosepix detector as an active personal dosimeter in pulsed photon fields. Further tests in different energy ranges need to be performed to identify the largest possible dose rate within the legal limits for the normalized response. The pulse duration independence of the dose measured by the prototype of a Dosepix dosimetry system is a direct result of the dead-time-free readout principle of the Dosepix acting as a camera-like radiation detector. Even the shortest pulse durations will not pose any problems to the Dosepix detector, provided that the dose rate during the pulse does not exceed certain limits. As demonstrated here, these limits concerning dose rate are substantial - i.e., in the order of 100 Sv/h and higher - compared to other commercial electronic dosimeters that saturate in the region of a few Sievert per hour. Therefore, it is concluded that the Dosepix detector is a viable detector for dosimetry of pulsed photon fields.

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