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Single crystal chemical vapor deposited diamond detectors for intensity-modulated radiation therapy applications

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We report here on first intensity-modulated radiation therapy (IMRT) clinical tests performed at the Gustave Roussy Institute in France using one small (0.117 mm^3) synthetic single crystal diamond detector (SCDD). We report the comparison between the point doses evaluated with our detector, with a PTW semiflex air ionization chamber (0.125 cm^3) and calculated with the treatment planning system (TPS), respectively. The obtained results show a maximum difference of 2.3% for the diamond detector and of 4.6% for the ionization chamber, as compared with the TPS calculations. These very promising results show the potentiality of chemical vapor deposited SCDD for dosimetry of IMRT fields and opens up the field for diamond dosimeters toward novel applications such as very small beam monitoring. © *2009 American Institute of Physics*.
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I. INTRODUCTION

Intensity modulated radiation therapy (IMRT) aims at providing accurately a dose distribution that tightly complies with the planned target volume and avoids the excess radiation to normal (healthy) neighbor tissues and critical organs. Dose gradients that often occur in intensity modulated (IM) beams lead to significant volume effects for many types of detectors that render the precise measurement of the dose extremely delicate. This has therefore motivated recent studies aiming at the development of novel dosimeters able to follow the dynamics of IM beams in order to improve dose measurement.[1]

One of the main goals for the improvement of the metrology during cancer treatment is the development of new tools for the precise measurement of the dose delivered to the patient. The requirements for an ideal dosimeter complying with IMRT plan verification[1] are (i) high spatial resolution of the measurement: this is limited by the active size of the detector (current ionization chambers (ICs) are applicable to irradiation field size from 2×2 cm^2), (ii) fast response, to follow fast changes of the dose rate, (iii) reliability and reproducibility, (iv) large dynamic range of response, and (v) tissue equivalence.

Diamond is an excellent material to fulfill all those requirements. Dose measurements with high position resolution can be obtained using diamond based detectors with extremely small active volume although they provide high signal to noise ratio and fast responses. In addition, there is no need for energy corrections with diamond, nor either for temperature and pressure corrections. Few preliminary studies have aimed at IMRT dosimeters using ICs based on natural,[2] polycrystalline[3] or high-pressure high-temperature (HPHT).[4] diamonds. The recurrent difficulties associated with the use of natural diamond devices is the fact that very few gems exhibit the required quality, thus prices are high and delivery time can be extremely long. Due to the growth process, polycrystalline chemical vapor deposition (CVD) diamonds usually show a slow response time and HPHT diamonds can present electronic defects that alter the detector response. This motivated studies aiming at the development of novel routes providing reliably high quality diamond material complying with radiotherapy dosimetry applications requirements.

We optimized in our laboratory at CEA-LIST novel processing routes to fabricate synthetic single crystal diamond detector (SCDD) for this application. The optimization of the CVD growth conditions[5] and the tests of the detectors in clinical environment[6] are the two main points that were filled to validate the use of such devices. In this paper we present results for point dose measurements obtained with SCDD during IMRT tests as used for retroperitoneal sarcoma treatments. We report here those evaluation tests, and compare them with measurements obtained using a Physikalisch-Technische Werkstätten (PTW) semiflex air IC and a Kon-Rad (Siemens OCS) treatment planning system (TPS).

II. MATERIAL AND METHODS

A. Prototypes

The typical device used here for the tests is a solid state IC exhibiting a small active volume (0.117 mm^3) and based on a synthetic single crystal CVD diamond grown in our laboratory using an ASTeX AX5400 reactor. Growth conditions were using pressure and temperature of 130 torr and 850 °C, respectively.[5] The device thickness was of 150 μm. Metal electrodes with a diameter of 1 mm were evaporated on both sides of the sample and connected to a coaxial cable via ultrathin contact wires, while all connections were isolated being embedded in a silicon gel. The cylindrical tissue equivalent housing with external sizes of 0.9×2.4 cm^2 was

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made of solid water material at IFJ in Poland. A semiflex 0.125 cm^3 IC (PTW) was used as the reference detector.

B. Detector position in tissue-equivalent phantom

The key issue of IMRT is to provide a delivery of the three dimensional (3D) dose distribution to the tumor, i.e., the volumetric distribution of the dose deposited, with respect to the planned dose distribution required by the oncologist. A direct assessment of the dose actually absorbed in the patient during treatment is generally impossible. Therefore, to perform 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. During our measurements, the phantom used was made of polymethylmethacrylate (PMMA) and exhibited sizes of $24\times 24\times 9$ cm^3. Two positions in the phantom at the depths of 7 cm were made (drilled) with different diameters of 7 and 10 mm to fit to detectors external sizes. The fine position of the phantom against each IMRT radiation field was adjusted independently whether the measurement was that made on the SCDD or on the air IC, in order to locate the devices precisely at the position where the value of the point dose was calculated with the TPS.

C. Electrometers

Two types of electrometer were used: an Unidos E from PTW Company working in integration mode was used for calibration purposes, whether current measurements for both the SCDD and semiflex IC were performed using a Keithley 6517A high resolution electrometer. The measured signal current value was taken every 200 ms using an in-house developed LABVIEW DAQ. The collected charge was then evaluated as the integrated current value as a function of time.

D. Irradiations

The dose response of the detector was tested using a 6 MV photon beam delivered by an ONCOR Siemens linear accelerator, in the radiation therapy department of Gustave Roussy Institute (IGR, France). The detector response dynamics, stability, and repeatability were tested using the following reference conditions: an irradiation field size of 10 $\times 10$ cm^2, a source-detector distance of 100 cm, and a detector depth in phantom of 2 cm and with a maximal initial dose rate of 300 MU/min (MU=Monitor Units). The dosimetric performances of the SCDD for their evaluation for fields obtained using the "step and shoot" technique was assessed with the same 6 MV photon beam at a depth of 7 cm. The IMRT treatment plan consisted of a retroperitoneal sarcoma composed of six modulated beams as calculated using the KonRad Siemens treatment planning system. In this work the dosimetric results for three of the six IMRT beams named F1, F5, and F6 composed from 9, 6, and 11 segments, respectively, are presented. Figure 1 shows the three fluence

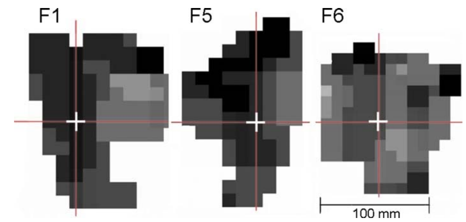

FIG. 1. (Color online) Calculated fluence maps for three IMRT fields F1, F5, and F6. The color grade corresponds to the applied dose. The position of the detector for each field is located at the cross.

maps corresponding to the F1, F5, and F6 irradiation fields. The position of the detector against each field is located at the position of the cross for each figure.

III. RESULTS AND DISCUSSION

A. Diamond detector characteristic

1. Dynamic response

A diamond sensitivity equal to 245 $nC/mm^3/Gy$ was evaluated at an applied voltage of 100 V. A dark current of 6 pA between irradiations was probed. The measured current signal is proportional to the applied dose rate. In the IMRT treatment the initial dose rate is constant for each irradiation segment, but the dose rate measured by the device depends from the location of the device against each segment of the IMRT field. The device response time strongly depends on the electrometer parameter adjustment and on the data acquisition system.

Figure 2 shows the signal current as a function of time for two measurement ranges of the Keithley electrometer used, and namely, using the autoscale or a fixed range. It is visible that for the high signals (high dose rates) a fast rise time is obtained, although it is limited by the data acquisition time interval of 200 ms. However, for lower values of the measured current (low dose rates) the response times strongly depend on the Keithley current range: with a much faster response when the adequate range is used. In our case, we used the range 2 nA, and using the 200 ms data interval, it corresponds to a highest dose rate delivery of 300 MU/

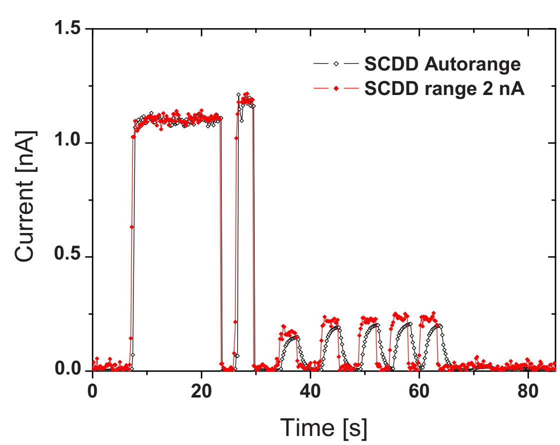

FIG. 2. (Color online) Measured current signals obtained on the SCDD device during irradiation using the IMRT field F1 and comparing the Keithley response time as a function of the measurement range (2 nA fixed range or autoranging mode).

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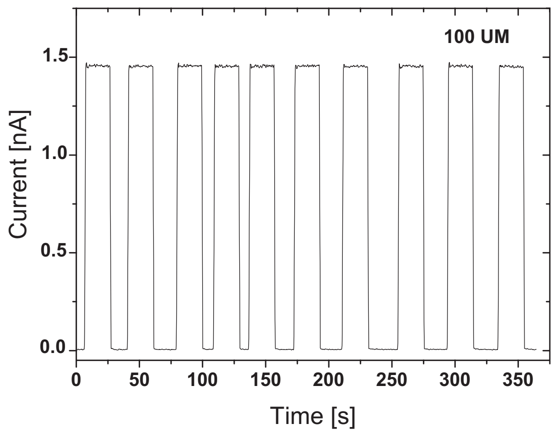

FIG. 3. SCDD was irradiated ten times under a dose of 100 MU (1.21 Gy). Repeatability equal to 0.2% was calculated from the data.

min. This allows the observation of dose variations at the level of one single monitor unit. This same signal dependence is also observed for the PTW IC.

2. Stability, repeatability, and linearity

The short term stability (calculated from the measured current value over its standard deviation) is equal to 0.44% for SCDD. Figure 3 shows the signal response as measured on the SCDD device when irradiated ten successive times at a dose of 100 MU (1.21 Gy). Repeatability values equal to 0.2% were obtained for this measurement, here using an initial dose rate of 300 MU/min. The dependence of the collected charge as a function of the applied dose for a constant dose rate of 300 MU/min is shown for the SCDD on Fig. 4. This measurement led to a calculated linearity factor R perfectly equal to 1.

IV. IMRT OF A RETROPERITONEAL SARCOMA

Figure 5 shows signals as measured using both the IC and the diamond detector during IMRT field (F1) delivery. The SCDD device exhibited a signal almost one order of magnitude higher than that of the IC. The integration of the signal as a function of time corresponds to the time-dependent dose distribution. Very similar time responses are probed on both detectors. However, since the SCDD volume is much smaller, the absolute sensitivity of the diamond detector when expressed in $[\mathrm{nC/Gy/mm^3}]$ raises to about 9000 times that of the IC device.

Figure 6 shows the signal response as a function of time measured at the isocenter for irradiation fields F5 and F6 and comparing the SCDD and IC devices. To highlight the dif-

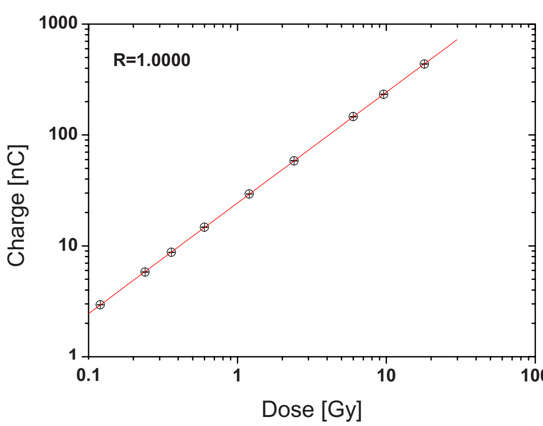

FIG. 4. (Color online) Charge signal as obtained using the SCDD as a function of the dose. The line represents a linear fit with a linearity factor $R=1$ with a precision of 10^{-4}.

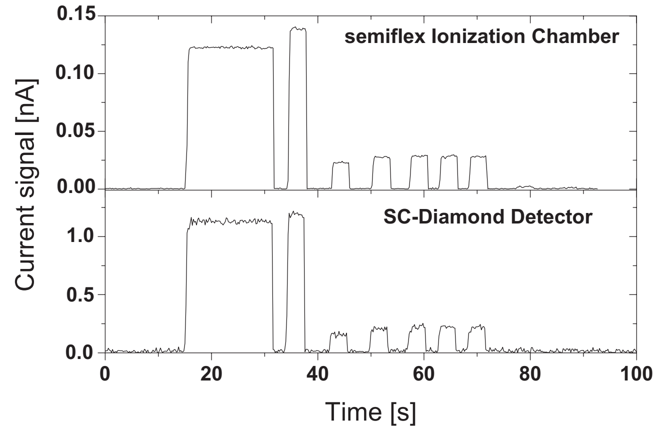

FIG. 5. Point dose measured for the beam F1 at the isocenter position for the SCDD and PTW IC. The same time responses for both detectors are observed.

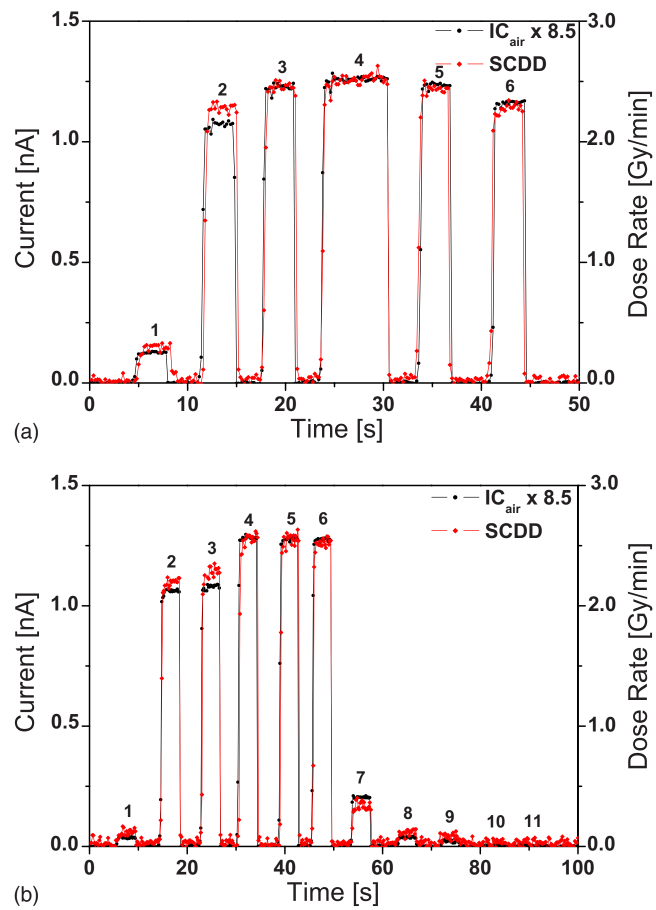

FIG. 6. (Color online) Point dose as measured at isocenter for beams F5 (a) and F6 (b) and comparing the SCDD (red line with diamond points) and the PTW IC (black line with dots). Measured signals correspond to the time-dependent spatial distribution of dose rates. To highlight the differences, we normalized both signals to the highest (dose rate).

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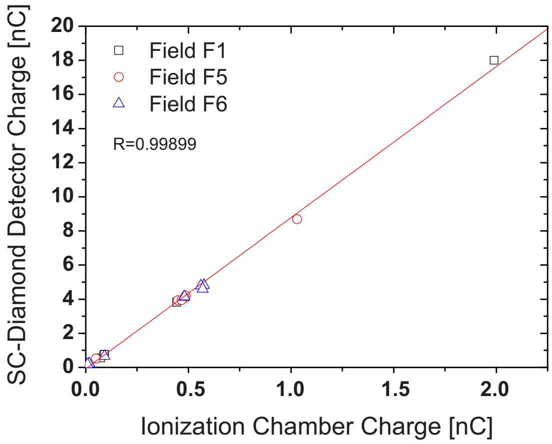

FIG. 7. (Color online) Linearity of the charge as measured at the isocenter position using the SCDD vs that probed on the semiflex air IC. The line represents a linear fit to all measurements, which compose the fields F1, F5, and F6. The point size corresponds to a measurement uncertainty of 2%.

ferences in the detector responses, we normalized the responses to the maximal measured signal (dose rate). This enables to probe the difference in the measured current signals, which became clearly visible for segment 2 of Field 5 and segments 2 and 3 of Field 6. This can be explained as the result of the difference in size of the detectors active volumes: at high dose gradients, the dose averaging is more important for the IC which active volume is about 1000× greater than that of the diamond detector. For correctly positioned detectors, a more precise point-dose measurement is therefore obtained with the smaller diamond device.

The current signal integrated as a function of irradiation duration is proportional to the applied dose. The charge values were calculated from the current measured using the Keithley 6517A electrometer. Figure 7 shows the integrated charge (calculated from previous Figs. 5 and 6) measured using the SCDD as a function of the charge measured with the air semiflex IC for the fields F1, F5, and F6. A linear fit performed on the data led to a linearity factor R equal to 0.999.

Table I presents a comparison between the integrated dose as calculated using the TPS and the values measured at isocenter and using the SCDD and the IC for 3 IMRT beams (F1, F5, and F6).

TABLE I. Integrated dose as calculated using TPS and measured at the isocenter position using both the SCDD and the IC, and for three IMRT beams (F1, F5, and F6). The deviations between the calculated and measured doses values are presented.

	Dose [Gy]		
IMRT beam	Calculated	SCDD	IC
F1	0.92	0.90	0.88
Deviation		−2.2%	−4.3%
F5	0.90	0.88	0.88
Deviation		−2.2%	−2.2%
F6	0.87	0.85	0.83
Deviation		−2.3%	−4.6%

A good agreement (deviation ≤ 1.2%) between the diamond detector and the IC is observed for all beams tested. A very good agreement between the SCDD measured data and the TPS calculations were obtained (discrepancies below 2.3% and 4.6% were obtained for the diamond and the IC, respectively). The variations from the calculated dose values are presented for each integrated irradiation field. Due to the differences observed on the spatial resolution between two measuring methods, deviations between doses measured with the SCDD and the air IC occur locally near the step dose gradient characteristics for IMRT fields. It shows that a more precise measurements of the point dose value can be achieved using the diamond detector.

V. CONCLUSIONS

Single crystal CVD diamond detectors exhibiting a reduced active volume of 0.117 mm^3 have been fabricated and tested. In order not to alter the tissue-equivalence properties of the detector, a special housing of cylindrical geometry was made from solid water material. The first clinical tests under IMRT beams were performed successfully. A very good agreement between the SCDD measured data and TPS calculations were obtained (discrepancies ≤ 2.3%). However, we have highlighted that a correct fine adjustment of the Keithley electrometer is required. Also, spatial dose distribution rather than point measurements are preferred to verify the calculated dose. To improve the signal to noise ratios of existing devices a larger sensitive volume is required. For the next device generation, we intend to replace the coaxial cable used with that of a triaxial cable in order to further reduce the noise levels, without affecting the 1 mm contact size leading to high position resolution, nor the tissue equivalence of the devices. In summary, this study demonstrated that SCDD is a perfect candidate for dose measurements with high spatial resolution (below 1 mm) of stereotactic beams (diameter from 2 cm), in strong dose gradient fields, small beams (diameter from 4 mm), and particle therapy fields.

ACKNOWLEDGMENTS

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[1]C. De Wagter, J. Phys.: Conf. Ser. **3**, 4 (2004).
[2]E. Barnett, M. MacKenzie, and B. G. Fallone, Radiol. Oncol. **39**, 71 (2005).
[3]C. De Angelis, M. Casati, M. Bruzzi, S. Onori, and M. Bucciolini, Nucl. Instrum. Methods Phys. Res. A **583**, 195 (2007).
[4]B. Marczewska, I. Kupriyanov, Yu. Pal'yanov, T. Nowak, P. Olko, M. Rębisz, and M. P. R. Waligórski, Diamond Relat. Mater. **16**, 191 (2007).
[5]N. Tranchant, D. Tromson, C. Descamps, A. Isambert, H. Hamrita, P. Bergonzo, and M. Nesladek, Diamond Relat. Mater. **17**, 1297 (2008).
[6]C. Descamps, D. Tromson, A. Isambert, A. Bridier, C. De Angelis, S. Onori, M. Bucciolini, and P. Bergonzo, Radiat. Meas. **43**, 933 (2008).

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