Radiation Physics and Chemistry 113 (2015) 6–13

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

The influence of detector size relative to field size in small-field photon-beam dosimetry using synthetic diamond crystals as sensors

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HIGHLIGHTS

- Influence of detector size relative to field size in small fields was investigated.
- OFs obtained with various diamonds and Diode E for 6 MV photons were compared.
- A dose deviation within 3% was obtained for detector size < 3/4 of field size.
- Selected diamond of a given size and orientation have OFs within ± 2%.
- Compared to Diode E, the diamond probe displayed a higher sensitivity value.

ARTICLE INFO

Article history:
Received 17 March 2014
Received in revised form
8 April 2015
Accepted 11 April 2015
Available online 15 April 2015

Keywords:
Synthetic diamonds
Small fields
Output factor
Detector size
Volume effect

ABSTRACT

The choice of a detector for small-field dosimetry remains a challenge due to the size/volume effect of detectors in small fields. Aimed at selecting a suitable crystal type and detector size for small-field dosimetry, this study investigates the relationship between detector and field size by analysing output factors (OFs) measured with a Diode E (reference detector), a Farmer chamber and synthetic diamond detectors of various types and sizes in the dosimetry of a 6 MV photon beam with small fields between 0.3×0.3 cm^2 and 10×10 cm^2. The examined diamond sensors included two HPHT samples (HP1 and HP2) and six polycrystalline CVD specimens of optical grade (OG) and detector grade (DG) qualities with sizes between 0.3 and 1.0 cm. Each diamond was encapsulated in a tissue-equivalent probe housing which can hold crystals of various dimensions up to $1.0 \times 1.0 \times 0.1$ cm^3 and has different exposure geometries (‘edge-on’ and ‘flat-on’) for impinging radiation. The HPHT samples were found to show an overall better performance compared to the CVD crystals with the ‘edge-on’ orientation being a preferred geometry for OF measurement especially for very small fields. For instance, down to a 0.4×0.4 cm^2 field a maximum deviation of 1.9% was observed between the OFs measured with Diode E and HP2 in the ‘edge-on’ orientation compared to a 4.6% deviation in the ‘flat-on’ geometry. It was observed that for fields below 4×4 cm^2, the dose deviation between the OFs measured with the detectors and Diode E increase with increasing detector size. It was estimated from an established relationship between the dose deviation and the ratio of detector size to field size for the detectors that the dose deviation probably due to the volume averaging effect would be > 3% when the detector size is > 3/4 of the field size. A sensitivity value of 223 nC Gy^{-1} mm^{-3} was determined in a 0.5×0.5 cm^2 field with HP2 compared to a value of 159.2 nC Gy^{-1} mm^{-3} obtained with the diode. The results of this study indicate that with careful selection of a suitable crystal type of a given size and orientation the relative dose measured with the diamond probe in small fields would agree favourably within ± 2% with that measured with a small-field detector but with a higher sensitivity value.

1. Introduction

Advanced techniques in external beam radiotherapy such as intensity modulated radiation therapy (IMRT), stereotactic radiosurgery (SRS), image guided radiation therapy (IGRT) and tomotherapy make use of small radiation fields (Zhu, 2010) in order to spare normal healthy tissues while high doses can be delivered to tumour volumes (Barnett et al., 2005; Das, 2009; Marsolat1 et al., 2013). Small fields are often used to treat conditions such as

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http://dx.doi.org/10.1016/j.radphyschem.2015.04.005
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benign and malignant, intra and extra-cranial tumours (Marsolat1 et al., 2013). Small-field dosimetry is well known to be challenging due to a number of factors such as the tissue-equivalence of detectors, the loss or lack of lateral electronic equilibrium and the volume averaging effect of detectors in small fields (Haryanto et al., 2002; Laub and Wong, 2003; Das, 2009; Lee et al., 2012; IPEM 103, 2010). The aspects of tissue-equivalence and volume effect have been noted to be both related to the absence of electronic equilibrium (Haryanto et al., 2002). It is known that the equilibrium of secondary electrons breaks down as soon as the distance to the closest field edge is smaller than the travel distance of laterally scattered secondary electrons which, as an estimate, is equivalent to the depth of dose maximum of a percent depth-dose curve in a $10 \times 10\ \text{cm}^2$ field (Wuerfel, 2013). As pointed out by Wuerfel (2013), any detector will average the dose across its sensing volume. If the dose varies across the volume of the detector, then the effect of averaging can give a different signal compared to the signal that an infinitesimally small detector would measure if placed in the centre of the large detector. This phenomenon called volume averaging effect (or just volume effect) leads to two distinct aspects (Wuerfel, 2013): an underestimation of the dose in the centre of a small field when measuring output factors (OFs) and blurring of the penumbra in profile measurements. Thus OF and penumbra measurements are two important aspects of small-field dosimetry. Although Wuerfel (2013) pointed out that the safest way to exclude the volume effect is to choose a detector which is small enough, the experimental relationship between detector and field size is yet to be established.

Based on the importance of OF measurements in small-field dosimetry (Laub and Wong, 2003), a number of studies have investigated and compared the performances of different commercially available detectors such as ion chambers, diodes and PTW natural diamond in small fields with the aim of selecting an appropriate detector (Haryanto et al., 2002; Laub and Wong, 2003; Björk et al., 2004; Barnett et al., 2005). Large deviations between OFs measured with the different detectors were reported and one reason for the observed variation has been attributed to the volume effect of detectors in addition to the tissue-equivalence of the detector material (Haryanto et al., 2002; Laub and Wong, 2003). Although the choice of a detector for accurate dose measurements in small-fields remains a challenge, the results of most of the studies however suggested that a diamond detector is the most suitable small-field dosimeter due to its excellent dosimetric properties such as its small physical size (high spatial resolution) and near-tissue equivalence (Haryanto et al., 2002; Laub and Wong, 2003; Björk et al., 2004).

The use of natural diamond detectors for dosimetry has been tested by a number of authors (Planskoy, 1980; Hoban et al., 1994; Vatnisky and Järvinen, 1993; Laub et al., 1997, 1999; Hugtenburg et al., 2001; Björk et al., 2000, 2002, 2004; Barnett et al., 2005; Sabino et al., 2012). However, the need for daily pre-irradiation due to the presence of uncontrolled amount of impurities; dose rate dependence; high cost and long delivery times due to the scarcity of suitable stones; lengthy selection processes of diamond stones for suitable detection properties and poor reproducibility between devices are the main limitations of natural diamond detectors (Yacoot et al., 1990; Guerrero et al., 2004, 2005, 2006; Marsolat1 et al., 2013). In addition to its high cost compared to other solid-state detectors and being a natural resource, natural diamond detectors are also not readily available (Das, 2009) and hence more difficult to provide.

Due to reproducible and optimized growth conditions, synthetic diamond has been considered and intensively investigated as an alternative to natural diamond for clinical dosimetry (van der Merwe and Keddy, 1999; Benabdesselam et al., 1999; Buttar et al., 2000; Bruzzi et al., 2000; Whitehead et al., 2001; Ramkumar et al., 2001; Fidanzio et al., 2002; Bergonzo et al., 2007; Marczewska et al., 2007; Górka et al., 2008; Tranchant et al., 2008; Gervino et al., 2010; De Angelis et al., 2010; Ade et al., 2012, 2013, 2014) as the impurity levels in synthetic diamond can be controlled to tailor its radiation detection properties (Marsolat1 et al., 2013). However, only a few researchers such as Ciancaglioni et al. (2012) and Marsolat1 et al. (2013) have reported its use under small field conditions. Although these two research groups reported on the dosimetric characterization of a synthetic single crystal diamond detector in small photon beams, the influence of crystal size relative to field size was not investigated. In addition, only Marsolat1 et al. (2013) to date has reported the performance of a diamond detector in small beam sizes down to $0.6 \times 0.6\ \text{cm}^2$.

This study investigates the relationship between detector size and field size by analysing OFs measured with synthetic diamond crystals of various types and sizes in the dosimetry of a 6 MV photon beam with small and very small fields down to $0.3 \times 0.3\ \text{cm}^2$ with the aim of selecting a suitable crystal type and detector size for small-field dosimetry.

2. Materials and methods

2.1. Radiation detectors

Eight commercially available synthetic diamond crystals of various types and sizes ranging between 0.3 and 1.0 cm and thicknesses of either 0.05 or 0.1 cm were examined. These included two high-pressure, high-temperature (HPHT) samples (HP1 and HP2) and six polycrystalline CVD (chemical vapour deposition) diamond crystals of detector grade (DG) and optical grade (OG) qualities. The labels and dimensions (in mm) of the crystals are presented in Table 1. The size of a detector in this study is defined as the lateral dimension (length, width or diameter) of the sensor perpendicular to the beam direction. Due to the rectangular shape of HP1, unlike the other crystals which are square-shaped, the two different sides with sizes of 0.64 and 0.80 cm are represented as HP1a and HP1b, respectively. The opposite surfaces of each of the diamonds were metallized as reported in a previous study (Ade et al., 2012) to provide the necessary Ohmic contacts for voltage biasing and acquisition of the ionization signal. A $0.03\ \text{mm}^3$ Dosimetry Diode E (Type T60017) of size 0.12 cm (diameter of sensor) acting as a reference detector and a $0.6\ \text{cm}^3$ Farmer chamber (Type 30013) of size 2.3 cm (length of sensor (air cavity)) were also used for comparative measurements.

Table 1
Synthetic diamond crystals and their parameters.

Diamond crystals	Dimensions of crystals (mm^3)	Lateral dimensions of crystals Normal to beam direction (mm)	Δ Values (±0.02)
HP1	$6.4 \times 8.0 \times 1.0$	HP1a: 6.4 HP1b: 8.0	0.96
HP2	$3.0 \times 3.0 \times 1.0$	3.0	1.02
DGA1	$5.0 \times 5.0 \times 1.0$	5.0	0.91
DGA2	$5.0 \times 5.0 \times 1.0$	5.0	0.87
DG A	$10.0 \times 10.0 \times 0.5$	10.0	0.91
DGB1	$10.0 \times 10.0 \times 0.5$	10.0	0.96
OGA	$10.0 \times 10.0 \times 1.0$	10.0	0.91
OGD	$10.0 \times 10.0 \times 1.0$	10.0	0.94