# Energy response improvement for photon dosimetry using pulse analysis

H. Zaki Dizaji[1)]

Faculty of Science, Imam Hossein Comprehensive University, Tehran, Iran

**Abstract:** During the last few years, active personal dosimeters have been developed and have replaced passive personal dosimeters in some external monitoring systems, frequently using silicon diode detectors. Incident photons interact with the constituents of the diode detector and produce electrons. These photon-induced electrons deposit energy in the detector's sensitive region and contribute to the response of diode detectors. To achieve an appropriate photon dosimetry response, the detectors are usually covered by a metallic layer with an optimum thickness. The metallic cover acts as an energy compensating shield. In this paper, a software process is performed for energy compensation. Selective data sampling based on pulse height is used to determine the photon dose equivalent. This method is applied to improve the energy response in photon dosimetry. The detector design is optimized for the response function and determination of the photon dose equivalent. Photon personal dose equivalent is determined in the energy range of 0.3–6 MeV. The error values of the calculated data for this wide energy range and measured data for $^{133}$Ba, $^{137}$Cs, $^{60}$Co and $^{241}$Am-Be sources respectively are up to 20% and 15%. Fairly good agreement is seen between simulation and dose values obtained from our process and specifications from several photon sources.

**Keywords:** personal dose equivalent, photon dosimetry, diode detector, energy compensation

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## 1 Introduction

Silicon semiconductor detectors are a useful technology for monitoring energetic charged particles, photons and neutrons. In comparison to gas chambers or scintillation techniques, these detectors have useful specifications, such as their small size, low weight, simple operation, low voltage power supply and high energy resolution. For these reasons, semiconductor detectors have found applications in physics research and in the field of radiation protection and dosimetry in recent years [1, 2].

Photons are detectable by secondary electrons, which produce charged carriers in matter, in this case, in semiconductors. Silicon diode detectors are less sensitive to high energy photon radiation than low energy photon radiation. Photons can produce secondary electrons via Compton scattering, the photoelectric effect and pair production. For low energy photons, the photoelectric effect is predominant, leading to a storage over-response in the low energy range and an under-response in the high energy range. One well-known solution consists of covering the detectors with adapted shields. In this type of detector, a cover compensating for the photon energy, consisting of carefully selected materials, is placed in front of the detector. The compensating cover has a modified energy dependence of the detection response function. The energy of the secondary electrons is deposited in the sensitive volume of the detector, partly as ionization energy. The generated charge carriers produce a pulse that can be registered by the electronic system. Silicon diode detectors coupled with an energy compensating cover are frequently used for active personal dosimeters (APDs) for monitoring of external radiation [1, 3].

In recent studies on photon dosimetry, the detectors were covered by a metallic layer with an optimum thickness. The metallic cover acts as an energy compensating shield [4–6]. A single diode for measuring photon and neutron dose equivalent has been already published by Luszik–Bhadra [7]. In this paper, photon dosimetry is based on an analysis of the secondary electron pulses in a pin diode detector. Signals acquired in a pulse height interval were used for photon response. The pulse analysis method was developed by introducing a data sample from the readout of the pin diode detector. Selective data sampling was performed for energy compensation in the range of 0.3–6 MeV.

The well-known MCNP code was used to simulate the photon transport in material, and calculate the optimum thickness and response functions [8].

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1) Corresponding author: hz.dizaji@yahoo.com

## 2 Theory

Photons interact with detector system materials and produce secondary electrons. Pin diode detectors have small dimensions in comparison with the typical electron range. Electrons lose part of their energy in the detector and produce signals. Energy deposition and pulse height of the photons are small and the response function of the detector depends on the active layer of the detector and the photon energy. In this study, a selective data sampling technique has been developed to flatten the energy response.

Various dose quantities have been designed by ICRP and ICRU. For external irradiation, operational quantities have been introduced and defined for use in dose measurements. Personal dose equivalent is the operational quantity for individual monitoring and is shown by $H_{\mathrm{p}}(10)$. It is defined as the dose equivalent in soft tissue at an appropriate depth, 10 mm, below a specified point on the human body [9].

Fluence to personal dose equivalent conversion factors (coefficients) was used for photon dosimetry [9]. The similarity between the detector response function and the fluence to personal dose equivalent conversion factors allows this detector to act as a dosimeter. In an ideal dosimeter, the detector response function is equal to the conversion function. Based on the pulse counting, the response is perfectly linear to the dose rate. This linearity has problems in pulsed fields and high dose rates due to saturation effects.

Based on the pulse height distribution, several energy intervals ($m=0,1,2,\cdots$) were selected, and the pulses in the energy intervals were counted to determine the response function. The energy interval selection to some extent is arbitrary and in order to achieve high statistics for the counts, their positions are located neighboring the pulse height distribution peak. Where m is the number of the energy interval: for $m=0$, the total number of pulses above a threshold of 100 keV is regarded as the detector response; for $m=1$, a single energy interval is used and the number of pulses within the energy interval is regarded as the detector response; for $m=2$, two energy intervals are used and the number of pulses within the energy intervals are regarded as the detector response; finally, for $m=i$, $i$ energy intervals are used and the number of pulses within the energy intervals are regarded as the detector response. Increasing the number of energy intervals provides the potential to apply separate weighting factors to the detector response, and then dosimetry calibration coefficients and the certainty of the measured data in photon dosimetry are increased. The energy intervals for each value of $m$ are selected to achieve the best dosimetry response of photons in the energy range of 0.3–6 MeV. A schematic view of the pulse height distribution for a semiconductor detector and the selective data sampling of the detector readout are shown in Fig. 1.

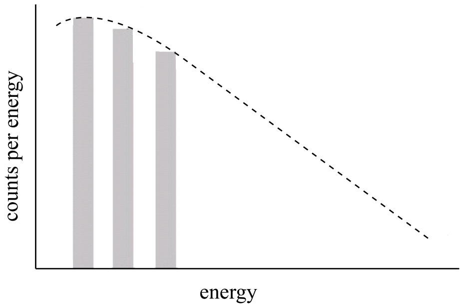

Fig. 1. Pulse height distribution and energy intervals for data sampling.

## 3 Calculation

In order to achieve high detection sensitivity and an appropriate dosimetry response, energy intervals were selected near the spectrum peak. The pulse height distribution and spectrum peak depend upon the photon energy and the depleted layer of the diode. Pulse height distributions obtained for the irradiation of diode detectors with 4, 40, 100, 300 and 500 microns thick depletion layers and 1.25 MeV photons are shown in Fig. 2.

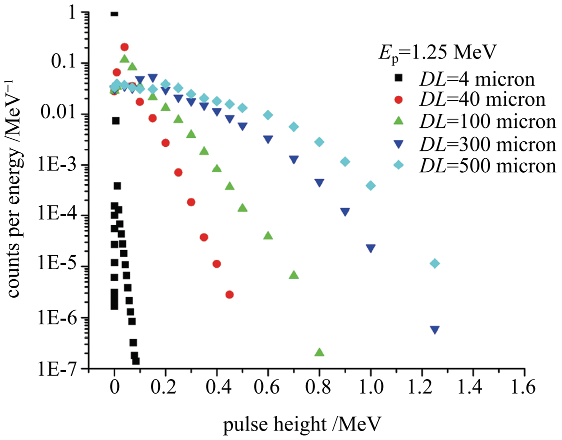

Fig. 2. (color online)Variation of the pulse height spectra with diode depletion layer thickness for irradiation with 1.25 MeV photons.

Increasing the thickness of the diode depletion layer increases the maximum energy of the pulse height distribution. The energy spectrum in a diode with a small depletion layer thickness is sharper than for a high depletion layer thickness. There is a cut-off due to the lack of total absorption of the incident photons. This is prominent for depletion layers of less than 300 μm.

Diodes with different depletion layer thicknesses were irradiated with different mono-energetic photons in the range of 0.3–6 MeV. For each depletion layer thickness, the pulse height spectrum exhibits a relationship with photon energy. The pulse height spectra for a diode with a 500 micron-thick depletion layer and irradiation of 0.3–6 MeV photons are shown in Fig. 3.

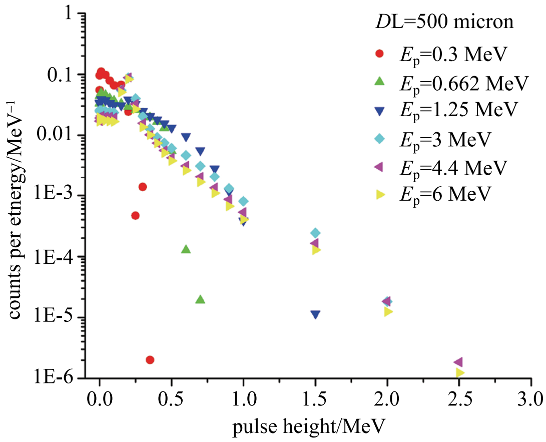

Fig. 3. (color online) Pulse height spectra for energy range of 0.3–6 MeV and $DL$=500 micron.

The intersection of the curves at low pulse heights shows that the simplest method for achieving an almost constant personal dose equivalent response for photons is to integrate the pulses in a single interval, or two or three energy intervals, above 100 keV. The pulses in the energy intervals were integrated to determine the dose equivalent.

In the $E_{\min}$–$E_{\max}$ energy interval ($m=0$), the total pulses above 100 keV are used to calculate the dose equivalent. The personal dose equivalent for a given photon spectrum is found from the following equation:

$$H_o(10)=C_0N_0. \tag{1}$$

For the first energy interval ($m=1$), the personal dose equivalent is given by the equation

$$H_1(10)=C_1N_1. \tag{2}$$

For the first and the second energy intervals ($m=2$), the personal dose equivalent is given by the equation

$$H_2(10)=C_1N_1+C_2N_2. \tag{3}$$

Finally, for m energy intervals, the personal dose equivalent is given by the equation

$$H_m(10)=\sum_i^m C_iN_i \quad i=1,2,\ldots,m, \tag{4}$$

where $H_m(10)$ is the personal dose-equivalent, $N_i$ is the pulse count and $C_i$ is a constant coefficient of the $i^{\text{th}}$ energy intervals. Using the linear combination of counts according to Eq. (4), the personal dose-equivalent is determined based on the detector readout. Eq. (4) is a system of $n$ linear equation with $m$ unknowns, where $n$ is the number of photon energies which are used for irradiation and $m$ is the number of energy intervals. The coefficients $H_m(10)$ and $N_i$ are given, and we are going to find the $C_i$ that is physically appropriate for these equations. Different monoenergetic photons in the range of 0.3–6 MeV were used for irradiation. Each of the photon energies has its own specific values for $C_i$ that satisfies the equation. So, for each photon energy, the constant coefficient $C_i$ was determined using photon transport simulation. This procedure was repeated for other energies and values of the coefficients $C_i$ were determined. For each value of m, the best values for $C_i$ were chosen from the mean value of $C_i$ in the different photon energies, such that the errors over the entire range of photon energies were lowest.

The energy interval for $m$=0 is higher than 100 keV, $m$=1 corresponds to 150–250 keV, and $m$=2 includes 150–250 keV and 300–450 keV. Calculations were performed for the different energy intervals. For three values of m, the photon dosimetry response was determined. For a broad range of photon energies, the determined personal dose equivalent $H_c(10)$ divided by the corresponding conventional true value $H_t(10)$ is shown in Fig. 4.

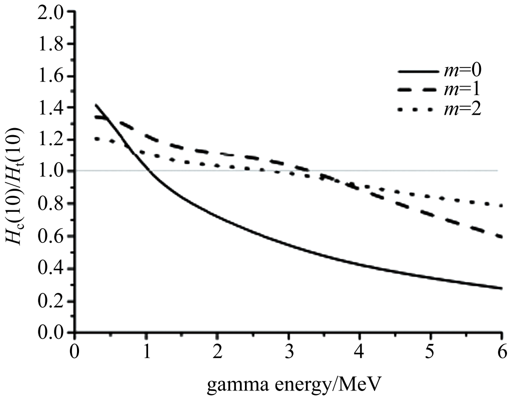

Fig. 4. Photon personal dose equivalent response as a function of energy.

By increasing the number of energy intervals, we increase dosimetry calibration coefficients and so, errors in the photon dosimetry for wide band energy are decreased.

## 4 Experiment

To investigate the dosimetry characteristics of this method, performance tests were performed for an actual photon radiation field. $^{133}$Ba, $^{137}$Cs, $^{60}$Co and $^{241}$Am-Be sources were used for irradiation of the dosimeter.

The NIM modules used consisted of an IAP 8100 high voltage power supply, IAP 3600 amplifier, IAP 3002 preamplifier and IAP 4110 ADC and multichannel analyzer. A silicon detector with a bias of 50 V, 500 micron sensitive depleted layer, 50 nm dead layer and active area of 1 cm$^2$ was used.

A detector system probe equipped with conventional nuclear electronics for signal amplification and processing was irradiated with photons from the different photon sources. Energy calibration was performed using alpha particles from an $^{241}$Am source. The measured pulse height spectra for irradiation from the $^{137}$Cs and $^{60}$Co sources were normalized to a single photon and are shown in Fig. 5.

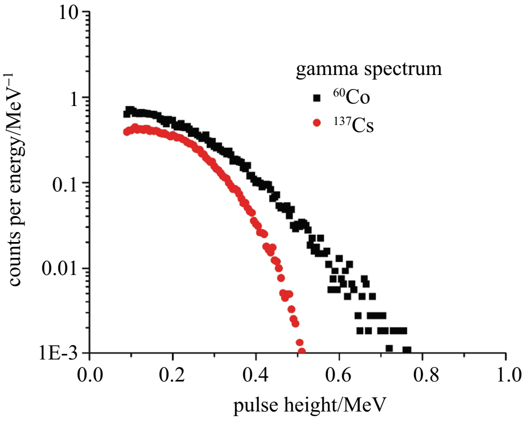

Fig. 5. (color online) Pulse height spectra measured for photon radiation in two energy intervals. Threshold energy was 100 keV.

The dosimetry responses of the detector were measured for different photon sources. Total pulses above 100 keV were used to measure the photon personal dose equivalent. Using Eq. (4) for two energy intervals, the personal dose equivalent for the photon was measured based on the detector readout. Experimental dosimetry data for the different photon sources deviated by less than 15% (see Table 1).

Table 1. Experimental mean errors for $m$=2 for four different photon sources.

| source | $^{241}$ Am-Be | $^{60}$Co | $^{137}$Cs | $^{133}$Ba |
|---|---|---|---|---|
| energy/keV | 4438 | 1173, 1332 | 662 | 80–384 |
| error (%) | 13 | 7 | 10 | 15 |

Different doses and dose rates could be achieved at various distances of the sources. The dosimetry response of the detector were measured for varying doses of the $^{241}$Am-Be source. In Fig. 6, measurement and simulation responses for the $^{241}$Am-Be source photon radiation are given. A fairly good agreement is seen between measurement and simulation dosimetry responses obtained from our process, and the errors for the $^{241}$Am-Be photons were less than 15%.

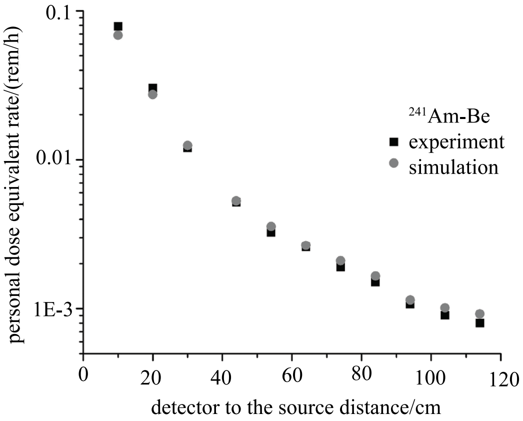

Fig. 6. Measurement and simulation responses for the $^{241}$Am-Be photons at different dose rates.

## 5 Conclusion

The thickness of depletion layer and accurate determination has a significant effect on the precision dosimetry technique. Photon dosimetry performed by this method has high precision and is reliable for active personal dosimeters. Accurate specification of narrow energy intervals can improve the energy response of an active personal photon dosimeter. This new technique represents an alternative method for photon dosimetry and has advantages when compared with other dosimetry methods. This method has a very simple structure and is composed of basic electronic devices; furthermore, this approach has fewer drawbacks than other methods.

This method was designed for photon dosimetry, but it can also be developed for photon-neutron dosimetry in a mixed field by adding a neutron converter. This approach is applicable to active personal dosimeters where a single diode was used for neutrons and photons [7].

The error values of the calculated data for photon dosimetry for an energy range of 0.3–6 MeV are less than 20% (see Fig. 4). The error values of the measured data for photon dosimetry for $^{133}$Ba, $^{137}$Cs, $^{60}$Co and $^{241}$Am-Be sources are less than 15%. For varying photon dose from an $^{241}$Am-Be source, the simulations and experiments results show fairly good agreement.

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