Applied Radiation and Isotopes 70 (2012) 1355–1359

Contents lists available at SciVerse ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Response functions of Si(Li), SDD and CdTe detectors for mammographic x-ray spectroscopy

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ARTICLE INFO

Available online 28 November 2011

Keywords:
Mammographic x-ray spectra
Response functions
Si(Li) detector
Silicon drift detector (SDD)
CdTe detector

ABSTRACT

In this work, the energy response functions of Si(Li), SDD and CdTe detectors were studied in the mammographic energy range through Monte Carlo simulation. The code was modified to take into account carrier transport effects and the finite detector energy resolution. The results obtained show that all detectors exhibit good energy response at low energies. The most important corrections for each detector were discussed, and the corrected mammographic x-ray spectra obtained with each one were compared. Results showed that all detectors provided similar corrected spectra, and, therefore, they could be used to accurate mammographic x-ray spectroscopy. Nevertheless, the SDD is particularly suitable for clinic mammographic x-ray spectroscopy due to the easier correction procedure and portability.

1. Introduction

High-resolution semiconductor detectors are used in a widely variety of applications, including measurements of x-ray energy spectra from diagnostic x-ray tubes (Miyajima, 2003; Künzel et al., 2004). However, accurate determination of x-ray energy spectra requires a proper correction procedure by the energy response functions of the detector used, in order to correct the spectral distortions and obtain the true photon spectra incident on the detector (Di Castro et al., 1984; Matsumoto et al., 2000; Miyajima, 2003).

In the last decades, several detectors have been used in mammographic x-ray spectroscopy (O'Foghludha and Johnson, 1981; Matsumoto et al., 2000; Wilkinson et al., 2001; Miyajima and Imagawa, 2002; Künzel et al., 2004; Bottigli et al., 2006; Abbene et al., 2007; Tomal et al., 2011). Among these detectors, the use of Si(Li) detector shows some advantages due to its good energy resolution, low atomic number, good charge transport properties and, consequently, small spectral distortion, which simplifies the spectral correction procedure (Chen et al., 1980). However, this detector has a low detection efficiency and can be used only for nonclinical spectra measurements, because of the necessity of cryogenic cooling (O'Foghludha and Johnson, 1981). Recently, measurements of mammographic x-ray spectra under clinical conditions have been performed with portable CdZnTe and CdTe detectors (Matsumoto et al., 2000; Miyajima and Imagawa, 2002; Künzel et al., 2004; Bottigli et al., 2006; Abbene et al., 2007). However, these detectors have a worse energy resolution than the Si(Li), absorption edges in the mammographic energy range and poor charge transport, which increases the spectral distortions and makes the correction procedure more difficult (Matsumoto et al., 2000; Künzel et al., 2004). In this way, the best choice for certain demanding applications involves many criteria, such as a good response function for a given energy range, in order to minimize the spectral distortions, a high energy resolution, and also portability. Moreover, more recently, new types of detectors, such as silicon drift detectors (SDD), have been used in spectroscopy techniques (e.g. EDXRF), since it combines the advantages of portability, high energy resolution, a low atomic number crystal, good carrier transport and high count-rate capabilities (Amptek Inc.; Eggert et al., 2006). However, the SDD was not yet employed to spectra measurement, and its response functions were not also studied in all mammographic energy range.

In this work, the energy responses of Si(Li), SDD and CdTe detectors were analyzed in the mammographic energy range (5-40 keV), in order to investigate the more suitable detector for mammographic x-ray spectroscopy. The energy response functions for each detector were calculated through Monte Carlo (MC) simulations, using the PENELOPE code (Salvat et al., 2003). The code was slightly modified to include carrier transport effects and the finite detector energy resolution. Simulated results were compared with experimental spectra obtained from radioactive sources. Finally, the corrected mammographic x-ray spectra obtained using the detectors evaluated were compared.

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doi:10.1016/j.apradiso.2011.11.044

2. Material and methods

2.1. Detectors used in this study

The detection systems used in this study were the following:

- A Si(Li) detector (Canberra, model SL30165), with 3 mm thick and 30 mm^2 active area, and a 8 μm beryllium (Be) window. The Si(Li) devices were cooled to liquid nitrogen temperature (−196 °C). The nominal bias voltage was −500 V.
- A Silicon Drift Detector (SDD) (Amptek, model XR-123SDD), with a silicon crystal with thickness of 450 μm and 7 mm^2 active area, and a Be window with thickness of 12.5 μm, coupled to digital pulse processor DP5 (Amptek). The crystal was cooled by Peltier cells to around −55 °C. A nominal bias voltage of −200 V was applied to the detector.
- A CdTe diode detector (Amptek, model XR-100 T-CdTe), with thickness of 1 mm and 9 mm^2 nominal area. The CdTe crystal is located behind a Be window of 100 μm. The crystal was peltier-cooled (approximately −20 °C). The nominal bias voltage was 400 V.

The energy calibration and the resolution of the each detection system were obtained using calibration sources of ^{55}Fe, ^{137}Cs, ^{137}Ba and ^{241}Am. For these measurements, a 2 mm thick tungsten collimator with a 0.5 mm diameter aperture was utilized. The rise time discrimination (RTD) circuit of all detectors was switched off during the measurements (Miyajima, 2003).

2.2. Determination of detector response

The response functions were calculated through Monte Carlo (MC) simulations, using the PENELOPE code version 2003 (Salvat et al., 2003). This code simulates accurately transport of photons and electrons in the mammographic energy range (Sempau et al., 2003). The incident radiation was assumed to be a monoenergetic pencil beam from 5 to 40 keV, at 0.25 keV intervals. For each incident energy, 10^7 photons were simulated in order to reduce the statistical uncertainties in the evaluated response functions. The geometrical detector model was based on the information provided by the manufacturers (Section 2.1). In the simulation code, the history of each incident photon, as well as secondary photons and electrons, is followed while their energy is higher than a cutoff value (0.1 keV). For each interaction inside the detector's crystal, the deposited energy was determined by modifying the code to take into account: (a) carrier trapping effects, modeled by the Hecht equation (Cross et al., 2005; Moralles et al., 2007); (b) the incomplete charge collection (ICC), modeled by the carrier collection probability (CCP) function (Campbell et al., 2001); and (c) the finite detector energy resolution, through the inclusion of a Gaussian sampling of the deposited energy (Campbell et al., 1998).

The input data of the Hecht equation (the mean paths of electrons and holes, λ_e and λ_h, respectively) and of the CCP function (effective diffusion coefficient to saturation velocity ratio, D/v, and reflection coefficient, RC), used to simulate the effects (a) and (b) for each detector, are summarized in Table 1. For the Si(Li) detector these parameters were obtained from previous works (Cross et al., 2005; Tomal et al., 2011). The values showed in Table 1 for the SDD and CdTe detectors were determined by changing these parameters until achieving the best coincidence between the simulated and experimental spectra of radioactive sources (Matsumoto et al., 2000). For simulation of the SDD, the carrier trapping effect was not taken into account due to some detector's characteristics, such as good carrier transport and thin crystal. In addition, it is worth to mention that due to the non-uniform electric field in this thin Si crystal (Amptek Inc.,), the Hecht equation is not appropriated to model this effect. Table 1 also includes the dead layer thickness (d_L) used in the model of each detector, which were adjusted to provide the best agreement between the simulated and experimental data for radioactive sources (Moralles et al., 2007).

Table 1
Parameters of the Hecht equation and CCP function, and dead layer thickness used in simulation of each detector.

Input parameters	Si(Li)	SDD	CdTe
λ_e (cm)	3.5×10^{3}[a]	–	12.3
λ_h (cm)	12.8[a]	–	0.73
D/v (μm)	0.1[b]	0.12	0.2
RC	0.5[b]	0.7	0.2
d_L (μm)	0.2	0.2	1.0

[a] Cross et al. (2005).
[b] Tomal et al. (2011).

The input data of the Gaussian distribution, relating the Gaussian peak width with the photon energy (Campbell et al., 1998, 2001), were adjusted from the experimental resolution curve, obtained using radioactive sources (Mesradi et al., 2008).

The modified code was validated through comparison with simulated results from the literature (Campbell et al., 1998; Cross et al., 2005; Miyajima, 2003) and with our experimental spectra obtained for radioactive sources.

2.3. Mammographic x-ray spectra measurements

In order to study the importance of the correction by the energy response functions of each detector, the mammographic x-ray spectra of standard radiation qualities (Tomal et al., 2011) were measured with the Si(Li), SDD and CdTe detectors. The x-ray source was an industrial x-ray tube (Philips, PW 2215/20) with a stationary molybdenum (Mo) target, adapted with filters of Mo or Al to reproduce the standard x-ray mammographic beam qualities (Tomal et al., 2011; PTB, 2010). The experimental setup is described by Tomal et al. (2011).

Measured x-ray spectra were corrected with the stripping method (Di Castro et al., 1984; Tomal et al., 2011), using the response function of each detector.

3. Results and discussions

3.1. Validation of the model: comparison of simulated and experimental data

Fig. 1 compares the experimental and simulated ^{55}Fe spectra for the (a) Si(Li), (b) SDD and (c) CdTe detectors. All spectra are normalized for the same peak intensity.

Fig. 1 shows a good agreement between the experimental and simulated ^{55}Fe spectra obtained with the three detectors, allowing the code validation for modeling the response of semiconductor detectors and indicating the good choice of the input parameters used in simulation.

As shown in Fig. 1(a) and (b), the spectra achieved with the Si(Li) and SDD detectors show similar features, which includes: (A) the main Mn–K peaks, (B) the Mn–K silicon escape peaks, and (C) the tail and the flat-shelf region, related mainly to the incomplete charge collection (ICC), and also to the carrier trapping effects and the partial energy loss of secondary radiation (Scholze and Procop, 2009; Tomal et al., 2011; Campbell et al., 2001). Small differences can be observed between these spectra in the Mn–K peaks region, due the better energy resolution of the