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Development of CVD diamond detectors for clinical dosimetry

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Abstract

The use of chemical vapour deposition (CVD) methods for the manufacture of diamonds could lead to detectors for high-resolution radiotherapy dosimetry that are cheaper and more reproducible than detectors based on natural diamonds. In this work two prototype designs (Diamond Detectors Ltd, Poole) of CVD diamond detectors were considered. The detectors were encapsulated in a water-proof housing in a form-factor that would be suitable for dosimetry measurements in water, as well as solid material phantoms. Stability of the dosimeter over time, the dose-response, dose-rate response and angular-response were examined. The study demonstrated that the detector behaviour conformed with theory in terms of the dose-rate response and had acceptable properties for use in the clinic.

Keywords: CVD diamond detector, radiotherapy dosimetry

1. Introduction

Dosimetry of megavoltage radiotherapy photon beams has become more challenging since the introduction in the clinical environment of new delivery techniques like intensity modulated radiotherapy (IMRT) and stereotactic radiation treatments. In the use of small radiation fields, which characterises these new delivery techniques (below 1 cm^2 in the case of stereotactic delivery), air-filled ionisation chambers are not the ideal detectors for dosimetry

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purposes due to their effect on charged-particle equilibrium and low sensitivity which leads to large sensitive volumes (1).

Solid-state detectors, like silicon diodes and diamond detectors, offer high sensitivity and high spatial resolution. Silicon diodes have shown good performances in the dosimetry of small photon beams, however silicon, unlike diamond(2), is far from a tissue-equivalent atomic composition, therefore it is necessary to use energy-dependent correction factors (3).

In the recent years the use of synthetic diamond detectors has been considered. The performance of in-house detector prototypes has been tested by different research groups with promising results (4; 5).

In this work the results following the characterisation of two different designs of commercial detector prototypes based on single crystal CVD diamond are presented. Measurements include the evaluation of the priming dose, response dynamics, short and long term reproducibility, angular dependence, dose and dose rate response, during the irradiation with a 6 MV photon beam.

2. Methods and material

2.1. CVD-diamond prototypes

Eight different detector prototypes based on single-crystal CVD diamonds were developed at Diamond Detectors Ltd (Poole). All the devices were cylindrical in shape with a diameter of 7 mm. The devices were divided into two groups: 5 prototypes of the first generation group and 3 prototypes of the second generation group.

The sensitive volumes were made of high purity single-crystal diamond (less than 1 ppm of Boron and Nitrogen concentration). The size of the sensitive volume was 1 mm×1 mm×0.5 mm for the first generation prototypes and 1 mm×1 mm×0.3 mm for the second generation prototypes.

The main difference between the two groups was in the encapsulation design and material.

The prototypes within the first generation group were identical. The sensitive volume was sandwiched within a cylinder of poorer quality synthetic diamond, at about 150 μm deep. The overall thickness of the diamond cylinder was about 1 mm and the diameter was 5 mm. The electrical contacts were

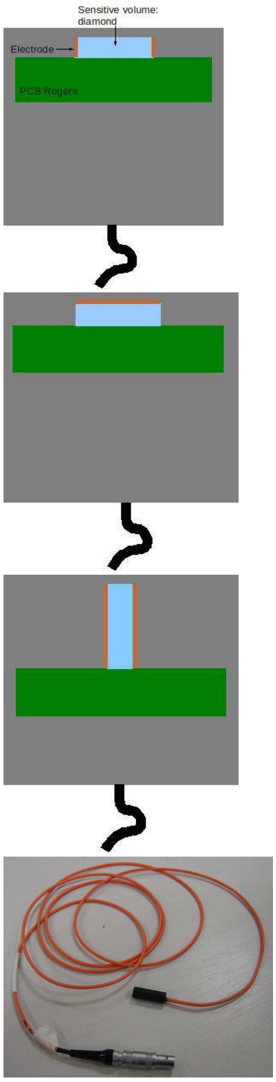

Figure 1: Schematic diagram of the design of the three second generation diamond detector prototypes. The diagram is not in scale. Figure (d) is an example of one of the encapsulated detectors.

made through top-bottom pads with a proprietary metallisation technique (DLC/Pt/Au) (6).

The prototypes within the second generation each had a different design. A schematic diagram (not to scale) is shown in figure 1. The diamond sensitive volume was placed on a PCB (Rogers Corporation) and surrounded by epoxy. The electrical contacts were of type DLC/Pt/Au, as for the first generation.

2.2. Experimental measurements

The experimental measurements were carried out at Singleton Hospital, Swansea. The detectors were irradiated with the 6 MV photon beams produced by the LINAC machines used to deliver the radiotherapy treatments. Most of the measurements were carried out with the detectors allocated in an in-house fabricated cubic PMMA phantom with a hole drilled in the middle. The side of the PMMA phantom was 8 cm. A multiblock Solid-Water phantom (7) was placed around the PMMA cube to build a bigger water equivalent phantom with a cross area of 30 cm×30 cm.

The charge generated in the diamond devices was acquired using an I-400 gated integrator electrometer and an A-300 loop controller (Pyramid Technical Consultants) used as interface between the electrometer. The connection between the A-300 loop controller and the I-400 electrometer was made by fiber-optic cables, while ethernet cables were used to connect the A-300 loop controller to the computer.

The I-400 electrometer measures the average current over a user-defined integration period. The integration periods allowed by the I-400 electrometer range between 100 μs and 65 s. The pulse repetition frequency of the clinical LINAC photon beams are of the order of hundreds hertz, therefore integration periods of 1 ms and below allow the evaluation of the charge collected by the detector on a pulse-by-pulse basis.

Most of the experimental data was acquired with the integration interval set to 100 ms. Figure 2 shows an example of the signal acquired. At each set-up the irradiation was repeated five times. The detector response was evaluated by calculating the mean value and the standard deviation of the total charge collected during each irradiation. The total charge was calculated by summing the signal from point A (the beginning of the irradiation session) to point B (the end of the irradiation session).

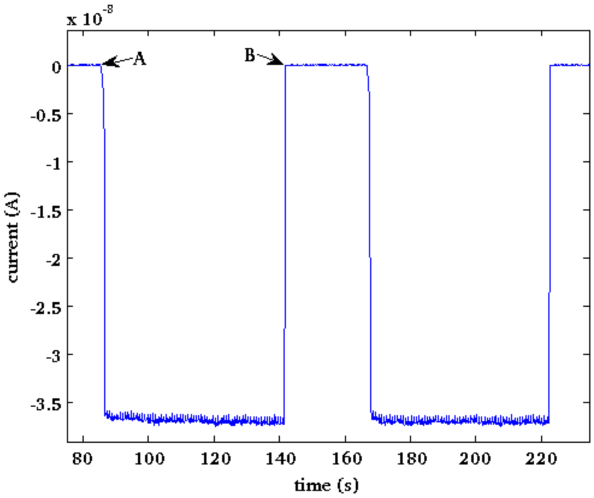

Figure 2: Example of the signal acquired by the diamond detectors with the integration interval set to 100 ms. The total charge is calculated by summing the charge from point A to point B. The mean current is calculated by dividing the total charge by the irradiation interval.

3. Results and Discussion

3.1. Priming dose

The priming effect is described by the variation of the detector sensitivity with the total absorbed dose. The pre-irradiation dose needed to stabilise the detector current was assessed by irradiating the detectors in the equivalent water phantom at 3 cm deep, 100 cm SSD and 10 cm×10 cm field size. 50 MU were delivered during each irradiation which amount to 0.4725 Gy at this set-up.

All the devices of the first generation reached a stable output after 5 Gy of total absorbed dose. The devices of the second generation did not need any pre-irradiation dose.

3.2. Response dynamics, stability and reproducibility

After irradiation of the first generation of detectors, a long decay time of the signal of tens of seconds was noticed. As a consequence, the detector response and the reproducibility were strongly influenced by the irradiation time pattern. The measurements carried out on detector DD66 showed a drop of the sensitivity up to 5% with increasing of the time interval between two consecutive measurements from 10 s to 120 s. Moreover, the reproducibility, calculated as the ratio of the standard deviation to the mean value of the collected charge during irradiation over 5 consecutive measurements, improved greatly below 0.7% when the first measurement was discarded.

The decay time of the signal after irradiation of the second generation of detectors was about 0.7 s. The sensitivity of these detectors was monitored for several months. Detectors DD3 and DD8 showed a broad range of variation of the sensitivity over time. The sensitivity of detector DD8 stabilised to a value of about 520 nC/Gy. Detector DD4 had stable sensitivity of about 180 nC/Gy.

The stability of the detector DD3 and DD4 during irradiation, calculated as the ratio of the standard deviation of detector current during the irradiation to its mean value, was always within 4% and 0.7% respectively. The stability of the DD8 device improved with time, achieving better than 0.4%.

The reproducibility of detector DD3 degenerated with time from 0.6% to 3.7% whilst the reproducibility of detector DD4 and DD8 was in general below 1%.

3.3. Angular dependence

The angular dependence was checked by irradiating the diamond detectors with a 3 cm×3 cm field size. The detectors were placed in a PMMA phantom shaped as a sphere with a radius of 3 cm. The sensitive volume reached the centre of the sphere. The centre of the sphere was placed at the isocentre, i.e. 100 cm from the source. The detectors were irradiated around the side. A schematic representation of the irradiation set up is shown in figure 3. The charge collected at each angle was normalised to the charge collected at 0° angle.

The angular dependence of the first generation of detectors was checked with detector DD63. The variation of the detector current with the gantry angle during the irradiation from the front side was within 1% in the range between −90° and 90°. This is in agreement with the results of the Monte Carlo simulations carried out with the DOSRZnrc code. In the case of irradiation from the side, a periodic pattern of the variation of the detector current with the angle was noticed (fig 4). This effect could be attributed to the detector design which has a metal wire going through a hole drilled in

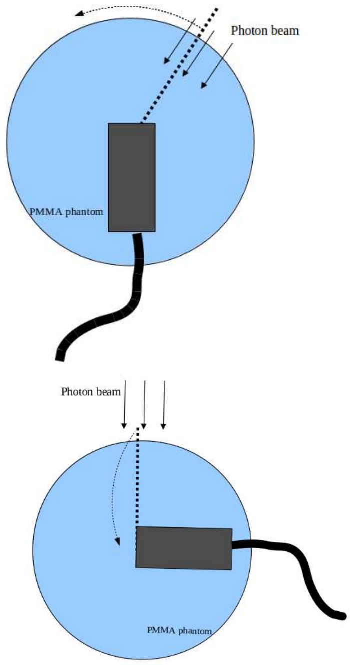

Figure 3: Schematic representation of the irradiation set up for the evaluation of the angular dependence: irradiation on the front (a) and on the side (b)

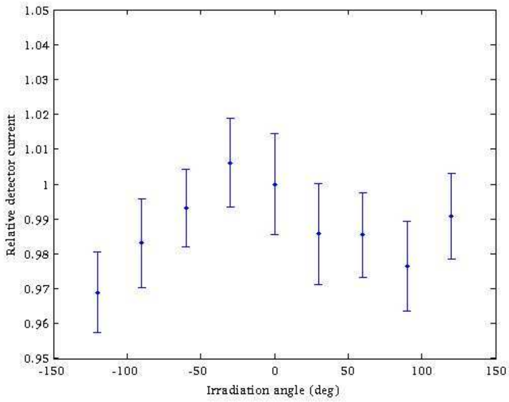

Figure 4: Angular dependence of detector DD63 irradiated with the 6 MV photon beam, irradiation from the side.

the diamond encapsulation to connect the upper electrode plate to the PCB, but this hypothesis was not investigated further.

Figure 5 shows the angular dependence of the DD8 detector of the second generation when irradiated from the front side (a) and from the side (b). A decrease of the charge collected of more than 5% was measured at large angles in the first case. In the second case the detector response showed a clear trend of the angular dependence varying below 2%. The same angular dependence trend was measured by rotating the detector only, suggesting that the angular dependence could be due to the detector design. A micro-CT scan of the detector showed the sensitive volume was not perfectly aligned along the central axis, and slightly tilted.

3.4. Dose response

The dose dependence was checked by irradiating the diamond detectors with different monitor units (MU) at 2 cm deep in the 30×30 cm^2 water equivalent phantom, 100 cm SSD and 10 cm×10 cm field size. The pulse repetition frequency was kept constant at about 400 Hz. The dose delivered ranged from 0.25 Gy to 9.88 Gy.

A linear response of the detector with dose is characterised by a constant sensitivity therefore, the detector response was evaluated by checking the

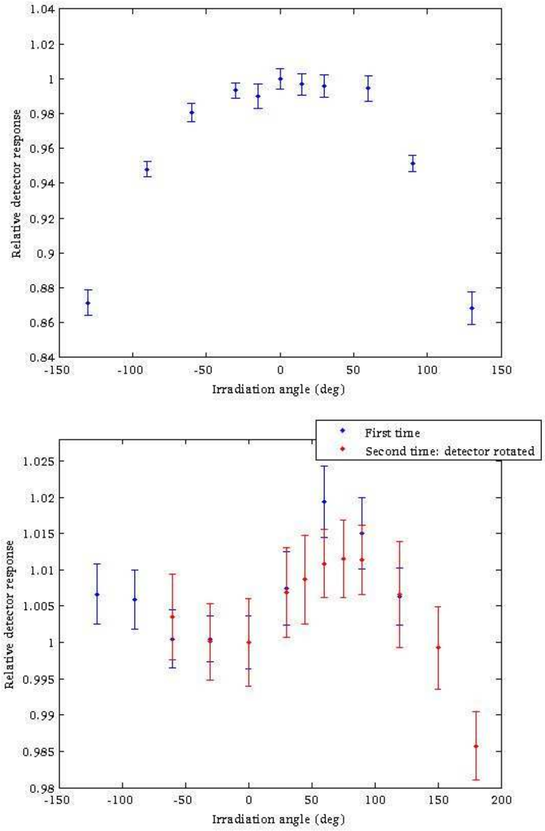

Figure 5: Angular dependence of detectors DD8 when irradiated with the 6 MV photon beam from the front side (a) and from the side (b).

sensitivity against the dose delivered. Detector DD3 of the second generation showed an increasing sensitivity with dose up to 30% whilst detector DD4 and DD8 showed a slight increase of 4% and 2% respectively. This could be due to transient phenomena, as for example the filling of traps or the polarisation effects, which influence the response of the diamond detectors at the beginning of the irradiation until an equilibrium is reached.

3.5. Dose rate response

The evaluation of the dose rate dependence was performed by irradiating the diamond detectors with a 6 MV photon beam at a pulse repetition frequency (PRF) of 400 Hz at various source-to-detector distances.

The detectors were placed inside a PMMA mini-phantom to minimise the phantom scatter perturbations due to the increase in the field size while moving away from the source. The mini-phantom diameter was 1.8 cm. A hole of 0.8 cm in diameter was drilled along the central axis to introduce the detector. The inner hole was drilled such that the detector was at a depth of 3 cm. The detector was therefore surrounded by 0.5 cm of PMMA on the side and 3 cm on the top. 100 MU were delivered at each source-to-detector distance.

The mean dose rate was calculated as the ratio of the dose delivered to the irradiation interval. Monte Carlo simulations were used to calculate the fraction of dose delivered in the mini-phantom compared to the nominal dose delivered, which is normalised to irradiations in a large water phantom.

The detector response at each dose rate value was taken as the current measured by the I-400 electrometer with the integration interval set to 100 ms.

Fowler theory (8) was used to explain the dose rate dependence which states that the current induced by the interactions of the radiation within an insulator material follows the equation $i = i_0 + \alpha \dot{D}^{\Delta}$, where i_0 is the leakage current, α the detector response and $\dot{D}$ the dose rate. The Δ factor varies between 0.5 and 1 depending on the distribution of the trapping centres in the crystal.

The Δ factors measured for the first generation of detectors ranged from 0.87 to 1.

The Δ factors for the second generation of detectors are summarised in table 1. The dose rate dependence was measured several times over few weeks because of instabilities of the detectors response. The Δ factor values compare well with the values found by other research groups (4; 5).

	Δ factor	95% confidence interval
DD3	0.73	[0.67 0.79]
	0.85	[0.82 0.87]
DD4	1.005	[0.990 1.020]
	0.99	[0.959 1.022]
	1.026	[0.981 1.071]
DD8	0.895	[0.844 0.945]
	0.897	[0.879 0.915]

Table 1: Δ factor values and 95% confidence intervals of DD3, DD4 and DD8. A non-linear fitting tool available in the Matlab code was used to fit the experimental data to the equation expressed in the Fowler theory.

4. Conclusions

The performance of 8 single crystal CVD diamond detectors was assessed for the dosimetry of radiotherapy megavoltage photon beams. The diamond detector prototypes were divided into first generation and second generation groups, with 5 prototypes belonging to the first group and 3 prototypes belonging to the second group.

For the first generation diamond detectors, the pre-irradiation dose was less than 5 Gy and the stability was below 1% for all prototypes. A decay time of the signal after irradiation of tens of seconds was observed. This feature makes the detector response dependent on the time pattern of the irradiations, therefore unsuitable for dosimetry purposes.

The performance of the second generation diamond detectors, DD4 and DD8, was very promising for dosimetric purposes, in terms of dynamic response, repeatability and stability. The stability and repeatability improved with time from the time of fabrication as more dose was delivered. Detector DD3 instead showed a deteriorating stability and repeatability, and a slight dependence of the sensitivity on the total dose delivered, especially at doses below 1 Gy.

Conversely, the angular response of the first generation diamond detectors was found to be of higher quality than second generation detectors suggesting improvements in the detector mounting could be achieved in future design iterations.

All of the second generation diamond detectors exhibited a dose-rate response that was broadly in agreement with Fowler theory that predicts Δ factors approaching 0.5 for the highest purity diamond materials. Sufficient variation was however observed to suggest effects relating to the irradiation history and metallisation processes were present.

5. Acknowledgements

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