Physica Medica 44 (2017) 66–71

Contents lists available at ScienceDirect

Physica Medica

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

Original paper

# Determination of small field synthetic single-crystal diamond detector correction factors for CyberKnife, Leksell Gamma Knife Perfexion and linear accelerator

T. Veselsky[a,b,c,*], J. Novotny Jr.[a,b,c], V. Pastykova[a,b], I. Koniarova[a,c,d]

[a] Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Department of Dosimetry and Application of Ionizing Radiation, Prague, Brehova 78/7, 110 00, Czech Republic
[b] Na Homolce Hospital, Medical Physics Department, Prague, Roentgenova 2/37, 150 30, Czech Republic
[c] Motol University Hospital, Oncology Clinic, Prague, V Uvalu 84, 150 00, Czech Republic
[d] National Radiation Protection Institute, Prague, Bartoskova 28, 140 00, Czech Republic

ARTICLE INFO

*Keywords:*
Small field dosimetry
Synthetic diamond detector
Output factor
Correction factor

ABSTRACT

*Purpose:* The aim of this study was to determine small field correction factors for a synthetic single-crystal diamond detector (PTW microDiamond) for routine use in clinical dosimetric measurements.

*Materials and methods:* Correction factors following small field Alfonso formalism were calculated by comparison of PTW microDiamond measured ratio $M_{Qclin}^{fclin}/M_{Qmsr}^{fmsr}$ with Monte Carlo (MC) based field output factors $\Omega_{Qclin,Qmsr}^{fclin,fmsr}$ determined using Dosimetry Diode E or with MC simulation itself. Diode measurements were used for the CyberKnife and Varian Clinac 2100C/D linear accelerator. PTW microDiamond correction factors for Leksell Gamma Knife (LGK) were derived using MC simulated reference values from the manufacturer.

*Results:* PTW microDiamond correction factors for CyberKnife field sizes 25–5 mm were mostly smaller than 1% (except for 2.9% for 5 mm Iris field and 1.4% for 7.5 mm fixed cone field). The correction of 0.1% and 2.0% for 8 mm and 4 mm collimators, respectively, needed to be applied to PTW microDiamond measurements for LGK Perfexion. Finally, PTW microDiamond $M_{Qclin}^{fclin}/M_{Qmsr}^{fmsr}$ for the linear accelerator varied from MC corrected Dosimetry Diode data by less than 0.5% (except for $1 \times 1\ cm^2$ field size with 1.3% deviation).

*Conclusions:* Regarding low resulting correction factor values, the PTW microDiamond detector may be considered an almost ideal tool for relative small field dosimetry in a large variety of stereotactic and radiosurgery treatment devices.

## 1. Introduction

Modern radiotherapy techniques often involve very small radiation fields or highly modulated radiation fields that are composed of very small field segments. Small radiation fields are used on accelerators or radionuclide machines for stereotactic radiotherapy and radiosurgery (e.g. Leksell Gamma Knife (LGK), CyberKnife, TomoTherapy, stereotactic linear accelerators or linear accelerators equipped with stereotactic cones or microMLC collimators), and are defined as fields smaller than $3 \times 3\ cm^2$ [1].

Small fields are challenging with regard to accurate dosimetry and verification of basic field parameters. Due to the collimation system, there is partial occlusion of the direct beam source. This effect becomes important in radiation fields with sizes on the order of the size of the direct beam source, which is typically not greater than 5 mm for beams produced with modern linear accelerators. Another dosimetric problem is lateral charged particle disequilibrium, which occurs in high energy photon beams and narrow radiation fields when the beam radius becomes small in comparison to the maximum range of secondary electrons. The lateral range of these electrons is energy dependent and can be calculated according to the quality index of the primary photon beam. Issues related to detector volume and material are also important when considering small field dosimetry. Due to the relatively large volume of even small detectors compared to the measured field size, significant perturbation may occur [2].

Considering the challenges stated above, detectors for small radiation field dosimetry should be chosen carefully. There are a variety of detectors with different sensitive volume sizes available, and the use of an inappropriate detector can lead to incorrect beam calibration and subsequent adverse events. The size of the sensitive detector volume is

* Corresponding author at: Motol University Hospital, Oncology Clinic, Prague, V Uvalu 84, 150 00, Czech Republic.
*E-mail address:* veselskyt@seznam.cz (T. Veselsky).

https://doi.org/10.1016/j.ejmp.2017.11.010
Received 22 July 2017; Received in revised form 9 October 2017; Accepted 9 November 2017

crucial for reliable results, especially in small field dosimetry.

In 2008 Alfonso et al. [3] presented new small field dosimetry formalism. The machine-specific reference field ($f_{msr}$) is defined as the largest possible radiation field for treatment units that cannot establish a $10 \times 10\,cm^2$ field. The field output factor $\Omega^{fclin,fmsr}_{Qclin,Qmsr}$, defined as:

$$\Omega^{fclin,fmsr}_{Qclin,Qmsr} = \frac{M^{fclin}_{Qclin}}{M^{fmsr}_{Qmsr}} \times k^{fclin,fmsr}_{Qclin,Qmsr}, \quad (1)$$

presents small field alternative of classic output factor (defined as a simple ratio of detector readings for large fields). $M^{fclin}_{Qclin}$ and $M^{fmsr}_{Qmsr}$ are detector readings in the clinical field $f_{clin}$ and in the machine-specific reference field $f_{msr}$, respectively. $k^{fclin,fmsr}_{Qclin,Qmsr}$ is a correction factor accounting for the difference between detector response in the fields $f_{clin}$ and $f_{msr}$. Monte Carlo (MC) simulations may be used to evaluate this correction factor.

Few years ago, a new synthetic single-crystal diamond detector has been introduced by PTW Freiburg. The PTW 60019 microDiamond detector (PTW, Freiburg, Germany) has a very small sensitive volume and with its tissue equivalence is considered the ideal tool for small field dosimetry. The detector is the successor to the earlier PTW 60003 natural diamond detector (with a sensitive volume of 1–6 $mm^3$), combining the good properties of a diamond detector with a very small sensitive volume [4]. Many authors have published their results of $M^{fclin}_{Qclin}/M^{fmsr}_{Qmsr}$ measurements with PTW microDiamond in small field dosimetry and comparison of these results with different clinically used detectors [5–18].

Several studies have tried to estimate small field correction factors for the PTW microDiamond detector. For field sizes larger than $1 \times 1\,cm^2$ several authors (O'Brien et al. [11], Azangwe et al. [5], Tyler et al. [17], Underwood et al. [18], Lárraga-Gutiérrez et al. [19], Papaconstadopoulos et al. [20], Ralston et al. [12] and Benmakhlouf [21]) have suggested using no or very small correction factors (2% maximum for field sizes $1 \times 1\,cm^2$–$2 \times 2\,cm^2$).

However, contradictory results have been reported below $1 \times 1\,cm^2$. Morales et al. [10] suggested almost no correction factor (0.6% for 4 mm Brainlab stereotactic cone). Several authors have reported continuous over-response of PTW microDiamond readings up to 5% for the smallest 5 mm field size. Azangwe et al. [5] compared PTW microDiamond measurements with alanine output factors used as a reference, Tyler et al. [17], Underwood et al. [18] and Ralston et al. [12] calculated PTW microDiamond correction factor by comparison with a plastic scintillator detector used as a reference detector, Barrett et al. [22] compared PTW microDiamond measurements with MC data for LGK Model C, and Morales et al. [23] compared PTW microDiamond with Gafchromic EBT3 film as a reference detector for linear accelerator with Brainlab stereotactic cones. A second group of authors reported initial over-response of PTW microDiamond with a sudden change to under-response for field sizes around $5 \times 5\,mm^2$ (O'Brien et al. [11] with semi-empirical correction factors, Lárraga-Gutiérrez et al. [19], Papaconstadopoulos et al. [20] and Benmakhlouf [21] with MC calculated correction factors). The multicenter results of Russo et al. [14] for CyberKnife small fields are also in good agreement with this second group of authors, their PTW microDiamond correction factors were determined using Dosimetry Diode measurements and MC simulation.

Andreo et al. [24] reported disagreement in MC calculated and measured PTW microDiamond correction factors. According to an X-ray of the detector, the shape and dimensions of the active detector volume did not match those stated by the manufacturer. Nevertheless, a study by Marinelli et al. [25] investigated several PTW microDiamond detectors showing high reproducibility of the PTW microDiamond fabrication process and also agreement in measured active detector volume with manufacturer dosimeter specifications.

There is still need for reliable PTW microDiamond small field correction factors. Thus, the aim of this study was to determine correction factors for routine use in clinical dosimetric measurements with PTW microDiamond. Due to contradictions around MC simulation of PTW microDiamond detector, MC calculated small field correction factors for the PTW 60017 Dosimetry Diode Type E (verified independently by Benmakhlouf et al. [26], Cranmer-Sargison et al. [27], Bassinet et al. [6], Underwood et al. [18] and Czarnecki et al. [28]) were used as a reference to estimate PTW microDiamond correction factors. Our study presents set of PTW microDiamond correction factors for CyberKnife (Accuray, Inc., Sunnyvale, CA, USA), Leksell Gamma Knife (LGK) Perfexion (Elekta Instrument AB, Stockholm, Sweden) and Varian Clinac 2100C/D linear accelerator (Varian Medical Systems, Palo Alto, USA) small fields, which are suggested to be used to improve PTW microDiamond results in small field dosimetry measurements.

## 2. Materials and methods

### 2.1. Detector

The PTW 60019 MicroDiamond detector (PTW, Freiburg, Germany) is (according to manufacturer specifications) waterproof and its sensitive volume is a disc-shaped synthetic single-crystal diamond 0.004 $mm^3$ in volume, with a radius of 1.1 mm and thickness of 1 μm. The diamond diode is encapsulated in a waterproof Aluminum cylindrical housing by epoxy resin and covered by a RW3 cap. The sensitive volume is perpendicular to the detector axis and the effective point of measurement lies 1 mm under the detector top [4]. During measurements, the detector was connected to a PTW Unidos electrometer (PTW, Freiburg, Germany), voltage was set to 0 V.

### 2.2. Radiation treatment devices

A CyberKnife (Accuray, Inc., Sunnyvale, CA, USA), Leksell Gamma Knife (LGK) Perfexion (Elekta Instrument AB, Stockholm, Sweden) and Varian Clinac 2100C/D linear accelerator (Varian Medical Systems, Palo Alto, USA) were used in the present study to set the list of PTW microDiamond small field correction factors.

The CyberKnife consists of a particularly lightweight and compact radiation device on a robotic arm which enables its movement and irradiation of the patient with 6 degrees of freedom. The linear accelerator of the CyberKnife produces a 6 MV flattening filter free (FFF) photon beam with a maximum dose rate of 800 MU/min. The radiation field was shaped and shielded by an Iris variable aperture collimator and fixed circular collimators.

The LGK Perfexion is a stereotactic radiosurgery device used for treatment of malignant, benign and functional intracranial diseases. The LGK Perfexion contains 192 Co-60 sources. These sources are located in 8 independent moveable sectors and photon beams produced from them can be collimated by 16 mm, 8 mm and 4 mm collimators.

The Varian Clinac 2100C/D linear accelerator was the last radiation treatment device used in this study. Its 6 MV photon beam with flattening filter (FF) was applied for irradiation of the detector. This accelerator is routinely clinically used for conformal radiation therapy (including IMRT treatment). Nevertheless, radiation fields in this study were shaped and shielded only by secondary collimator jaws. A clinically used dose rate of 300 MU/min was set for the measurements.

### 2.3. Measurement conditions

Measurements on the CyberKnife were performed in a PTW MP3 Phantom Tank (PTW, Freiburg, Germany). The PTW 60019 microDiamond detector was positioned in the isocenter of the CyberKnife using a laser from the collimator head. The detector was set with its effective point of measurement to 1.5 cm depth in water; SAD was set to 80 cm (detector axis parallel to the beam axis). The central position of the detector in the radiation field was checked and verified using measured dose profiles. $M^{fclin}_{Qclin}/M^{fmsr}_{Qmsr}$ for each CyberKnife radiation field size was measured subsequently. There were 12 collimator