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Single crystal CVD diamond detector for high resolution dose measurement for IMRT and novel radiation therapy needs

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ABSTRACT

One of the main aims for the improvement of the metrology during cancer treatment is the development of new tools for the real time measurement of the dose delivered to the patient. In the frame of The MAESTRO project (*Methods and Advanced Equipment for Simulation and Treatment in Radio-Oncology*, 6th FP) CEA-LIST in collaboration with the Gustave Roussy Institute (IGR in France) and the Institute of Nuclear Physics (IFJ in Poland) have realised clinical tests towards the use of single crystal diamond detectors (SCDD) for dose measurements for Intensity Modulated Radiation Therapy (IMRT). We present here a summary of the most significant steps realised with our dosimeter for the evaluation of IMRT clinical tests. After a brief presentation of the optimised single crystal diamond growth performed at CEA, we probed the performances of the SCDD with conventional radiotherapy fields. Performance evaluated in agreement with IAEA 398 Code of practise allows the dosimeter to be tested in IMRT beams. The evaluation of the doses measured with our 0.534 mm^3 SCDD is compared respectively to that obtained with the 0.125 cm^3 air ionisation chamber (IC) and with the TPS (Treatment Planning System) calculations respectively. The results exhibit a good agreement between the doses evaluated with the SCDD, the IC and TPS calculations. These very promising results show the potentiality of diamond for such a use and open up the field towards novel applications such as for very small beam dosimetry. For this specific topic a new miniaturised dosimeter is currently being developed at CEA and is briefly presented here.

1. Introduction

Diamond has been well known for many years as a very attractive material for applications in the detection field and more specifically for the radiation therapy dosimetry [1–3]. The nature of the material, the wide band gap and the tissue-equivalence avoid the correction factors for pressure, temperature and energy concerning the estimation of the dose. More recently our research has focused on IMRT (Intensity Modulated Radiation Therapy) [4]. In that particular case the very small sensitive detection volume (max 1 mm^3) appears as the most important criteria with respect to the possibility of very small and inhomogeneous field of irradiation used. Natural diamond dosimeter are provided commercially by the PTW Company [5,6]. The difficulty associated with the fabrication of such devices based on natural diamonds is the selection of natural gems that exhibit the required performances. Preliminary studies have focused on the use on natural [7], polycrystalline [8] or high-pressure high-temperature (HPHT) diamonds [9] for IMRT dosimeters. Also, due to the growth process, polycrystalline CVD diamonds usually show a slow response time inappropriate for this application, and HPHT diamonds exhibit electronic defects that alter the detector response. Alternatively, we have demonstrated in previous studies that it is now possible to grow single crystal diamonds from the chemical vapour deposition (CVD) process that satisfy the dosimetric requirements [2,4,10]. The aim of the present study is to present a summary of our results obtained with SCDD for radiotherapy and more specifically for IMRT. Finally, preliminary results obtained on a novel miniature diamond dosimeter developed in our laboratory are presented.

2. Experimental procedure

CVD synthetic diamond was obtained from a 3×3 mm^2 (100) oriented HPHT substrate in a 5 kW AsteX 5400 reactor. We operated with a plasma flame type deposition at a relative high pressure of 240 mBar, a low microwave power of 700 W and a temperature of 1010 °C. After growth, the sample was laser cut to remove the HPHT

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substrate and then polished. After this step the crystal was cleaned with a hot-acid process. Electrodes of nickel and gold were respectively deposited on upper and back faces of diamond crystal to obtain a sandwich structure and mobility of sample was estimated using a time of flight (ToF) method as referred in our previous papers [11,12]. For this sample we found a zero field mobility of 1860 $cm^2 V^{-1} s^{-1}$ for holes and 2450 $cm^2 V^{-1} s^{-1}$ for electrons.

For dosimetry study the sample was mounted on cylindrical solid water holder made at IFJ (Krakow, Poland) with an external size of 0.9×2.4 cm^2. The active volume of the SCDD is 0.534 mm^3 (170 µm thick). The dosimetric response of the detector was tested at the Gustave Roussy Institute (IGR) in France. We measured the SCDD response in conventional radiotherapy field with a Varian Linear accelerator working at 6 MV. The distance source axis (DSA) was 100 cm with the device located at 2 cm depth in a flat solid phantom. The aim was at first to quantify our SCDD in an irradiation field size of 10×10 cm^2. We then also measured the device performance under intensity modulated beams from an ONCOR Siemens Linear accelerator working at 6 MV photons. The dose measured with our SCDD in IMRT fields was compared to the PTW Semiflex type 31002 ionisation chamber (PTW IC) used daily at IGR. Measurements were performed with a DSA of 100 cm, with a detector situated at a 5 cm depth in the phantom. For both tests (conventional radiotherapy and IMRT), in order to measure the current during the irradiation, we used a Keithley 6517A electrometer with an in-house developed Labview data acquisition system. The measured current value was taken every 200 ms. The charge and the resulting dose were then calculated from the data by integrating the current versus the irradiation time. This data acquisition system is useful to follow directly the response of the device during the irradiation. For PTW IC we used the CEA data acquisition system and the Unidos Electrometer respectively, in order to compare the signals as measured with an electronics setup as used daily in the hospital.

3. Results

3.1. Conventional radiotherapy

In conventional radiotherapy field, we have evaluated the dosimetric properties of our device according to the IAEA 398 and the MAESTRO project performance requirements [13]. The evaluation of the signal to noise ratio is straightforward from the comparison of the measured current with and without irradiation. A dark current of 2 pA between irradiations was probed for the SCDD. At a dose rate of 300 MU min^{-1} we measured a signal to noise ratio (S/N) of 2600 for SCDD and 1600 for IC. The SCDD sensitivity is 215 nC Gy^{-1} mm^{-3} as evaluated at an applied voltage of −50 V. The sensitivity of the IC was estimated to be equal to 0.284 nC Gy^{-1} mm^{-3} (Table 1). This result is of great importance for the use of SCDD at very low dose rates as such values can be reached for some fields of IMRT. Fig. 1 shows the SCDD response during irradiation with a dose rate of 200 MU min^{-1} (2.46 Gy min^{-1}). The short term stability calculated from the measured value of the current signal over its standard deviation is here equal to 0.45% for SCDD when irradiated 10 successive times at a dose of 100 MU (1.21 Gy) with a dose rate of 200 MU min^{-1} (2.46 Gy min^{-1}). The repeatability is equal to 0.37% for SCDD as calculated from the data. For both parameters namely stability and repeatability, the estimated values are below a 0.5% limit threshold in agreement with the IAEA and the MAESTRO project dosimetric requirements. The linearity of the measured charge as a function of the applied dose and the dependence of the measured current signal with the applied dose rate were also evaluated (the measured current signal is proportional to the applied dose rate). The linearity with the dose was estimated using 5 successive measurements for each dose value to improve statistics and the data points were fitted with a linear fit. We observe a very good linearity with a regression factor of $r^2 = 0.9999$. The dependence of the SCDD and PTW IC current signals with the dose rate was estimated in the range of 1 to 8 Gy min^{-1}. We fitted the data points using the Fowler equation:

Table 1
Signal to noise ratio and sensitivity of SCDD and IC at 300 MU min^{-1}.

Detector	S/N	Sensitivity [nC Gy^{-1} mm^{-3}]
SCDD	2600	215
IC	1600	0.284

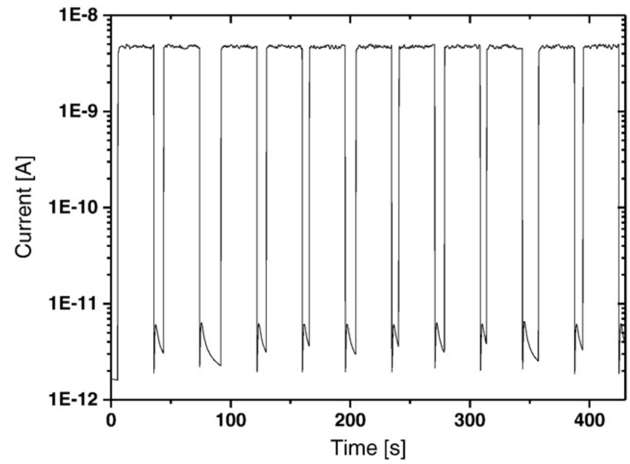

Fig. 1. The current signal of the SCDD registered for 100 MU with a dose rate of 200 MU min^{-1}.

$$I = I_0 + R \times \dot{D}^{\Delta}$$

where I is the detector current, I_0 the dark current, R the fitting factor, $\dot{D}$ the dose rate, and Δ the Fowler parameter. In the ideal case the delta value is equal to 1.

To fit the data with the Fowler equation, we imposed the mean value of the dark current to a value of 2 pA. We found a delta parameter value equal to 1.04 ± 0.04 for the SCDD and 0.9958 ± 0.0008 for the IC respectively.

3.2. IMRT

The goal of IMRT is to deliver a 3D dose distribution to the tumour while preventing any detrimental irradiation of the surrounding healthy tissues. It thus implies the maximisation of the dose within the tumour and its minimisation in the healthy tissues. To achieve this, a modulated field of irradiation is used to fit as near as possible the shape of the tumour in a 3D conformation. It aims at creating a volumetric distribution of the dose deposited with respect to the planned dose distribution required by the oncologist and calculated by TPS (Treatment Planning System). To perform such controls before treatment, the planned dose distribution is delivered to a phantom and the phantom-measured dose distribution can be compared to the dose distribution that is recomputed for the phantom from the patient treatment plan.

We present here the estimation of the dose delivered to a tumour in the case of an IMRT treatment of a Nasopharyngeal carcinoma (cancer of throat and neck). The IMRT treatment plan is composed of 7 modulated beams. We performed two series of measurements by very precisely adjusting the point measurement of the SCDD and the PTW IC, respectively, to be located at the position where the point dose was calculated by TPS. In this work we present as an example the results for an IMRT beam named F4 and composed from 10 segments of irradiation. As mentioned previously, to get the dose evaluation with SCDD we have to follow the medical physicist procedure for