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Brachytherapy dosimeter with silicon photomultipliers

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Abstract

In-vivo and in-situ measurement of the radiation dose administered during brachytherapy faces several technical challenges, requiring a very compact, tissue-equivalent, linear and highly sensitive dosimeter, particularly in low-dose rate brachytherapy procedures, which use radioactive seeds with low energy and low dose deposition rate. In this work we present a scintillating optical fiber dosimeter composed of a flexible sensitive probe and a dedicated electronic readout system based on silicon photomultiplier photodetection, capable of operating both in pulse and current modes. The performance of the scintillating fiber optic dosimeter was evaluated in low energy regimes, using an X-ray tube operating at voltages of 40-50 kV and currents below 1 mA, to assess minimum dose response of the scintillating fiber. The dosimeter shows a linear response with dose and is capable of detecting mGy dose variations like an ionization chamber. Besides fulfilling all the requirements for a dosimeter in brachytherapy, the high sensitivity of this device makes it a suitable candidate for application in low-dose rate brachytherapy. Accordingly to Peralta and Rego [1], the BCF-10 and BCF-60 scintillating optical fibers used in dosimetry exhibit high variations in their sensitivity for photon beams in the 25 to 100 kVp energy range. Energy linearity for energies below 50 keV needs to be further investigated, using monochromatic X-ray photons.

1. Introduction

1.1. Scintillators in radiation dosimetry

The use of scintillators as detection medium is one of the most common options in radiation physics. In general, some precautions should be taken when using scintillators as radiation detectors, such as considering stem effect (including Cherenkov light) [2-7], temperature dependence and energy linearity. Organic scintillators present some advantages over inorganic ones, such as faster decay time, small temperature dependence, and energy and dose linearity. In the last decades several groups evaluated the feasibility of organic scintillators as dosimeters [6, 8-14]. However, most of those applications used high doses, high-dose rates and high-energy radiation sources [15-18]. In low-dose rate (LDR) regimes like in prostate LDR-brachytherapy, low energy radioactive sources (^{125}I, ^{103}Pd. ^{131}Cs) are permanently implanted inside the tumor. The emissions of these isotopes are below the threshold energies for Cherenkov in common plastics such as polymethyl-methacrylate (PMMA) [5]. Considering the low energy and low-dose rate, only a highly sensitive dosimeter would perform properly on dose quantification in these procedures.

1.2. Dosimeters for Brachytherapy

Brachytherapy is a radiation therapy modality where the radioactive sources are placed near (intracavitary) or inside (interstitial) the region to be treated. Skin, breast and prostate brachytherapy are some of the most common. The justification for in-vivo dosimetry is presented in [19]. An ideal dosimeter should present the following characteristics [17, 19-21]:

- high sensitivity
- no dependencies on beam parameters
- real-time dose measurement
- universality (ability to function with proton and electron beams)
- dose-rate independence
- dose linearity
- temperature independence

- tissue equivalence
- easy to use and calibrate
- detectable in the anatomic volume to allow checking its position
- not expensive / disposable use of its implantable part.

Ismail [9] refers that MOSFETs are a good approach to in-vivo measurements. There are some available commercial options for in-vivo and real-time dosimetry, but they can be bulky and very expensive, have a short-lifetime and are not tissue equivalent [19]. On the other hand, detectors based on scintillating optical fibers are promising systems.

1.2. Fiber optic dosimeter for prostate low-dose rate brachytherapy

Brachytherapy procedures may be classified as low-dose rate (LDR) when dose is delivered at a rate below 2 Gy/hr, medium-dose rate (MDR) in the range of 2 to 12 Gy/hr and high-dose rate (HDR) when dose is delivered at 12 Gy/hr or more [22]. In prostate LDR-brachytherapy, very low dose rate permanent radioactive seeds are implanted permanently inside the prostate delivering a dose of about 150 Gy in one or more months. The typical radioactive seeds used in prostate LDR-brachytherapy are made of ^{125}I (28.5 keV, $T_{1/2}$ = 3 months), ^{103}Pd (20.8 keV , $T_{1/2}$ = 17 days) and ^{131}Cs (30.4 keV, $T_{1/2}$ = 9.7 days). Several factors may alter the dose distribution: extension of edema after therapy, edema reabsorption and isotope half-life [23]. A major concern related to prostate LDR-brachytherapy is the lesion of healthy tissues and organs, such as the urethra. A small sized dosimeter, capable of measuring in-vivo and in real-time, would allow determining the precise dose in critical regions. The ideal would be a flexible dosimeter, with a diameter smaller than 1 mm, capable of being inserted in a typical applicator seed implant needle (17 gauge) used in brachytherapy. A scintillating fiber optic coupled to a fiber optic light guide would fit these criteria, but the reduced light yield from organic scintillators in conjunction with their fast decay times, demand a fast and high gain single-photon counting photodetector, such as a photomultiplier tube (PMT) or silicon photomultiplier (SiPM). SiPMs are small-size photodetectors with an easy readout and require low bias voltages, being perfect for a portable and reliable system, as well as cost attractive.

Plastic scintillators are reasonably water-equivalent for photon energies above 100 keV [9, 24] but a major concern is the linearity with dose and energy in the range below 100 keV. In addition, Wooton and Beddar [25] showed that the BCF-12 scintillating fiber presents a 0.13% decrease in measured dose per ºC increase. Some preliminary studies were performed.

2. Materials and methods

2.1. The developed dosimeter

The developed dosimeter is composed of a sensitive probe and an electronic readout system. The dosimeter sensitive probe consists of a scintillating optical fiber coupled to a clear light guide fiber, both covered with a polyethylene jacket for ambient light isolation and mechanical resistance increase. The scintillating optical fiber is a 1 mm ø BCF12-A (Saint-Gobain Crystals, France) 5 mm long, aluminized on one end by vacuum deposition, to increase the light trapping efficiency. The other end of the scintillating optical fiber is coupled to a 1 mm ø, 5 m long HFBR-R optical fiber waveguide made of PMMA (Avago Technologies, USA). The photodetector is a Hamamatsu S10362-11-100U MPPC (Hamamatsu Photonics, Japan). The developed system allows a real-time measurement and is suitable for in-vivo applications, comprising a dedicated readout system that allows both pulse and current operation modes [26].

2.2. Methods and results

To evaluate the dosimeter response in low energy regimes and under low doses, an X-ray tube was used: 1 mA, 50 kV max, 125 μm thick Be window and 25º cone angle (5000 series, Oxford Instruments, UK).

A PTW 23342 ionization chamber (PTW, Germany) was positioned at 40 cm in line with the X-ray tube window inside a 15 cm squared PMMA phantom at 1 cm deep. The ionization chamber was read with a UNIDOS E universal dose meter (PTW, Germany). The PTW 23342 is the reference ionization chamber recommended by the IAEA for the quality of radiation used. The ionization chamber calibration is described in [1] and followed the recommendation of TRS-398 [27] for dosimetry in X-rays beams up to 100 kVp.

Dose values were measured at 40 and 50 kV tube potentials for several tube currents below 1mA, with and without filtering (0.5 mm thick 99.9% Al filter). For each tube potential and current, we obtained the average value of 100 acquisitions.

The setup was then changed to the dosimeter, maintaining the same configuration X-ray – ionization chamber (Fig. 1).

Fig. 1

The SiPM was biased at 1 V overbias and a 6487 picoammeter (Keythley, USA) was used to measure the MPPC response. The room temperature of 25 ºC was constant during the measurements. Measurements were done in the same conditions as with the ionization chamber, with results presented in Fig. 2. The uncertainty of the measurements with the ionization chamber is below 2% (standard deviation) and 2% for the scintillators' readings.

Fig. 2

Making the correspondence of the ionization chamber dose measurements with the dosimeter response, for the same conditions, we can plot the dosimeter response in terms of dose (Fig. 3).

Fig. 3

The scintillating fiber optic dosimeter shows a linear response and is capable of detecting dose variations below 5 mGy. Some authors reported possible non-linearity of plastic scintillator at energies below 200 keV [6, 10, 24, 28]. In that sense, a wide energy range study is needed to verify energy linearity of the developed system. The small variation in the measured dose with the temperature reported by Wooton and Beddar [25] may not be an issue if we consider a constant internal body temperature, although it is an aspect deserving attention, considering the envisaged clinical application. In a prostate brachytherapy, several needles (40 to 60) are introduced in the prostate for the radioactive seed deposition, so this could lead to a temperature increase in the region.

3. Conclusion

The developed system revealed a high sensitivity, capable of detecting mGy doses like the ionization chamber. The dosimeter response is linear at different X-ray tube potentials in a wide range of X-ray dose rates, from 2 to 70 Gy/hr. This is a major aspect, since the regimes of low-dose rate brachytherapy are characterized by low-dose rates (< 2 Gy/hr) and low energies (< 50 keV) requiring a highly sensitive device to properly perform dosimetry and quality assurance. In addition to the mathematical dose calculation formalism [14], the complexity of radiotherapy quality assurance is increased by several other factors required in a dosimeter, such as tissue equivalence, no disturbance to the radiation field, temperature and energy independence, etc. When the goal is to do in-vivo dosimetry in situations such as prostate low-dose rate brachytherapy, a small sized and flexible dosimeter is mandatory. Our results validate this type of dosimeter and reveal that it is possible to properly measure dose in such regimes, although the energy linearity at energies below 50 keV should be further investigated, using monochromatic X-ray photons.

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Figure captions

Fig. 1. Experimental setup: sensitive probe, comprising a 1 mm diameter BCF-12 scintillating fiber optic positioned at 40 cm in line with the X-ray tube window inside a 15 cm squared PMMA phantom and at 1cm deep.

Fig. 2. Dosimeter current mode response for 40 and 50 kV tube potentials and currents below 1 mA with and without Al filter. Uncertainties below 2%.

Fig. 3. Dosimeter response with dose. Uncertainties below 2%.

Figure1
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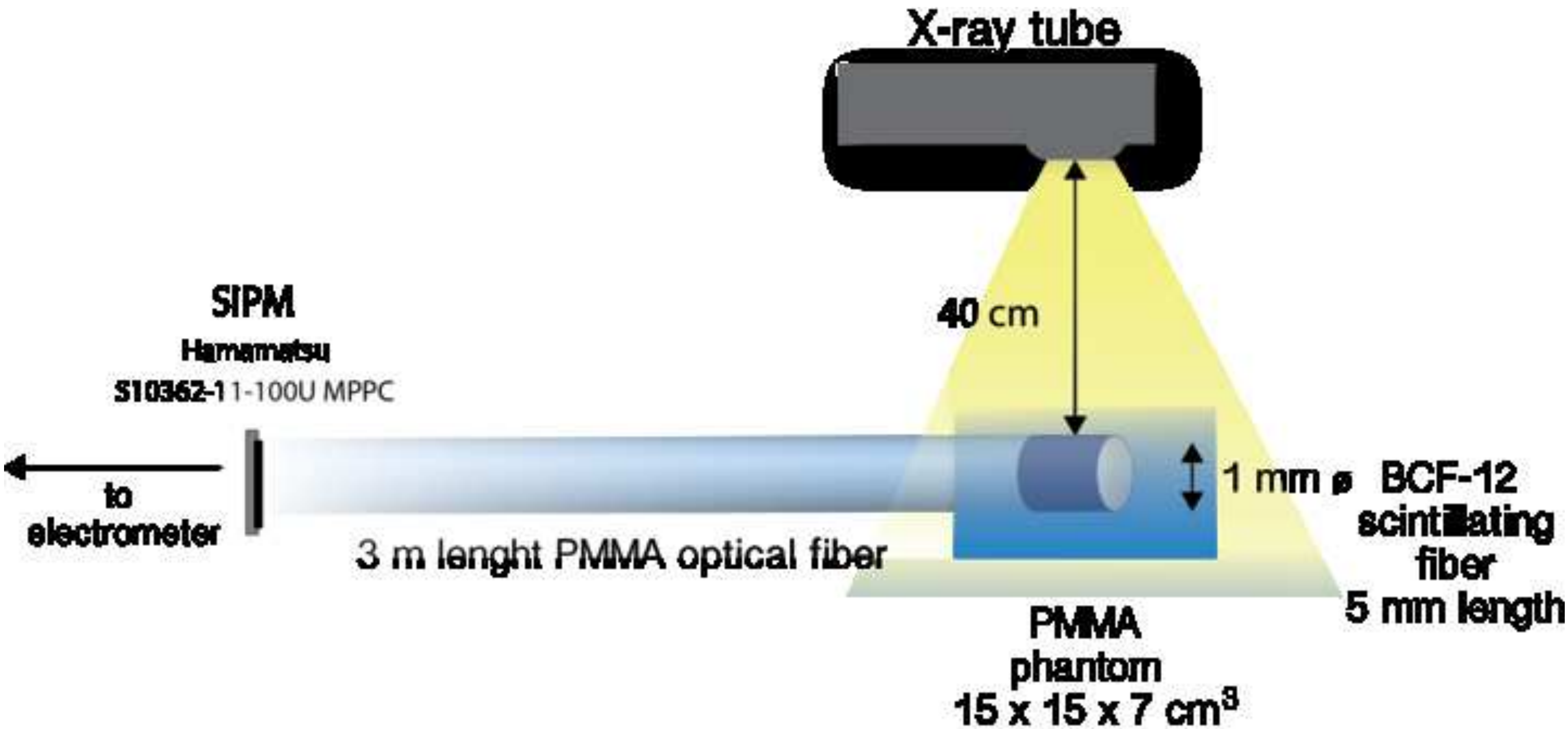

Figure2

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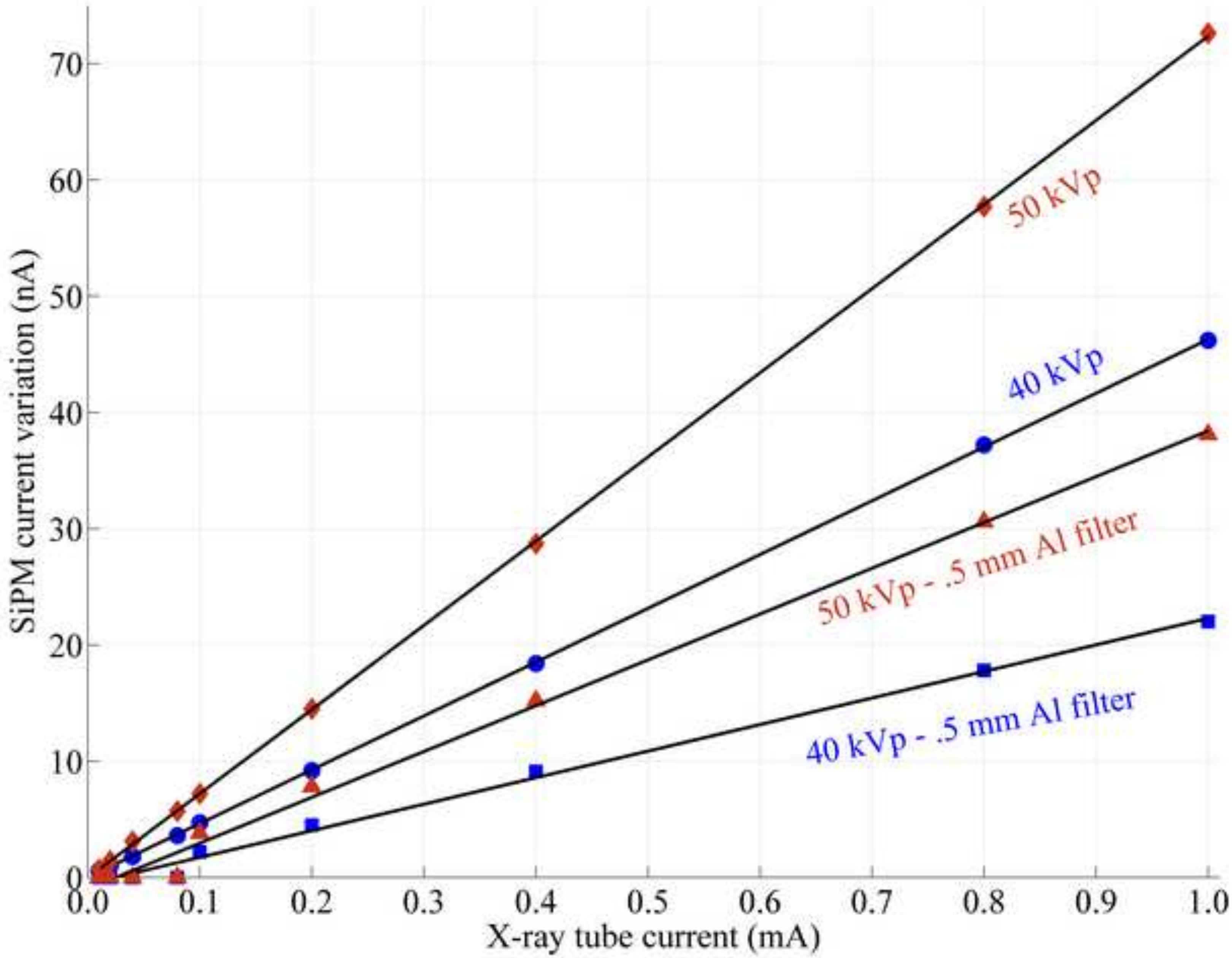

Figure3
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