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Abstract. The study aimed to determine appropriate detectors for output factor measurement of small fields in 6 and 10 MV flattening filter free photon beams using five different detectors. Field sizes were varied between 0.6 × 0.6 and 4.0 × 4.0 cm$^2$. An indirect method (daisy-chaining) was applied to normalize the output factors. For the smallest field size, the variations of output factors compared among the detectors were 13%. Exradin A16 had the lowest output factor and increasing in sequence with CC01, microDiamond, microLion and EDGE detectors, respectively, for both energies. The similarity between CC01 and microDiamond output factor values were within 1.6% and 1% for all field sizes of 6 and 10 MV FFF, respectively. EDGE and microLion presented the highest values while Exradin A16 gave lowest values. In conclusion, CC01, Exradin A16, microLion, microDiamond and EDGE detectors seem to be the detectors of choices for small field output factor measurement of FFF beams down to 1.6 × 1.6 cm$^2$. However, we could not guarantee which detector is the most suitable for output factor measurement in small field less than 1.6 × 1.6 cm$^2$ of FFF beams. Further studies are required to provide reference information for validation purposes.

1. Introduction

Radiotherapy has been greatly developed for both treatment machines and delivery techniques. High energy photon linear accelerator can be divided in three major subtypes, namely helical linac, robotic linac and standard linac. The former two are without a flattening filter while the standard linac, typically comes with flattening filter (FF) to produce uniform dose for certain depths, could also be used without flattening filter (fluence filter free; FFF). Several studies used the FFF photon beams for clinical treatment particularly for stereotactic radiotherapy, stereotactic body radiotherapy, intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) [1-3]. The main advantages of FFF technology are increasing in dose rate and reducing in head scatter which provided a short delivery time with reducing out of field dose. For IMRT and VMAT techniques, they are based on delivery of non-uniform fluence distribution; thus flattened beam is not required [4].

Generally these advanced techniques are used in small field or segment deliveries which are non-equilibrium conditions. A concise definition of small field is still unclear. Typically, it is considered from the field dimension which is less than the lateral range of charged particle which leads to the occlusion of source from collimating device [5]. Dosimetry of small fields remains a challenging topic.
and difficult to achieve with accurate measurements because of loss of charged particle equilibrium, source occlusion and finite size of detectors [6]. Detectors with high spatial resolution, good tissue equivalence, and high precision are preferred. Several studies examined measurement of output factor with various detectors in small field. Dieterich and Sherouse assessed performance of various commercially available diodes by measuring SRS cone factors [7]. They demonstrated the “daisy-chaining” method to limit biasing effects of spectral differences between field sizes. Small field output factor of CyberKnife® and linear accelerator (Novalis) with microMLC and circular cone were determined and compared with different types of detectors by Bassinet et al. Their results showed significant differences among output factor values measured by several detectors, particularly in the smallest field size, was more than 20% [5]. Wolfgang et al. studied output factor measurements of FF and FFF beams at field size of 10 × 10 cm² down to 0.6 × 0.6 cm² by using various detectors [8]. They reported that the dose response ratio (ratio of the relative output measured with online detectors to alanine) had no significant difference between FF and FFF beams and concluded that microDiamond and unshielded diode (SFD and EFD) were suitable candidates for small field dosimetry in FF and FFF beams. The purpose of this study was to determine appropriate detector types for output factor measurement of small fields in the 6 and 10 MV FFF mode of a standard linac.

2. Materials and methods

2.1. Linear accelerator

A TrueBeam linear accelerator (Varian) at Chulabhorn Hospital (Bangkok, Thailand) is a new C-series machine designed to deliver both flattened photon beams and flattening filter free (FFF) photon beams. In this study, FFF beam energy of 6 and 10 MV at maximum dose rate of 1400 and 2400 MU/min, respectively, were used for measurement of output factor of collimator jaw-shaped square field sizes of 0.6 to 4.0 cm at 10 cm depth in water.

2.2. Detectors

Detectors which have small size of active volume including the followings: air filled ionization chambers (IBA CC01 and Exradin A16), liquid filled ionization chambers (microLion PTW 31018), Synthetic single crystal diamond detector (PTW 60019 microDiamond), and Sun Nuclear EDGE detector were included in the study, details as shown in table 1.

| Detector | Detector type | Sensitive volume (mm) | Volume | Material | Effective point |
|----------|---------------|-----------------------|--------|----------|-----------------|
| PTW 60019 microDiamond | Synthetic diamond | Thickness 0.001 Diameter 2.2 | 0.004 mm³ | Carbon Polystyrene | 1 mm |
| Sun Nuclear Edge detector | Shielded diode | Thickness 0.03 Diameter 0.8 | 0.0019 mm³ | Silicon Brass | 0.5 mm |
| IBA CC01 | Airfilled IC | Cavity length3.6 Diameter 2 | 0.01 cm³ | Air Wall: C-522 Electrode: Steel | 0.6r |
| Exradin A16 | Airfilled IC | Diameter 2.4 | 0.007 cm³ | Air Wall: C-522 | 0.6r |
| PTW 31018 microLion | Liquid filled IC | Thickness 0.35 Diameter 2.5 | 0.002 cm³ | Liquid isoctane | 0.975 mm |

All detectors were positioned inside Blue Phantom® System (ScanditronixWellhofer GmbH, Schwarzenbruck, Germany). For CC01, Exradin A16 and Edge detectors, their stems were placed perpendicular to the beam axis. In contrast, microDiamond and microLion were placed with their stem parallel to the beam axis. In the first step of measurement, the effective point of measurement of all
detectors was placed at water surface. And then, it was moved to depth of 10 cm with a source axis distance of 100 cm. In order to align the center of the detectors to the maximum dose, beam profiles were scanned for field size of $1.0 \times 1.0$ cm$^2$ in step mode with OMNIPRO-ACCEPT software.

2.3. Measurement conditions

Each detector measured the output factor by opening collimator jaw-shaped for field sizes of $0.6 \times 0.6$, $1.0 \times 1.0$, $1.6 \times 0.6$, $2.0 \times 2.0$, $2.6 \times 2.6$, $3.0 \times 3.0$, $4.0 \times 4.0$ and $10 \times 10$ cm$^2$ at 10 cm depth with a source axis distance of 100 cm. The measurements were performed using 150 MU. According to the manufacturer’s specifications, the nominal voltages for CC01, Exradin A16 and microLion are +400V, +300V, and +800V, respectively. Edge and microDiamond have no bias voltage.

Practically, the output factors were normalized to their corresponding values at calibration reference field of $10 \times 10$ cm$^2$. In this study, relative output factor for small volume detectors was calculated by daisy-chaining method which is the ratio of output reading for small field size to intermediate $4.0 \times 4.0$ cm$^2$ field size of small volume detector and renormalized by applying the ratio of output reading of suitable ionization chamber at intermediate field of $4.0 \times 4.0$ cm$^2$ to reference field of $10 \times 10$ cm$^2$ according to equation (1).

$$\text{Output factor} = \frac{M_{SD(S_{\text{small})}}}{M_{SD(S_{\text{intermediate})}}} \cdot \frac{M_{IC(S_{\text{intermediate})}}}{M_{IC(S_{\text{ref})}}}$$ (1)

where $SD$ is small field detector, $IC$ refers to a suitable ionization chamber for intermediate field (CC13), $S_{\text{intermediate}}$ refers to the intermediate field $4.0 \times 4.0$ cm$^2$ and $S_{\text{small}}$ refers to small defined fields.

3. Results

Table 2 and figure 1 showed the result of output factors measured with each of small detectors in 6 MV FFF photon beams with the maximum dose rate of 1400 MU/min. The largest variations of output factor values compared among detectors were found to be 13% in the field size of $0.6 \times 0.6$ cm$^2$. It is noteworthy that output factor of all detectors obtained good proximity within 2% except the field size equal or less than $1.0 \times 1.0$ cm$^2$. For the smallest field size, output factors measured by Exradin A16 was much smaller than those of the other detectors while output factors measured with microLion and EDGE were the largest.

| Field size(cm$^2$) | Detectors |
|------------------|-----------|
|                  | Exradin A16 | CC01 | microDiamond | microLion | EDGE |
| 4.0 ×4.0         | 0.880      | 0.880 | 0.880        | 0.880     | 0.880 |
| 3.0 ×3.0         | 0.846      | 0.844 | 0.849        | 0.852     | 0.844 |
| 2.6×2.6          | 0.832      | 0.830 | 0.834        | 0.839     | 0.830 |
| 2.0×2.0          | 0.805      | 0.804 | 0.810        | 0.816     | 0.807 |
| 1.6×1.6          | 0.778      | 0.783 | 0.786        | 0.794     | 0.786 |
| 1.0 ×1.0         | 0.689      | 0.701 | 0.713        | 0.724     | 0.725 |
| 0.6×0.6          | 0.501      | 0.531 | 0.537        | 0.566     | 0.569 |
Figure 1. Output factors for 6MV FFF (1400 MU/min) measured with various detectors.

Figure 2. Output factors for 10MV FFF (2400 MU/min) measured with various detectors.

Table 3 and figure 2 present the output factors of 10 MV FFF photon beam with the maximum dose rate 2400 MU/min. At the smallest field size, the output factors significantly differed with the largest deviation was at 12.9%. The range of the output factors was within 3% for all field sizes larger than 1.6 × 1.6 cm². For microLion and EDGE detectors, the output factors are mutually within 1.5% and higher than the other detectors while Exradin A16 obtains the lowest value. For CC01 and microDiamond, the output factors agree within 1.2% for all field sizes and within the range of the other detectors.

Table 3. Output factors for 10MV FFF (2400 MU/min) measured with various detectors at depth of 10 cm of SAD 100 cm.

| Field size(cm²) | Exradin A16 | CC01 | microDiamond | microLion | EDGE |
|----------------|-------------|------|--------------|-----------|------|
| 4.0 × 4.0      | 0.920       | 0.920| 0.920        | 0.920     | 0.920|
| 3.0 × 3.0      | 0.889       | 0.892| 0.891        | 0.893     | 0.893|
| 2.6 × 2.6      | 0.872       | 0.871| 0.876        | 0.878     | 0.879|
| 2.0 × 2.0      | 0.833       | 0.834| 0.827        | 0.843     | 0.847|
| 1.6 × 1.6      | 0.789       | 0.794| 0.798        | 0.805     | 0.812|
| 1.0 × 1.0      | 0.661       | 0.675| 0.681        | 0.696     | 0.707|
| 0.6 × 0.6      | 0.452       | 0.475| 0.469        | 0.506     | 0.511|

4. Discussion

For field size equals or less than 1.6 × 1.6 cm², the air filled ionization chambers including Exradin A16 and CC01 showed the lowest values with decreasing field sizes may be caused by the volume averaging effect. In fact the larger the volume of detector gives the smaller output factor. In this work, the output factor measured by Exradin A16, which has the smallest volume, shows the lowest values instead of CC01, which has the largest volume size, owing to its electrode made by air equivalent plastic while CC01 made by steel which causes more scatter to the output factor. Although, CC01 provided less values, but it agrees with alanine detector within 2% over the range of fields shown by Lechner W [6] and within 3.5% for field size of 0.6 × 0.6 cm² demonstrated by Godfrey A [9].

For microDiamond, made of tissue equivalent material, its output factor value was intermediate of other detectors. The agreement between CC01 and microDiamond output factor values are within 1.6% and 1% for all field sizes of 6 and 10 MV FFF, respectively.

Most of all filed sizes, microLion shows mostly higher value of output factor and it was only one to use highest voltage and concern about ion recombination effect in FFF beams as shown by Stephanie L [10] and Eunah C [11]. In addition, the output factor values were closed to the values of EDGE for all field sizes down to 1.0×1.0 cm² within 1.5% which agrees with the result of Shin H J [12].

For EDGE, is made of silicon chip and brass shielded material which might increase the scatter dose.
5. Conclusion
In this work, we experimentally measured output factors for 6 and 10 MV FFF photon beams of Varian TrueBeam using five different detectors. The output factors obtained by different detectors differ significantly in smallest field size of $0.6 \times 0.6 \, \text{cm}^2$ for 6MV FFF and field size equals or less than $1.6 \times 1.6 \, \text{cm}^2$ for 10MV FFF. The variation can reach to 12.9% for smallest field size for both energies and within 2% and 3% for field sizes $1.6 \times 1.6 \, \text{cm}^2$ and above of 6 and 10 MVFFF, respectively.

The CC01, Exradin A16, microDiamond, microLion, and EDGE detectors seem to be the detector of choices for small field output factor measurement of FFF beams down to $1.6 \times 1.6 \, \text{cm}^2$. However, we could not guarantee which detector is the most suitable for output factor measurement in small field less than $1.6 \times 1.6 \, \text{cm}^2$ of FFF beams as we did not applying a reference detector for comparing and calculating correction factor of the detectors. Further studies are required to seek for the reference information to be compared with.

References
[1] Sharma S D 2011 Unflattened photon beams from the standard flattening filter free accelerators for radiotherapy: Advantages, limitations and challenges J Med Phys. 36 123–5
[2] Kragl G, Wetterstedt S, Knausl B, Lind M, Georg D et al. 2009 Dosimetric characteristics of 6 and 10 MV unflattened photon beams Radiother. Oncol. 93 141-6
[3] Hrbacek J, Lang S and Klöck S 2011Commissioning of photon beams of a flattening filter-free linear accelerator and the accuracy of beam modeling using an anisotropic analytical algorithm Int. J. Radiat. Oncol. Biol. Phys. 80 1228-37
[4] Georg D, Knöös T and McClean B 2011 Current status and future perspective of flattening filter free photon beams Med. Phys. 38 1280-93
[5] Bassinet C et al. 2013 Small fields output factors measurements and correction factors determination for several detectors for a CyberKnife® and linear accelerators equipped with microMLC and circular cones Med. Phys. 40 071725
[6] Indra J D, X Ding G and Ahnesjö A 2008 Small fields: nonequilibrium radiation dosimetry Med. Phys. 35 206-15
[7] Dieterich S and Sherouse G W 2011 Experimental comparison of seven commercial dosimetry diodes for measurement ofstereotactic radiosurgery cone factors Med. Phys. 38 4166
[8] Lechner W, Palmans H, Sölckner L, Grochowska P and Georg D 2013 Detector comparison for small field output factor measurements in flattening filter free photon beams Radiotherapy and Oncology. 109 356-60
[9] Azangwe G et al. 2014 Detector to detector corrections: a comprehensive experimental study of detectorspecific correction factors for beam output measurements for small radiotherapybeams Medical Physics 41 072103
[10] Lang S, Hrbacek J, Leong A and Klöck S 2012 Experimenta analysis of general ion recombination in a liquid-filled ionization chambers in high dose rate flattening-filter-free photon beams Phys. Med. Biol. 57 2819-27
[11] Chung E, Davis S and Seuntjens 2013 Experimental of general ion recombination in a liquid-filled ionization chamber in high energy photon beams Med. Phys. 40 062104
[12] Shin H J, Khang Y and Jung J Y. 2012 Evaluation of the EDGE Detector in Small-filed Dosimeter Journal of the Korean Physical Society 63 128-134

Acknowledgements
The authors gratefully appreciate the Department of Radiology, Ramathibodi Hospitalfor loaning of the microDiamond andExradin A16 detector and thank Dr. Danupon Nantajit at Chulabhorn Hospital, for grammar review of the manuscript.