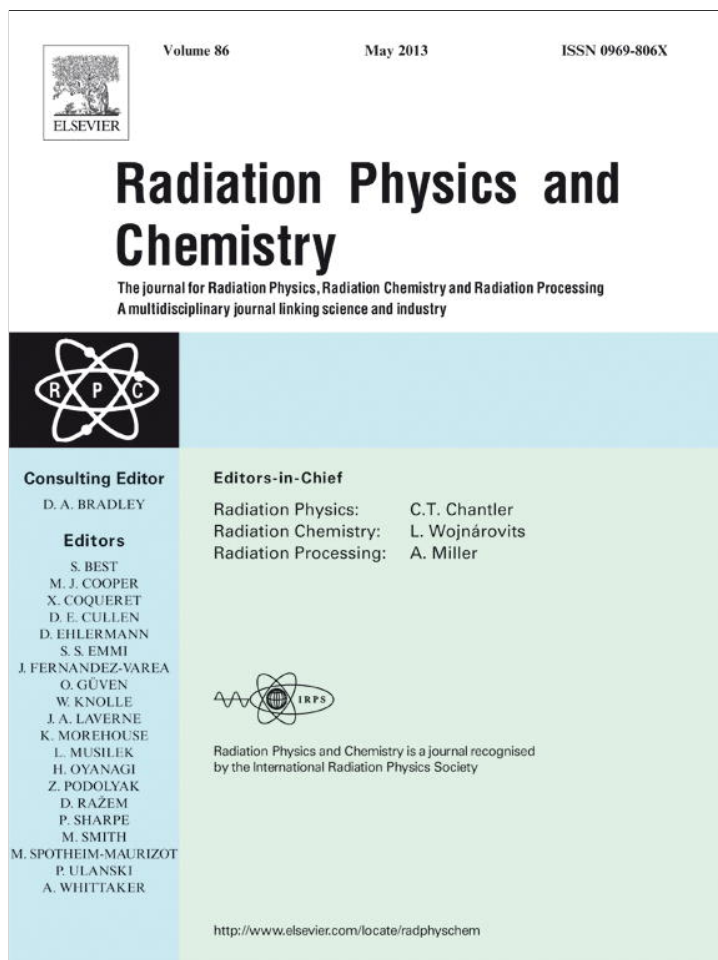




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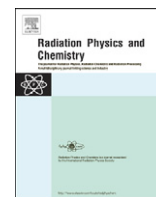
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An evaluation of some pertinent parameters that influence the dosimetric performance of synthetic diamond detectors

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H I G H L I G H T S

- We evaluated the response characteristics of diamond detectors to two beam types.
- The unstable response of the detectors was attributed to the presence of ambient light.
- The diamond detectors were found to not require dose rate dependence corrections.
- The change in the angular response of the diamond detectors is within 4%.
- An optimized design would make the probe to be independent of beam direction.

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Although the near-tissue equivalence of diamond allows the direct measurement of dose for clinical applications without the need for energy-corrections, it is often cited that diamond detectors require pre-irradiation, a procedure necessary to stabilize the response or sensitivity of a diamond detector before dose measurements. In addition it has been pointed out that the relative dose measured with a diamond detector requires dose rate dependence correction and that the angular dependence of a detector could be due to its mechanical design or to the intrinsic angular sensitivity of the detection process. While the cause of instability of response has not been meticulously investigated, the issue of dose rate dependence correction is uncertain as some studies ignored it but reported good results. The aims of this study were therefore to investigate, in particular (1) the major cause of the unstable response of diamond detectors requiring pre-irradiation; (2) the influence of dose rate dependence correction in relative dose measurements; and (3) the angular dependence of the diamond detectors. The study was conducted with low-energy X-rays and electron therapy beams on HPHT and CVD synthesized diamonds. Ionization chambers were used for comparative measurements. Through systematic investigations, the major cause of the unstable response of diamond detectors requiring the recommended pre-irradiation step was isolated and attributed to the presence and effects of ambient light. The variation in detector's response between measurements in light and dark conditions could be as high as 63% for a CVD diamond. Dose rate dependence parameters (Δ values) of 0.950 and 1.035 were found for the HPHT and CVD diamond detectors, respectively. Without corrections based on dose rate dependence, the relative differences between depth-doses measured with the diamond detectors and a Markus chamber for exposures to 7 and 14 MeV electron beams were within 2.5%. A dose rate dependence correction using the Δ values obtained seemed to worsen the performance of the HPHT sample (up to about 3.3%) but it had a marginal effect on the performance of the CVD sample. In addition, the angular response of the CVD diamond detector was shown to be comparable with that of a cylindrical chamber. This study concludes that once the responses of the diamond detectors have been stabilised and they are properly shielded from ambient light, pre-irradiation prior to each measurement is not required. Also, the relative dose measured with the diamond detectors do not require dose rate dependence corrections as the required correction is only marginal and could have no dosimetric significance.

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1. Introduction

Diamond has been considered as an attractive material for medical applications due to its appealing dosimetric properties

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(Keddy et al., 1988; Heydarian et al., 1993; Hoban et al., 1994; Buttar et al., 1997; van der Merwe and Keddy, 1999; Manfredotti et al., 2001; Ramkumar et al., 2001; Ade et al., 2012). The interest in using diamond for medical applications stems principally from its near-tissue equivalence ($Z_C=6$ is close to the effective atomic number of human tissue, $Z_{\text{eff}}=7.42$). The near-tissue equivalence of diamond implies its energy response to radiation is equivalent to that of human soft tissue which enables the straightforward measurement of dose for clinical applications without the need for energy corrections (Guerrero et al., 2004) since, in principle diamond shows negligible energy dependence (Laub et al., 1997; van der Merwe and Keddy, 1999; Ade et al., 2012) and the detector signal is directly proportional to the absorbed dose rate to tissue (Vatnisky and Järvinen, 1993). This offers diamond detectors an advantage over air ion chambers and Si diodes in dosimetry which show energy dependence requiring energy corrections for absorbed dose measurements. Das (2009) noted in particular that a diamond detector is suitable for relative dosimetry because the mass attenuation coefficient and stopping power ratio of water to carbon are nearly constant over a wide range of photon and electron energies.

Another appealing dosimetric property of diamond attractive for electron dosimetry is its physical size (Keddy et al., 1988). Since electron dosimetry typically implies the measurement of steep dose gradients, small-sized detectors offering high spatial resolution are required to minimize the gradient effects (van der Merwe and Keddy, 1999). By virtue of the solid-state/air density ratio, which is of the order of 3.0×10^3 (Bruzzi et al., 2000) and with a high atomic number density of 1.75×10^{23} atoms cm^{-3} (Mainwood, 2000) corresponding to a molar volume of $3.44 \text{ cm}^3 \text{ mol}^{-1}$, diamond detectors with sizes of a few mm^3 can be fabricated for high resolution measurements which is an advantage over large volume detectors such as air ion chambers. Silicon diodes have high spatial resolution comparable to diamond detectors (Vatnisky and Järvinen, 1993), but they suffer a significant disadvantage of being non-tissue equivalent ($Z_{\text{Si}}=14$), show dose rate dependence and separate shielded and unshielded diode detectors are usually required for the dosimetry of photon and electron beams (Heydarian et al., 1993; Hoban et al., 1994; Björk et al., 2000). Thus unlike Si diodes, a diamond detector has an advantage of being more cost effective as it was shown in a previous study (Ade et al., 2012) that a single synthetic diamond probe could perform effectively in the dosimetry of both low-energy X-rays and electron therapy beams.

Although diamond is attractive for medical applications due to its appealing dosimetric properties, diamond detectors (both natural and synthetic) are often noted to require pre-irradiation (Vatnisky and Järvinen, 1993; Laub et al., 1999; Buttar et al., 2000; Fidanzio et al., 2004; Cirrone et al., 2006), a procedure necessary to stabilize the response or sensitivity of a diamond detector before dose measurements (Guerrero et al., 2004, 2005). In addition, it has been pointed out that the relative dose measured with a diamond detector requires a correction factor based on dose rate dependence (Laub et al., 1997, 1999; Björk et al., 2000; Fidanzio et al., 2004), and that the angular dependence of a detector could be due to its mechanical design or to the intrinsic angular sensitivity of the detection process (Brahme, 1985). While the rationale for pre-irradiation remains, the major cause of instability of response has not been meticulously investigated. Also, the issue of dose rate dependence correction is uncertain as some studies (Heydarian et al., 1993; van der Merwe and Keddy, 1999; Almaviva et al., 2010; Ade et al., 2012) ignored it but reported good results. The aims of this study were therefore to investigate, in particular the major cause of the unstable response of diamond detectors requiring pre-irradiation, the influence of dose rate dependence correction in relative dose measurements and the angular dependence of HPHT and CVD synthesised diamonds.

2. Experimental

A high-pressure high-temperature (HPHT) and two polycrystalline chemical vapour deposition (CVD, CVD1 & CVD2) commercially available diamond crystals were examined. The dimensions of CVD1, CVD2 and the HPHT sample were $10 \times 10 \times 0.5 \text{ mm}^3$ (50 mm^3), $10 \times 10 \times 1.0 \text{ mm}^3$ (100 mm^3) and $7.94 \times 6.38 \times 0.96 \text{ mm}^3$ (48.63 mm^3), respectively. CVD1 is of detector grade (DG) quality whereas CVD2 is of optical grade (OG) quality. Although rectangular in shape, the HPHT crystal has a slightly irregular geometry. The opposite surfaces of each of the crystals have been metallised as reported in a previous study (Ade et al., 2012) to provide the necessary ohmic contacts for voltage biasing and acquisition of ionization signal. For quality control, the crystals were characterised using Raman spectroscopy and Electron spin resonance (ESR). The Raman spectra were acquired using a Jobin-Yvon T64000 Raman spectrometer with the 514.5 nm line of an Ar^+ laser as excitation source. The ESR measurements were carried out with a Bruker ESP300E ESR spectrometer.

The study was conducted with low-energy X-rays (25–30 kVp) from a Senographe 500 T mammography X-ray machine and electron therapy beams (7, 12 & 14 MeV) produced by a clinical linear accelerator (Siemens Primus) at the Charlotte Maxeke Johannesburg Academic Hospital. Each diamond crystal, biased at either +50 V (for studies using X-rays) or +200 V (for measurements using electron beams), was encapsulated in a probe housing as described in two previous studies (Ade et al., 2012; Nam and Ade, 2011) and the probe, placed in its customised Perspex phantom was connected to a commercial PTW-Freiburg UNIDOS E electrometer system operated manually in the 'charge' mode. The probe, constructed of entirely tissue-equivalent material with a Perspex body can hold diamond crystals of various sizes up to $10 \times 10 \text{ mm}^2$ in dimension, has different exposure geometries¹ for X-rays ('edge-on') and electron beams ('flat-on').

Dosimetric measurements in electron beams (using only CVD1 and the HPHT sample) included dose rate dependence, percent depth-dose distributions, output factors and angular response measurements. Percent depth-dose distributions (for exposures to 7 and 14 MeV electron therapy beams) and angular dependence (for exposure to a 14 MeV electron beam) measured with the diamond detectors were obtained in a similar procedure as reported in a previous study (Ade et al., 2012) using a dose rate of 3 Gy/min, a 100 cm SSD (source-to-surface distance) with an applicator defined field of $10 \times 10 \text{ cm}^2$ and 50 monitor units corresponding to a dose of 0.5 Gy were used to irradiate the detectors. Reference ion chambers recommended for the dosimetry of high-energy electron beams (a 0.055 cc Markus chamber (Type 23343) and a 0.66 cc Farmer-type chamber) were used for comparative measurements. For studies using low-energy X-rays, the response of each crystal was measured as a function of absorbed dose. The dose values were measured with an IC10 ion chamber as a function of X-ray tube voltage (kVp) at a constant tube loading of 200 mAs.

3. Results and discussion

3.1. Raman spectroscopy and electron spin resonance (ESR)

Raman spectroscopy, which evaluates the material quality (phase and crystalline qualities) of diamond crystals showed only

¹ In the 'flat-on' geometry, the incident radiation is normal to the face of the diamond wafer, which has a larger area but with reduced attenuation depth. In the 'edge-on' geometry, the incident radiation is normal to a wafer edge which has a smaller area but with greater attenuation depth.

the characteristic diamond Raman peak at 1332 cm^{-1} over a linear background with no evidence of non-diamond component for both the HPHT and CVD diamond samples confirming phase purity of the crystals. The measured Raman widths (full-width-at-half-maximum (FWHM)) of the crystals were 2.27 ± 0.04 , 2.37 ± 0.11 and $2.42 \pm 0.11\text{ cm}^{-1}$ for the HPHT, CVD1 and CVD2, respectively. The broadening of the FWHM of the Raman peak is an indication of a more defective crystal lattice (Faggio et al., 1999; Fish et al., 1999), i.e., an indication of the presence and concentration of defects (such as point defects, crystal defects, grain boundaries, etc).

Nitrogen is a commonly observed impurity in diamond affecting its electrical properties. Nam et al. (1991) established that single substitutional nitrogen (Ns) is responsible for many performance characteristics of diamond radiation detectors. ESR, which determines the concentration of Ns ([Ns]) gave values of $130 \pm 2\text{ ppm}$ and $10 \pm 2\text{ ppb}$ for the HPHT and CVD1 samples, respectively. The much higher levels of Ns impurities of the HPHT crystal compared to its CVD counterpart observed in this study could be attributed to the technique normally used to grow diamond by the HPHT method. Although the [Ns] of CVD2 (an OG crystal) has not been determined, the difference between a DG and an OG diamond is that the [Ns] of an OG crystal is always, at least a factor of two more than that of its DG counterpart, and we have been informed that nitrogen is intentionally introduced during the growth of CVD OG diamonds (private communication). The factor of two, difference between the DG and an OG diamond w.r.t [Ns] has been confirmed in a previous study by this group (Mavunda et al., 2008).

3.2. Studies using low-energy X-rays—instability of response of diamond detectors

It is often cited that diamond detectors require pre-irradiation. As pointed out by Guerrero et al. (2004), diamond has a large band-gap of about 5.5 eV within which defects caused by impurities, dislocations and crystal defects co-exist. The effect of pre-irradiation (priming or pumping effect) is influenced by these trapping or defect levels and two types have been identified (Guerrero et al., 2004; Bergonzo et al., 2007): shallow levels which are unstable at room or near room temperature and deep levels which remain stable at room temperature. Priming thus defines the pre-irradiation that enables the filling up of shallow as well as deep traps in order to stabilise the response of a diamond detector (Vatnisky and Järvinen, 1993; Guerrero et al., 2004).

The recommended pre-irradiation step prior to each measurement is an annoying property and could be a major drawback of diamond detectors that could lead to wrong or inaccurate determination of radiation dose if the correct priming dose is not given. Van der Merwe and Keddy (1999), however first pointed out that pre-irradiation was not required for their synthetic diamond detector, although no investigation as to the reason was carried out. Subsequently, Assiamah (2004) and Mavunda (2008) also noted in their studies that some synthetic diamond crystals were found not to require pre-irradiation. Assiamah (2004) in addition reported that the sensitivity of one diamond crystal was found to increase with successive X-ray irradiation. This observation was assumed to be due to the filling of traps present within the crystal by charge carriers and a few attempts to stabilise the response did not improve its performance. Buttar et al. (2000) also observed and attributed the initial increase in response to dose with their CVD diamond detector to the filling of trapping states. Although the performance of the detector was improved through priming, it was pointed out that further work is required to understand and remove the priming effect.

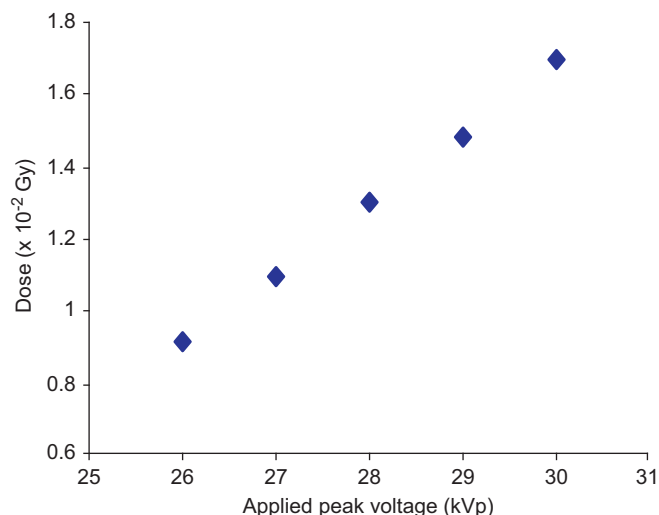


Fig. 1. Absorbed dose response of IC10 ion chamber to changes in kVp (nominal values) at 200 mAs tube loading.

In this study, the cause of the unstable response of diamond detectors requiring pre-irradiation was systematically investigated in light and dark conditions² by measuring and monitoring the response of each of the diamond sensors as a function of absorbed dose (X-ray energy or progressive X-ray irradiations). The absorbed dose has been measured with an IC10 ion chamber, the results of which are shown in Fig. 1. From a previous study presented by this group (Assiamah et al., 2007) using mammography X-rays, it was established that the 'edge-on' and 'flat-on' detection geometries (which have different attenuation depths) of a diamond probe have different absorption levels. Mammography X-rays were therefore chosen for this part of the study to serve as a possible tool to probe the presence, distribution and effects of trapping levels of varying depths with changes in X-ray energy or kVp.

The investigation was carried out over a period of 3 consecutive weeks. Tables 1 and 2 display a summary of the percent variations of detectors' response for the measurements in light and dark conditions. Firstly, measurements were taken in light conditions for 2 consecutive days. As illustrated in Fig. 2 for CVD1, it was observed that the response of each diamond crystal was lower on the following day (Day2) compared to the previous day (Day1). It has been pointed out that in a diamond crystal, white light plays a role in emptying low level traps by a shift occurring in the Fermi level (Burgemeister, 1983), and in a previous study (Ade et al., 2012) it was found that a synthetic diamond probe was sensitive to ambient light which had a detrimental effect on its performance as it caused random fluctuations of the noise level of the probe. With this in mind, it could be assumed that the lower response of the crystals on the second day compared to the first day could also be due to the presence and effects of ambient light which emptied the trapping levels present within the crystals.

The variation of response of each diamond crystal in light conditions for the two consecutive days is displayed in Table 1. It could be observed that the percent variations with kVp for CVD1 and CVD2 are higher (with CVD2 showing a much higher variation) compared to the HPHT diamond. Although the percent variation of CVD1 is much higher than that of the HPHT sample, the variations for both crystals are almost constant compared to

² In this study, light conditions refer to the presence of ambient light of intensity $\sim 1912\text{ lux}$ measured with a lux meter (Model 91150V, Oriel Instruments) and dark conditions refer to its absence.

Table 1

Variations of detectors' response in light and dark conditions for various kVp settings. The values quoted are obtained for the measurements recorded for 2 consecutive days and over a period of 2 weeks in light and dark conditions, respectively.

Detector type	kVp setting	Percentage (%) variation	
		Light conditions	Dark conditions
HPHT	26	8.4	~0.0
	27	6.3	2.2
	28	7.2	1.4
	29	5.4	1.6
	30	6.8	1.4
		Mean: 6.8 ± 1.1	Mean: 1.3 ± 0.8
CVD1	26	13.8	2.2
	27	13.0	3.0
	28	13.6	1.6
	29	15.0	1.7
	30	15.5	0.4
		Mean: 14.2 ± 1.0	Mean: 1.8 ± 0.9
CVD2	26	5.2	3.6
	27	11.9	4.2
	28	16.1	0.4
	29	17.8	1.5
	30	19.3	1.8
		Mean: 14.1 ± 5.7	Mean: 2.3 ± 1.6

Table 2

Variations of detectors' responses between light and dark conditions for various kVp settings. The variations are calculated from the average readings obtained for the measurements in light and dark conditions.

kVp setting	Percentage (%) variation between light and dark conditions		
	HPHT	CVD1	CVD2
26	0.6	34.6	63.1
27	3.3	27.7	63.2
28	3.4	23.7	62.7
29	2.9	21.9	62.7
30	3.7	18.1	63.3
	Mean: 2.8 ± 1.2	Mean: 25.2 ± 6.3	Mean: 63.0 ± 0.3

CVD2 which shows a greater spread. These two observations could be explained in terms of trap distribution and concentration as follows: (i) there could be a uniform distribution of traps in both the HPHT sample and CVD1 with the concentration of traps in CVD1 greater than that of the HPHT crystal; (ii) the greater spread and much higher percent variation with kVp observed for CVD2 could be attributed respectively to uneven trap distribution and a greater concentration of deeper traps. Evidence for trap concentration presented in this study is shown by Raman spectroscopy where the CVD crystals are more defective (broader Raman width values of 2.37 and $2.42 \pm 0.11 \text{ cm}^{-1}$ for CVD1 and CVD2, respectively) than the HPHT diamond which has a Raman width of $2.27 \pm 0.04 \text{ cm}^{-1}$. At 26 kVp tube setting, it is observed that CVD2 shows the lowest percent variation (5.2%) in light conditions compared to the other crystals and tube settings. This could be due to a faster rate of trapping and de-trapping mechanism.

To test and confirm the hypothesis attributed to the presence and effects of ambient light, the crystals were shielded from ambient light for a week before subsequent measurements were taken for the rest of the study. Over a period of 2 weeks, three sets of measurements (**Set1**, **Set2** and **Set3**) were recorded in dark conditions, with two sets (**Set1** and **Set2**) taken for 2 consecutive days for the first week and one set (**Set3**) recorded for the second week at each kVp setting. It was observed that the response of each diamond crystal for the three sets of measurements taken in

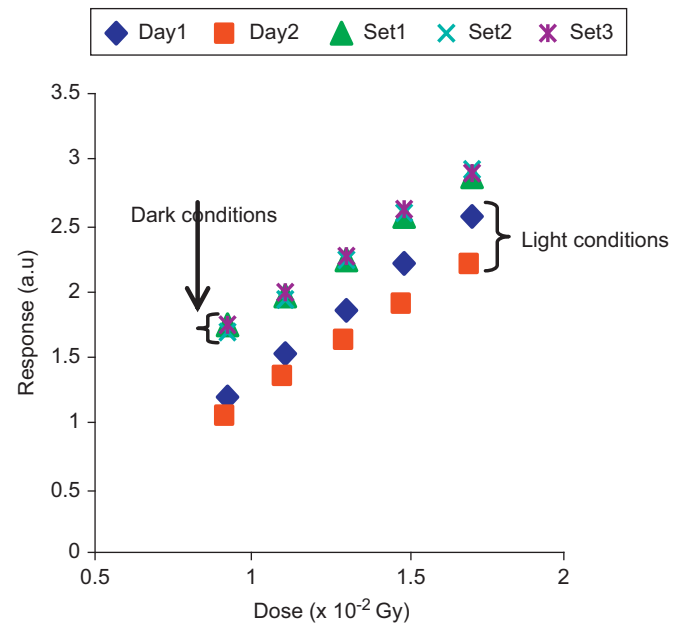


Fig. 2. Variation of response of CVD1 diamond in light and dark conditions with kVp and converted to absorbed dose values using Fig. 1. The figure shows the data taken in light conditions for two consecutive days (Day1 & Day2) and the three sets (Set1, Set2 & Set3) recorded in dark conditions for 2 weeks.

dark conditions was higher compared to the response recorded in light conditions (Fig. 2). This was attributed to the filling of the trapping levels emptied previously by ambient light during the first week. In addition, the response of the crystals taken in dark conditions was more stable compared to the response obtained in light conditions. When traps have been depopulated, the first effect of irradiation is to supply charge carriers to fill them and to stabilise the response. Thus the first set (**Set1**) of measurements taken in dark conditions could be interpreted as pre-irradiation.

Also displayed in Table 1 is the variation of each detector's response for the measurements in dark conditions. The analysis however considered only the 2nd set (**Set2**) of measurements recorded during the first week (since the first set acted as priming dose) together with the single set (**Set3**) taken during the second week. The results show that the percent variations are lower in dark conditions compared to light conditions confirming the hypothesis attributed to the presence and effects of ambient light. That is, that the lower response of the crystals on the second day compared to the first day for the measurements in light conditions was due to the depopulation of shallow traps by ambient light. At tube settings of 26 and 27 kVp, the percent variations of both CVD1 and CVD2 are much higher than that of the HPHT sample. This observation could be attributed to the phenomenon of pre-irradiation, i.e., the given priming dose was not sufficient to stabilise the response of the crystals. This therefore suggests that at these tube settings of 26 and 27 kVp, an extra pre-irradiation dose should be given else less accurate dose value would be recorded as earlier mentioned when the correct priming dose is not given. At higher values of X-ray energy ($> 27 \text{ kVp}$) which correspond to greater penetration depths where deeper traps could be present, the variations of detectors' response are relatively low and almost constant indicating that the given priming dose was enough to stabilise their responses. This also confirms that deep traps are more stable at room or near room temperature compared to shallow traps.

Table 2 displays the variation of each detector's response between the measurements in light and dark conditions. The variation reached values (mean values) up to 2.8, 25.2 and 63.0%

for the HPHT, CVD1 and CVD2 samples, respectively. The presented results illustrate that the performance (in terms of stability) of the single crystal HPHT diamond is better compared to its CVD counterparts. This could be attributed to two possible reasons: (1) polycrystalline materials have high defect densities due to their non-homogeneous structure (Bergonzo et al., 2007). In particular, it is well known that polycrystalline CVD diamond films have a high concentration of grain boundaries (Balducci et al., 2005) where electron traps are concentrated or in more defective regions (Manfredotti et al., 2006). The more defective nature of the CVD samples as confirmed by Raman spectroscopy compared to the HPHT sample would thus introduce more trapping levels within the crystals. The drawback of Raman spectroscopy is that it does not isolate defect types responsible for the broadening of the Raman peak; (2) it is known, for HPHT diamonds that there is an inverse link between nitrogen level and trap concentration, i.e., diamonds with high [Ns] tend to have much lower trap concentrations than those synthesized with lower nitrogen levels (Nam, 1989; Nam et al., 1991). Trapping and de-trapping mechanism should thus be less pronounced with the HPHT diamond due to its higher level of [Ns] (130 ppm) compared to a CVD crystal with much lower [Ns]. The close to zero percent variation in dark conditions of the HPHT diamond at 26 kVp could be attributed to the presence of fewer shallow traps.

The results of this study have thus established and highlighted that the major cause of the instability of response of diamond detectors requiring pre-irradiation could be attributed to the presence and effects of ambient light. In light conditions, the increase in percent variations of response for the CVD diamonds with X-ray energy depicted the presence and concentration of deeper traps. The near constancy in variation with kVp observed for both the HPHT and DG CVD (CVD1) diamonds suggested uniform distribution of trapping levels. In dark conditions, the variation of response was lower and almost constant compared to that in light conditions. The results do suggest that once the response of the diamond detectors have been stabilised in dark conditions, pre-irradiation prior to each measurement is not required as long as they are properly shielded from ambient light. Extra precaution could then be taken in the design of such diamond detectors, for instance by coating their probe housing with a thin opaque layer as pointed out in two previous studies (Ade et al., 2012; Nam and Ade, 2011). This would serve as an advantage over commercial natural diamond detectors which have been reported to require daily pre-irradiation (Laub et al., 1999; Björk et al., 2000). In particular, Laub et al. (1999) pointed out that the pre-irradiation has to be repeated if the detector is not used for more than about an hour. In addition, an extra dose is required if the detector bias has remained switched on while irradiation was interrupted even for some minutes.

3.3. Dosimetric performances of the diamond detectors in electron beams

As mentioned earlier, only CVD1 (hereafter referred to as CVD for simplicity) and the HPHT diamond were used for measurements in electron beams.

3.3.1. Dose rate dependence

The relationship between detector current I (corrected for leakage) or conductivity and absorbed dose rate $\dot{D}$ as suggested by Fowler (1966) is of the form:

$$I \propto \dot{D}^{\Delta} \quad (1)$$

where, Δ is a parameter accounting for the dose rate dependence. It is known that conductivity in equilibrium is proportional to

recombination time and that this time is inversely proportional to the number of holes, which is equal to the sum of the equilibrium density of both free and trapped electrons (Fowler, 1966). The change in conductivity or current with dose rate as depicted in Eq. (1) is therefore influenced by the change in the recombination time between electrons and holes. The number of trapped electrons relative to the number of free electrons dictates the number of vacant holes, hence the change in conductivity with dose rate (Fowler, 1966; Hoban et al., 1994). Depending on the purity, the capture cross sections and the distribution of traps within the detector material, Δ can take on values from less than one (sub linear) to one (linear) and greater than one (supra linear). In particular, uniform and quasi-uniform trap distributions over a wide range of depths in the forbidden gap lead to $\Delta \approx 1$ (Fowler, 1966). As linearity is assumed if $\Delta \approx 1$ (which implies the detector is independent of dose rate), it is an objective of this study to determine the Δ values of the HPHT and CVD diamond detectors and investigate whether deviations from unity or linearity would significantly affect their dosimetric performances.

The dose rate dependence measurements were performed for a 14 MeV electron therapy beam in a Perspex phantom at the depth of dose maximum $d_{\max}$. Since dose rate varies with distance according to the inverse square law (Khan, 2003), the dose rate was varied from 1.43 to 3 Gy/min by changing the SSD from 145 to 100 cm using a fixed applicator defined field of $10 \times 10 \text{ cm}^2$. The measurements obtained using the HPHT and CVD diamond crystals, and a 0.6 cc thimble ion chamber were fitted by Eq. (1) using a log-to-log plot. The current plotted was the collected charge for a dose of 0.5 Gy divided by the irradiation time. Δ values of 0.950 and 1.035 for the HPHT and CVD diamond detectors, respectively, compared to a value of 1.005 for the thimble ion chamber were obtained. In comparison, Δ values between 0.940 and 1.16 have been reported by other researchers (Fidanzio et al., 2004; Laub et al., 1997, 1999; Cirrone et al., 2006; Björk et al., 2000; Hoban et al., 1994; Lansley et al., 2009; Betzel et al., 2010) for both natural and CVD diamonds. The results of this study show deviations from linearity by 5% and 3.5% for the HPHT and CVD diamond detectors, respectively and 0.5% for the ion chamber. The difference between the Δ values for the CVD and HPHT crystals could be attributed to a difference in their defective natures and thus trap distribution as evidenced by the results of Raman spectroscopy and ESR. A tantalizing question as to whether the 3.5 and 5% deviations from linearity shown by the diamond detectors have any significant effects on relative dose measurements is examined in the next sections.

3.3.2. Depth-dose distributions

Since dose rate decreases with distance (according to the inverse square law), the dose rate dependence of a diamond detector should manifest itself in a percent depth-dose (PDD) curve which would show a shallower fall-off, appearing to give an over response as depth increases (Hoban et al., 1994). Some studies (Laub et al., 1997, 1999; Björk et al., 2000; Fidanzio et al., 2004) have pointed out that the shallower fall-off (i.e., an over-estimation) in a PDD curve could be removed by the application of the following Laub et al. (1997) expression:

$$D_{\text{rel}}(d) \rightarrow D_{\text{rel}}(d)^{1/\Delta} \quad (2)$$

where $D_{\text{rel}}(d)$ is the relative dose measured with a diamond detector at the depth of measurement, d , and Δ is the correction factor based on dose rate dependence referred to in Eq. (1). Relative dose distributions are usually renormalized to dose maximum after performing the operation in Eq. (2) (Björk et al., 2000). With this, the authors reported that the relative depth-dose values measured

with their diamond detectors agreed favourably with those obtained with ion chambers.

A recent study from this group (Ade et al., 2012) reported the performance of a single synthetic diamond probe in both low-energy X-rays and high-energy electron beams and illustrated that percent depth ionization data measured with the diamond probe in the 'flat-on' orientation exposed to 7 and 14 MeV electron therapy beams showed close agreement with energy-corrected depth-dose data generated from measurements with a Markus chamber. Dose rate dependence was however not investigated, neither was it observed. Due to the shape of the curves (similarly to other studies (Heydarian et al., 1993; van der Merwe and Keddy, 1999; Almaviva et al., 2010)), it was claimed that the depth ionization data needed no correction based on dose rate dependence. Although van der Merwe and Keddy (1999) evaluated the dose rate dependence of their synthetic diamond probe and Almaviva et al. (2010) noted that their diamond detector was independent of dose rate, a fitting based on Fowler's model was not investigated. Slight deviations between depth-dose curves measured with their (van der Merwe and Keddy, 1999) diamond probe and a Markus chamber were attributed to a small air cavity that surrounded the diamond crystal and its contacts which could introduce some energy dependence.

Another confusing or challenging aspect is that while Fidanzio et al. (2004) reported using the dose rate dependence correction for relative dose measurements for both photon and electron beams,

Laub et al. (1999) reported using the correction only for depth-dose curves measured with photon beams. The difference between depth-dose curves for electron beams measured with their diamond detector and a Markus chamber was attributed to the energy dependence of the Markus chamber and the difference in the spatial resolution of both detectors, with the diamond detector having a distinctly better spatial resolution than the chamber. As pointed out by Laub et al. (1999), application of energy correction and spatial averaging of the Markus chamber gave excellent agreement between depth-dose curves with both detectors. With all the claims pointed out in the various studies, it was therefore an objective of this study to investigate the influence of dose rate dependence correction using two different synthetic diamond detectors.

Fig. 3(a) and (b) shows the depth ionization data taken with the HPHT and CVD (CVD1) diamond detectors respectively, compared with depth dose data generated from measurements with a Markus chamber (with its response corrected for stopping power ratios (energy correction) and other effects), for exposure to a 14 MeV electron beam. Shown in the figures are the uncorrected ('uncorr') and corrected ('corr') data based on dose rate dependence for the diamond detectors. To quantify the discrepancies in response, the relative differences between the percent depth-doses measured with the diamond detectors and the Markus chamber were analysed, as plotted in Fig. 4 for the CVD diamond detector for the 14 MeV electron beam. The figure illustrates that with (Fig. 4a) or without

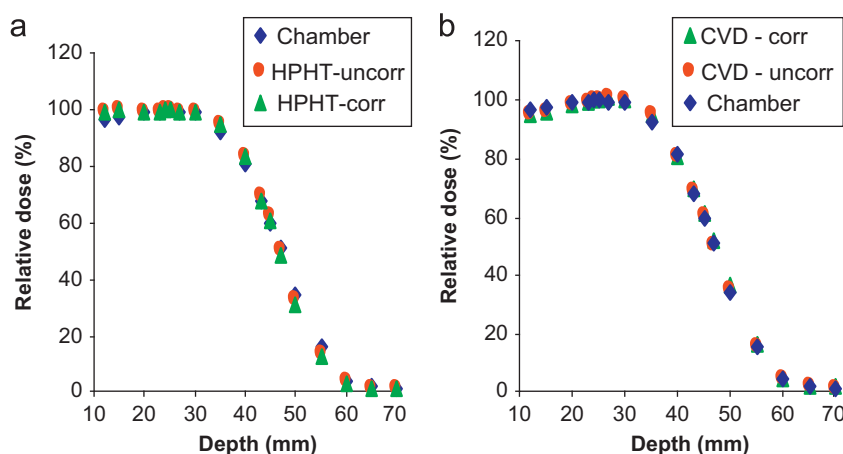


Fig. 3. Normalised depth-dose ionization in Perspex obtained with the (a) HPHT and (b) CVD diamond detectors compared with energy-corrected depth-dose curves as measured with a Markus chamber, for a 14 MeV electron beam.

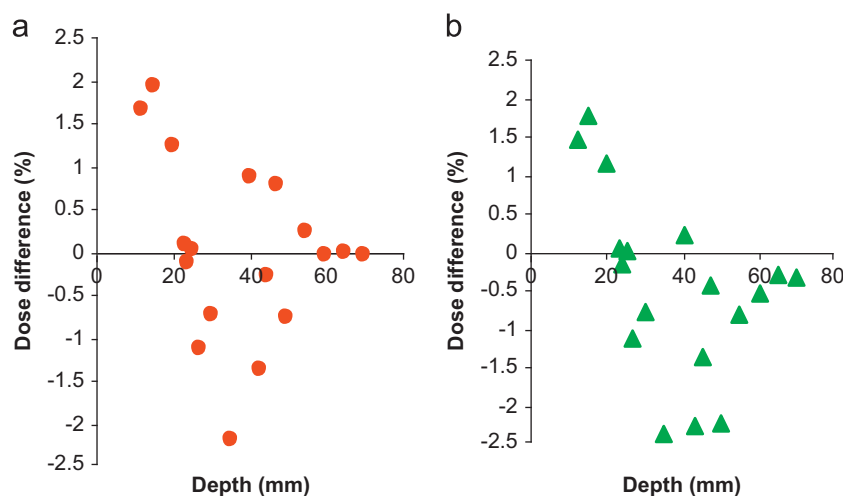


Fig. 4. Relative difference between the depth-doses measured with the CVD diamond detector (CVD1) and a Markus chamber, for a 14 MeV electron beam. The figures show the data before (a) and after (b) correction for dose rate dependence.

(Fig. 4b) dose rate dependence correction, the relative dose difference is within 2.5%. Similar results, i.e., the 2.5% dose difference, were obtained with the HPHT and CVD diamond detector for the two electron energies of 7 and 14 MeV, except at a depth of 23 mm at 7 MeV where a 4.2% difference in response (uncorrected data) was observed for the HPHT sample. In addition, while the dose rate dependence correction had a marginal effect on the performance of the CVD sample, it instead degraded that of its HPHT counterpart at a few depths. For instance, at 7 MeV the response of the HPHT diamond is degraded from 4.2 to about 6% after applying the dose rate dependence correction, and from 1.3% to about 3.3% at depths between 25 & 30, and between 45 & 50 mm for both 7 and 14 MeV electron beams, respectively. The slightly better performance of the CVD specimen compared to the HPHT sample could be attributed to one or a combination of several possible effects such as scattered radiation and positional uncertainties (positioning the effective measuring point (which is assumed to be the physical centre of the detector) of the HPHT sample relative to the phantom could be prone to error as this crystal is irregular in shape).

The results presented illustrate that the relative dose distributions measured with the diamond detectors do not require dose rate dependence corrections as the correction is only marginal and could have no dosimetric significance. It should be noted that the shape of a depth-dose curve could be affected by energy dependence, dose rate dependence or background signal (noise). As it is well known that high atomic number metals used to form contacts (Laub et al., 1999; Górká et al., 2008) and air cavities could introduce some energy dependence, the results do suggest that with a properly designed diamond probe with negligible energy dependence and minimal or stable background signal (Ade et al., 2012), the relative dose distributions measured with any such diamond detector would not require dose rate dependence corrections if Δ deviations from linearity are within 5%. It should be noted that diamond is known to show negligible energy dependence over typical therapy electron energies up to 20 MeV (van der Merwe and Keddy, 1999; Ade et al., 2012). Thus relative ionisation measurements taken with a properly designed diamond detector could be interpreted as dose values without energy corrections.

Despite the drawbacks of silicon diodes such as energy dependence ($\sim 5\%$ between 1 and 20 MeV) compared to diamond detectors, it has been pointed out that diodes can be used to measure relative dose distributions directly (Khan, 2003) provided the distributions have been checked against ion chamber or iron-sulphate

dosimeter measurements (ICRU, 1984). The results of this study seem to imply that when relative dose distributions measured with a diamond detector agree favourably with those measured with ion chambers, then negligible dose rate dependence could be assumed provided other parameters such as energy dependence and background signal have been eliminated.

3.3.3. Output factors (OFs)

In addition to depth-dose distributions, the influence of dose rate dependence correction on OFs was also investigated. The correction, as reported by Fidanzio et al. (2004) made use of an expression similar to the expression in Eq. (2) as follows:

$$OF = \left[\frac{M(d_{max}, f)}{M(d_{max}, f_0)} \right]^{1/4} \quad (3)$$

where $M(d_{max}, f)$ and $M(d_{max}, f_0)$ are the ionization signals obtained for a square field of size f and f_0 is a reference square field of size $10 \times 10 \text{ cm}^2$, respectively.

Fig. 5 shows the relative dose difference between the uncorrected and corrected (for dose rate dependence) OF values as a function of field size measured with the diamond detectors and a 0.6 cc thimble ion chamber. Changing the field size from 8×8 to $25 \times 25 \text{ cm}^2$, the OF values were determined at d_{max} for a 12 MeV electron beam in a Perspex phantom at 100 cm SSD using a dose rate of 3 Gy/min and a dose value of 0.5 Gy. The field size was varied by opening the photon jaw size. Similar to depth-dose curves, Fig. 5a shows that the dose rate dependence correction only has a 1% negative influence on the OF value obtained with the HPHT diamond detector for the $8 \times 8 \text{ cm}^2$ field as the correction degrades the performance from 2 to 3% but it has no effect on the performance of the CVD sample. Fig. 5 further illustrates that the performance of the CVD diamond detector is slightly better than that of its HPHT counterpart for the fields investigated as that the OF values measured with the CVD diamond agree favourably with the ion chamber within 1% (Fig. 5b) while a 2% agreement is observed with the HPHT sample (Fig. 5a).

3.3.4. Angular dependence

In an electron field, the distribution in energy and direction of electrons changes rapidly with the depth of penetration necessitating the use of detectors which are independent of energy and beam direction (Brahme and Svensson, 1976). This means that the angular response is important in depth-dose measurements since, with

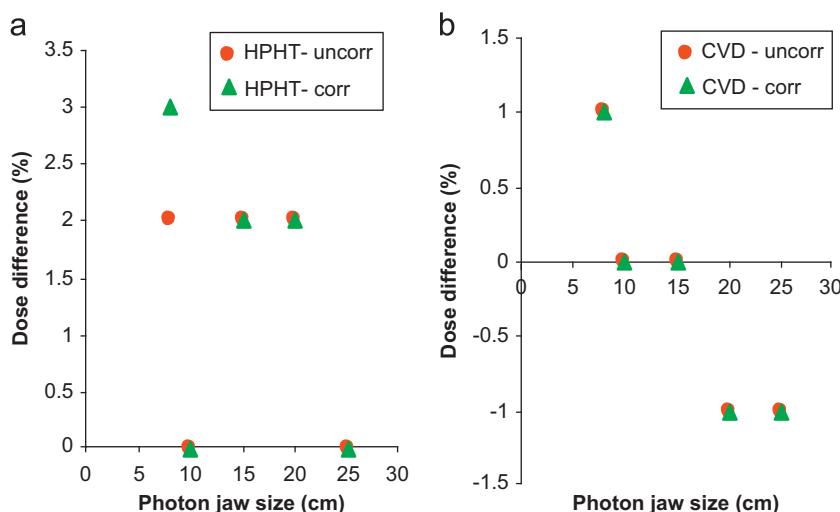


Fig. 5. Relative difference between the output factors measured with the diamond detectors ((a) HPHT; (b) CVD (CVD1)) and 0.6 cc thimble ion chamber before and after correction for dose rate dependence, for a 12 MeV electron beam.

a beam from an electron applicator, the mean square scattering angle increases with depth and reaches an equilibrium value at larger depths (Björk et al., 2000). The drawback of plane-parallel chambers in electron dosimetry is their size and directional response. It is also known that a 10 to 15% angular dependence is not uncommon for some detectors such as semiconductor diodes (Brahme, 1985).

Measurements of the angular dependence of the diamond detectors and a 0.6 cc cylindrical chamber (acting as a reference), were performed at $d_{\max}$ for a 14 MeV electron beam in a similar procedure as reported in a previous study (Ade et al., 2012). The response of each detector was measured as a function of gantry rotation at intervals of 15° from 0° to 105°. Figs. 6 and 7 show the relative response, normalised to the response at normal incidence (i.e., at 0°) for all three detectors. Owing to its construction, the cylindrical chamber has no structural angular dependence and its response remains flat to within 0.7%. The diamond detectors however, show some angular dependence. The change in angular response measured in the 'flat-on' orientation (Fig. 6(a)) is within 2% between 0° and 60° and within 3.7% between 60° and 105° for the diamond detectors.

It has been pointed out that the angular dependence of most detectors used for measurements in electron and photon beams may be due to the mechanical design of the detector or to the intrinsic angular sensitivity of the detection process (Brahme, 1985), and that a detector with a smaller surface area should improve the angular response (Rikner, 1985) as shown by van der Merwe and Keddy (1999) and Lansley et al. (2009). The directional response of solid state detectors such as silicon and diamond detectors has been attributed to a changing interface effects (Rikner, 1985; Heydarian et al., 1993) where a varying degree of secondary electron spectrum (or delta-particle) equilibrium is reached within the sensing volume of a detector (ICRU, 1972). Górká (2008) reported that for a CVD diamond detector, the magnitude of the interface effects (i.e., the distortion of the mean absorbed dose in the sensing volume of the detector) due to metallic electrodes (contacts) strongly depends on the thickness of the metallised diamond (i.e., all three layers—metal/diamond/metal), the atomic number of the metal contacts and the energy of radiation; with the effect decreasing with increasing diamond thickness and radiation energy, but increases with increase in electrode thickness and their atomic number. For instance, the interface phenomenon would drop from 45% for a 50 μm thick diamond to about 6% for a 10 times thicker (500 μm) crystal, and a front silver electrode would reduce the intensity of 1.25 MeV photon beam by < 1% for thicknesses below 180 μm and by 2.7% and 3.8% for 500 and 700 μm , respectively (Górká, 2008).

The reason for the directional response of the diamond detectors for the present study could be attributed to two possible effects: (1) the interface phenomenon which dominates between 0° and 60°;

and (2) a geometry effect (a combined effect of both the surface area and attenuation depth between the 'edge-on' and 'flat-on' orientations giving rise to a 'differential effect' of energy deposition and attenuation when the beam is rotated from 0° to 90°) which is dominant beyond 60°. The response remains flat within 2% for both diamonds (Fig. 6(a)) between 0° and 60° due to two parameters (the thicknesses of the crystals (≥ 0.5 mm) and an angstrom thickness of the contact layers (Ti (200 Å)/Pt (200 Å)/Au (2000 Å))), both of which minimise the interface effect. In this interval between 0° and 60°, the geometry effect could be assumed negligible as the surface area and attenuation depth for each diamond do not vary as the beam is impinging on the 'flat-on' diamond surface. The minimal change in surface area implies that the electron fluence does not vary greatly. Beyond 60° however, (and especially at 90°), the geometry effect dominates with the diamond detectors showing a stronger dependence ($\approx 3.6\%$ for the HPHT sample and 3.7% for the CVD crystal).

Beyond 60° the change in both surface area and attenuation depth becomes significant and at 90° it is more pronounced as the beam is incident on the diamond edge (i.e., the 'edge-on' orientation) which has a greater attenuation depth but with reduced surface area. The 'dip' in response at 90° of the CVD diamond could be attributed to the greater attenuation and less energy deposition on the diamond edge compared to the flat surface. To support and confirm the hypothesis that the stronger dependence or 'dip' at 90° is due to the geometry effect, the CVD detector was also rotated when the gantry was rotated in order to

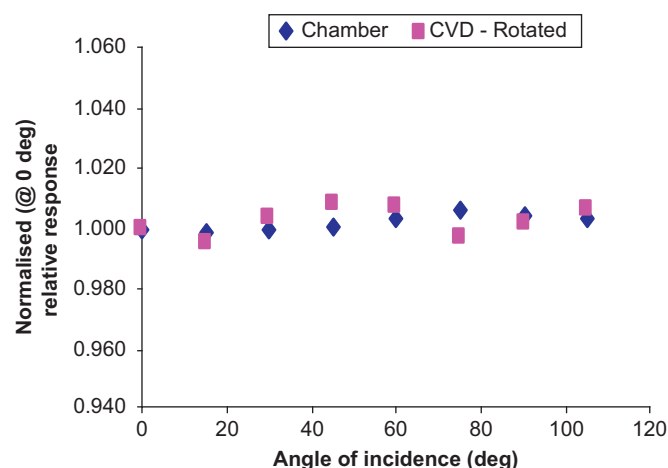


Fig. 7. A comparison of the directional response of the CVD diamond detector and the 0.6 cc cylindrical chamber when diamond probe is rotated as the gantry is rotated.

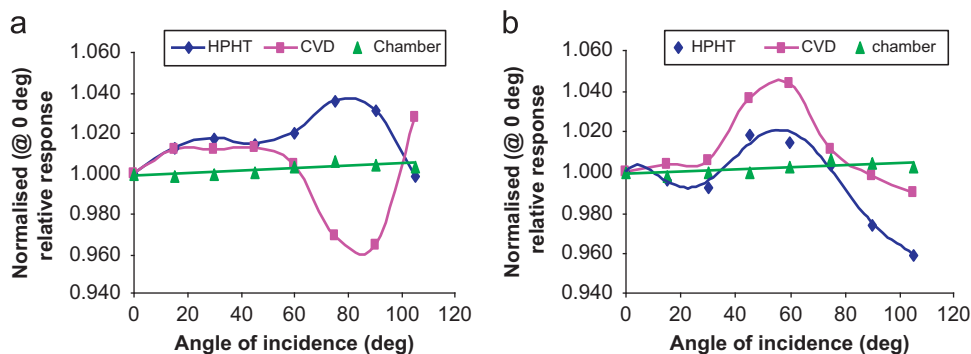


Fig. 6. A comparison of the directional responses of the diamond detectors (measured in the (a) 'Flat-on' orientation; (b) 'Edge-on' orientation) and a 0.6 cc cylindrical chamber, for a 14 MeV electron beam. It should be pointed out that the results for the HPHT crystal shown in Fig. 6(a) have already been reported by Ade et al. (2012).

keep all the parameters (surface area, fluence and attenuation depth) constant w.r.t those at 0°. As Fig. 7 shows, its response with this configuration is similar to that of the cylindrical chamber. This illustrates that the diamond detector would behave exactly the same as the thimble chamber provided its orientation is the same as that of the gantry. The design of the diamond probe allows a jig to be incorporated (an optimised design) for such orientation for clinical applications.

Compared to the CVD sample which shows a ‘dip’ at 90°, the HPHT crystal shows the opposite effect—a peak (Fig. 6(a)). This could be attributed to the irregular geometry (shape, size and sloping edges) and positional inaccuracies associated with the HPHT crystal ($7.94 \times 6.38 \text{ mm}^2$) compared to the flat CVD sample ($10 \times 10 \text{ mm}^2$). In particular, as positional accuracy is an important feature to be considered in electron dosimetry and the effective point of measurement of each crystal is assumed to be the physical centre of the diamond probe (Ade et al., 2012), the HPHT diamond would be susceptible to positional uncertainties due to its irregular geometry.

To further support and confirm the hypotheses attributed to both the interface and geometry effects, the angular response of the crystals were also measured using the ‘edge-on’ orientations (Fig. 6(b)). In this orientation, the interface effect is constant as there are no metal contacts on the diamond edge. The radiation in this case impinges on the bare diamond. On the other hand, the geometry effect is not constant as the geometry changes. This accounts for the sharp increase in response between 45° and 60° for both crystals. Due to its rectangular shape, the geometry (both surface area and attenuation) of the HPHT crystal changes greatly from 0° through 90° compared to the square CVD sample, giving rise to the lower response of the HPHT diamond beyond 75° compared to the CVD crystal.

The smaller angular dependence of the diamond detectors compares favourably with the results obtained by other researchers (Heydarian et al., 1993; van der Merwe and Keddy, 1999; Björk et al., 2000; Lansley et al., 2009) which in addition showed the angular dependence of diamond detectors to be better than that of silicon diodes. The results of this study have illustrated that the angular response of a diamond detector strongly depends on its mechanical design or geometry rather than the intrinsic angular sensitivity of the detection process.

4. Conclusions

In this study through systematic investigations, the major cause of the unstable response of diamond detectors requiring the recommended pre-irradiation step was isolated and attributed to the presence and effects of ambient light suggesting therefore that as long as the diamond detectors are properly shielded from ambient light and their responses stabilised, pre-irradiation prior to each measurement is not required. In addition, dose rate dependence correction factors (Δ values) determined for the diamond detectors tested had a negligible effect on their performances as there was no significant differences between the uncorrected and corrected (using the Δ values) relative dose distributions measured with the detectors. The results thus suggest that with a properly designed diamond probe with negligible energy dependence and minimal or stable background signal (Ade et al., 2012), the relative dose measured with any such diamond detector might not require dose rate dependence correction (if the deviation from linearity of its Δ value is within 5%) as the correction would only be marginal and could have no dosimetric significance.

The results of the study further illustrate that the design of the diamond probe could be optimised (by incorporating a jig) for its response to be independent of angle. In this case the relative dose

measured with the probe would not require directional response correction in angulated electron beams. Without the added need for priming prior to each measurement, a probe of such optimized design would serve as an advantage over other commercial diamond detectors.

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