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Beta Skin Dosimetry using Passivated Planar Silicon Detector

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HIGHLIGHTS

- Accurate measurement of beta skin dose remains a challenge that needs to be address.
- Passivated Planar Silicon (PIPS) detector was tested for estimating skin dose by measuring beta spectra.
- Three sources, a low energy beta source, (^{147}Pm), a medium energy source, (^{204}Tl), and a high energy beta source, ($^{90}Sr/^{90}Y$) were used to cover the range of beta energies.
- Experimental measurements with 300 µm thick, 3 cm^2 PIPS and using sources identified above showed good agreement with MCNPX results.
- MCNPX modelling with 100 µm thick, 1.5 cm^2 PIPS - and skin, -showed beta dose could be accurately predicted within 17% of beta energies tested.

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ABSTRACT

Accurate measurement of beta skin dose remains a challenge. This dose is defined as the dose to the basil layer at 7 mg/cm^2 (approximately 70 µm) below the surface of the skin and averaged over an area of 1 cm^2. This dose is dependent upon the energy of the beta contamination on the surface of the skin, the area of contamination and the attenuation of this radiation through the 7 mg/cm^2 epidermal layer. Ideally, knowing the energy spectra of betas at this level below the surface of the skin would allow accurate prediction of dose. In this work, a Passivated Planar Silicon (PIPS) detector was tested by measuring beta spectra in a geometry simulating skin and, from that, estimating dose. Three calibrated beta sources were used, a low energy beta source, (^{147}Pm), a medium energy source, (^{204}Tl), and a high energy beta source, ($^{90}Sr/^{90}Y$) to cover the range of beta energies typically found in skin contamination events. Modelling utilized the MCNPX and VARSKIN 4.0 computer codes to calculate dose in skin and were found to be in good agreement with each other. Experimental measurements using a 300 µm thick, 3 cm^2 PIPS and the three sources identified above showed good agreement with MCNPX results (and thus, also with VARSKIN). Finally, MCNPX modelling compared the dose rates from a commercially available, 100 µm thick, 1.5 cm^2 PIPS detector and skin, and found that the beta dose could be accurately predicted within 17% over the range of beta energies tested. This result can be obtained with a single measurement and without the need for post data collection analysis.

1. Introduction

The monitoring of personal skin dose rates in radiation settings is required to demonstrate regulatory compliance. The hazard from beta radiation can occur from skin surface contamination (either a large area contamination or from ~ 1 mm sized hot particles in nuclear power plant settings), or from being in close approximation to beta emitting sources. The severity of the dose deposited depends on the beta source strength, energy, and area of contamination. The basal skin layer of the epidermis is the area of the skin that is particularly sensitive to radiation because it represents the uppermost region of the skin. ICRP 60 (International Commission on Radiological Protection, 1991) and 10 CFR 20 (Cool and Peterson, 1991) require dose from skin contamination to be assessed at a depth of 7 mg/cm^2 (approximately 70 µm) over an average skin area of 1 cm^2. To account for the situation were the beta particles are not on the surface of skin, the average skin area was change to 10 cm^2 (National Council on Radiation Protection and Measurements, 2001; United States Nuclear Regulatory Commission, 2002). The annual dose limit has been established at 500 mSv.

Monitoring is achieved by use of radiation detectors. An ideal detector would be one that can measure energy deposited at the depth of 70 µm. Typical issues associated with standard dosimetry

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instrumentation include the presence of thick windows that exceed the 70 μm depth requirement, detector size which exceeds the 1 cm^2 skin dose definition, the presence of backscattering of high-Z materials surrounding the detecting volume, and/or the lack of energy measurement capabilities. If the beta spectrum and the size of contamination are known, then these systems can be normalized to predict dose, but that calibration is only good for that specific situation.

Thin window (with 1–4 mg/cm^2 of mica) Geiger Müller counters are typically used in nuclear power plants for frisking radiation personnel and can be used to measure the number of beta particles from surface contamination. However, they do not measure skin dose directly, but only measure the number of beta particles entering the sensitive volume of the detector. The dose delivered by each detected count is widely variable depending upon the energy of that beta particle, and as a result they can only be used to approximate skin dose.

The ionization chamber is widely used for measuring dose. The response of the chamber is directly proportional to the energy deposited in the active portion of the instrument. An example is the Model RO-02 ion chamber manufactured by the Eberline cooperation which is widely used as a personal monitoring instrument to survey radiation facilities in the United States. The Model RO-2 has a diameter of 7.6 cm, a window thickness of 7 μm and effective air thickness of 5 mg/cm^2. Measurement is first done with the window opened and later with the window closed. These two readings are provided as the beta/gamma ratio, which is used to interpret the dose. The ion chamber is very useful when the source is known. However, the ion chamber does not accurately measure dose at the depth of 70 μm. Martz et al. (1986) found that the response of this instrument for measuring skin dose was constantly low by a factor of two or three.

Martz et al. (1986) developed a portable beta spectrometer for tissue measurement. The dosimeter utilizes a tissue equivalent plastic scintillator 2.5 cm in diameter by 0.9 cm thick. It can measure dose due to beta and photons. Two separate spectra are collected with the detector in a radiation field. The first spectrum with an open window, the second with a 1 cm Lucite cap covering the window to shield the betas. The resulting instrument has the ability to measure dose within approximately 25% but requires considerable analysis to predict skin dose.

Thermoluminescent dosemeters (TLDs) with different multiple filter designs are also widely used as personal dosimeters to interpret doses from photons and beta radiation. They have the advantage of a small size which makes them applicable for skin dose measurements. Although the detection medium is not a tissue–equivalent detector, it has the ability of evaluating mixed beta/gamma field separately. Separation is possible by using pairs of filters of different atomic numbers. The problem is that it difficult to incorporate more filters into a badge due to lack of film space (Christensen, 1986). TLDs are only approximate in estimating skin dose because it does not represent the 10 μm layer of basal cells at a depth of 70 μm for which skin dose is defined. Also, they do not measure dose in real time.

Silicon detectors have been widely used for radiation measurements. Chung et al. (1991) developed a silicon monitor skin for measuring skin dose. The dosemeter is an ion implanted silicon detector with area of 3 cm^2 and a thickness of 300 μm. Skin dose is estimated by taking two different readings. The first reading is taken with an open window, while the second reading is taken when the detector is covered with an aluminum shield of an equivalent of thickness of skin (70 μm). The dose rate is calculated based on the two readings. Using a thickness of 300 μm is not an appropriate approximation for representing the dose in a thin ∼ 10 μm basal layer at a depth of 70 μm.

Silicon detectors, however, have promise since the charge collected is directly proportional to the incident beta energy since an electron-hole is created for every 3.6 eV deposited in the active area of a silicon detector, which depends on the type of beta radiation, self-shielding of the source, attenuation from air and the thickness of the detector window. These detectors have lower noise due to low leakage current (typically 1/10 to 1/100 of a surface barrier detector), high efficiency, are more rugged, and have good energy resolution. The issue is to determine how the beta dose delivered to a relatively thick detector (100–300 μm) of silicon can be normalized to the dose delivered to 10 μm of skin at a depth of 70 μm.

This paper compares two Passivated Planar Silicon (PIPS) detectors with different thicknesses and their suitability for use in converting silicon dose rate to skin dose rate. The detector response was measured with a Canberra Genie 2000 spectroscopy system and compared with the MCNPX for validation and calibration. The skin dose was determined using MCNPX (Pelowitz, 2005) and results were validated with the Varskin 4.0 (Hamby et al., 2014) computer code.

2. Method

Two different computer codes were used in this work for theoretical modelling. VARSKIN is used by US Nuclear Regulatory commision to estimating skin dose due to exposure from beta radiation and photons. The code uses six pre-programed source geometries which includes a point source and a wide range of user-selected radionuclides. The estimated dose rate is based on the numerical integration of the Berger Point Kernel. The output contains a list of all input data with identification headings, date of run, the running time and the energy deposited by electrons in each layer of target.

The Monte Carlo N particle code MCNPX (Hamby et al., 2014) is a versatile code which can be used for modelling a detector especially when a complex geometry is required. The dose distribution is calculated by defining a series of volumes in MCNP geometry called cells. The geometry used for skin modelling was a cylinder with a height of 70 μm thick and an area of 1 cm^2 (for surface contamination). Beta spectral data was obtained from Eckerman (Eckerman et al., 1994) and was placed at the center of the skin geometry and energy deposition was tallied over a 10 μm thickness (approximately the thickness of the basil skin layer) at the depth of 70 μm. The F8 tally was used to model the detector pulse height spectrum. The beta dose rate deposited in the detector was calculated by multiplying the counts at each channel number by the corresponding energy and summing the result to obtain the total energy deposited as given by Eq. (1). Dividing the total energy deposited by the mass of the active layer of the detector and the detection live time gives the dose rate (Eq. (2)).

$$E_{total} = \sum_i N_i \times E_i \tag{1}$$

where

E_{total} = total energy deposited in the active area of the detector (MeV)
N_i = Number of counts channel i
E_i = Energy at channel i (MeV)

$$\dot{D}\left(\frac{Rad}{hr}\right) = \frac{E_{total}(MeV)}{Detector\ mass(gm)} * 1.6x10^{-10}\frac{Gy}{\left(\frac{MeV}{gm}\right)} * 100\frac{Rad}{Gy} * \frac{1}{Count\ Time(s)} * 3600\frac{s}{hr} \tag{2}$$

For experimental work, a Model PD300-15-300AM detector was obtained from the Canberra (Canberra Industries, Inc., Meriden, CT). It has a thickness of 300 μm and an active area of 3 cm^2. It has a thin gold window with equivalent silicon thickness of 50 nm and aluminum back contact with thickness of 20 μm.

Calibrated beta sources were obtained from Eckert & Ziegler Isotope Inc. Three sources were utilized to cover a broad range of beta source energies: a $^{90}Sr/^{90}Y$ source with an E_{max} of 2.27 MeV, a ^{204}Tl with an E_{max} of 0.763 MeV and ^{147}Pm with E_{max} of 0.225 MeV. The sources had active diameters of 41 mm and an activity of 187 Bq for the Tl-204 and Pm-147 sources, electroplated onto a disk of thickness 3.18 mm. The $^{90}Sr/^{90}Y$ source had an active diameter of 45 mm and 174.4 Bq of