Original Article

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Dosimetric Verifications of the Output Factors in the Small Field Less Than 3 cm^2 Using the Gafchromic EBT2 Films and the Various Detectors

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The small field dosimetry is very important in modern radiotherapy because it has been frequently used to treat the tumor with high dose hypo-fractionated radiotherapy or high dose single fraction stereotactic radiosurgery (SRS) with small size target. But, the dosimetry of a small field (<3×3 cm^2) has been great challenges in radiotherapy. Small field dosimetry is difficult because of (a) a lack of lateral electronic equilibrium, (b) steep dose gradients, and (c) partial blocking of the source. The objectives of this study were to measure and verify with the various detectors the output factors in a small field (<3 cm) for the 6 MV photon beams. Output factors were measured using the CC13, CC01, EDGE detector, thermoluminescence dosimeters (TLDs), and Gafchromic EBT2 films at the sizes of field such as 0.5×0.5, 1×1, 2×2, 3×3, 5×5, and 10×10 cm^2. The differences in the output factors with the various detectors increased with decreasing field size. Our study demonstrates that the dosimetry for a small photon beam (<3×3 cm^2) should use CC01 or EDGE detectors with a small active volume. And also, Output factors with the EDGE detectors in a small field (<3×3 cm^2) coincided well with the Gafchromic EBT2 films.

Key Words: Small field, Output factors, EDGE detector, Gafchromic EBT2 film

Introduction

Modern radiotherapy for the treatments of cancer has made tremendous technological progress in X-ray production, delivery, imaging systems integrated into a medical linear accelerator (LINAC), and computer-based treatment planning. Nonetheless, there are the issues to solve the problems in radiotherapy, such as 4D calculations,[1)] tumor tracking on a moving tumors,[2,3)] image quality and absorbed dose during cone beam computed tomography (CBCT) acquisition to verify patient set-up,[4)] calculation-accuracy of radiation treatment planning system (RTPs) in an inhomogeneous area on low density,[5,6)] and dosimetry of a small field (<3×3 cm^2).[7-20)] These issues have been great challenges in modern radiotherapy. Especially, small field dosimetry is the most important in modern radiotherapy because it has been frequently used to remove the tumor with high dose hypo-fractionated stereotactic radiosurgery (SRS) or high dose single fraction SRS with small size target.

Small field dosimetry is difficult because of (a) a lack of lateral electronic equilibrium, (b) steep dose gradients, and (c) partial blocking of the source.[7)] Some authors published measurements of the total scatter factor, profiles, tissue maximum ratio, and penumbra using an ion chamber and Gafchromic EBT2 films in a small field.[8-11)] Bassinet et al. reported the output fac-

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tors measurements of small fields as well as a determination of the correction factors with a variety of detectors for a cyber-knife and linear accelerators.[12] Other authors reported the results of Monte Carlo simulations with measurements, such as an ion chamber, semiconductor detector, chemical, films for small fields in stereotactic radiosurgery (SRS), stereotactic body radiotherapy (SBRT), intensity-modulated radiation therapy (IMRT), and image-guided radiation therapy (IGRT).[13-20] Das et al. concluded that the accuracy of small field dosimetry under non-equilibrium conditions can be improved significantly based on the following developments.[13] (a) new protocols for absolute dosimetry, (b) small volume detectors (ion chambers, diodes and others) and (c) Monte Carlo simulation.

The aim of this study was to examine the output factors for various detector in a small fields (<3 cm) in a medical LINAC. The beam characteristics was examined using a range of detectors, such as CC13 (IBA Dosimetry, Schwarzenbruck, Germany) ion chamber, CC01 (IBA Dosimetry, Schwarzenbruck, Germany) ion chamber, edge (Sun Nuclear Inc., Melbourne, FL) diode detector, Thermoluminescent dosimeter (TLD; Harshaw/Bicon, Solon, Ohio, USA), and Gafchromic EBT2 (International Specialty Products, Wayne, NJ) films for output factors in a small field.

Materials and Methods

1. Characteristics of a medical linear accelerator

The Novalis Tx which is the state-of-the-art medical linear accelerator, was used in these experiments. Fig. 1 present photograph of the Novalis Tx used to treat patients. The Novalis Tx linear accelerator system has HD-120 MLC (High Definition Multi Leaf Collimator, 64 inner leaves with 2.5 mm and 56 outer leaves with 5 mm). The collimator consists of 8 cm for the inner leaves and 7 cm for both outside of the inner leaves. Moreover, the Novalis Tx includes an image guide system to verify the set-up position of the patient, such as the ExacTrac (BrainLAB, Feldkirchen, Germany) and On-Board Imager (OBI; Varian Medical System, CA, USA), as shown in Fig. 1.

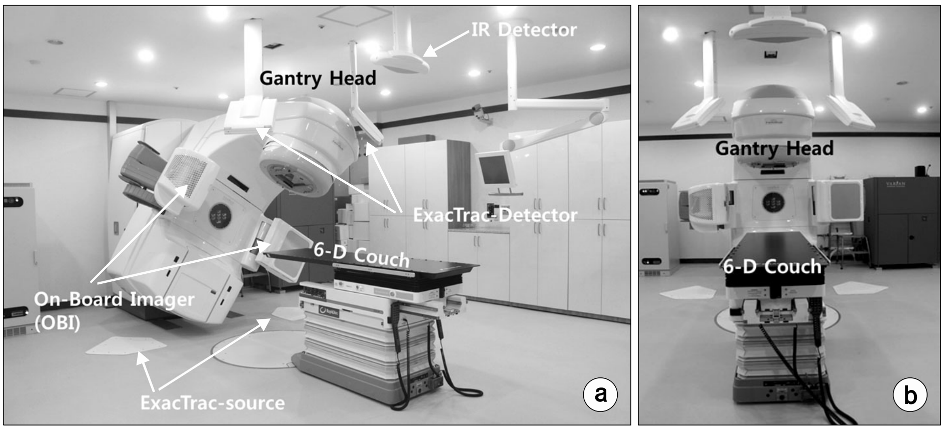

Fig. 1. Photograph of the Novalis Tx for a medical linear accelerator: (a) side view, (b) front view.

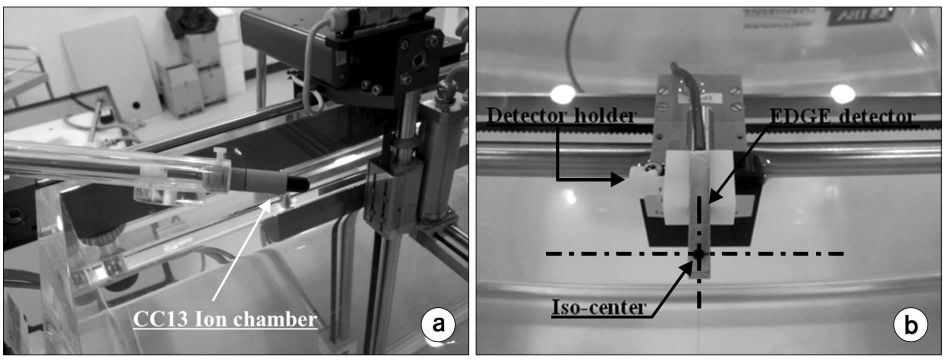

Fig. 2. Photograph of the detectors combined with the blue phantom; (a) CC13 ion chamber, (b) EDGE detector.

Table 1. Specifications of the CC13, CC01, and EDGE detectors.

Feature	CC13	CC01	Feature	EDGE
Active Volume (cm^3)	0.13	0.01	Active Volume (mm^3)	0.0019
Chamber type	Ion chamber	Ion chamber	Chamber type	Diode
Maker	IBA	IBA	Maker	Sun Nuclear
Cavity length (mm)	5.8	3.6	Cavity length (mm)	0.8
Cavity radius (mm)	3.0	1.0	Thickness (mm)	0.03
Wall material	C552	C552	Width (mm)	0.8
Wall thickness (g/cm^2)	0.070	0.088	Active detection area (mm)	0.8×0.8
Central electrode material	C552	steel	Water depth equivalent (mm)	0.5
Water-proof	Y	Y	Water-proof	Y

2. Water phantom with various ion chambers and EDGE detector

The radiation fields of the medical linear accelerators (Novalis Tx; Varian Medical Systems, CA, USA and BrainLAB, Feldkirchen, Germany) are measured using an IBA Blue phantom (IBA Dosimetry GmbH, Schwarzenbruck, Germany). The accelerator is comprised of a 3 dimensional servo (the Blue Phantom tank with mechanics), a control unit with integrated two channel electrometer (CU500E) and two single detectors (ionization chambers). For this system, it can be attached to the Blue phantom including single semiconductor detectors, cylindrical and parallel ionization chambers. The output factors were measured using CC13 thimble ion chambers (IBA Dosimetry, Germany), CC01 thimble ion chambers (IBA Dosimetry, Germany) and an EDGE detector (Sun Nuclear, USA) with varied field sizes (0.5×0.5～10×10 cm^2).

Fig. 2a shows the CC13 ion chamber for the reference field with the Blue water phantom. The CC13 was positioned at the edge of the field to eliminate the interference of the field channel. Fig. 2b presents the indicated the EDGE diode detectors combined water tank, which is connected by only one channel for radiation fields. All measurements for the radiation field are selected by continuous scanning mode and a low speed of 1.74 mm/s.

Table 1 lists the specifications of various detectors for dosimetric parameters, such as the active volume, chamber type and maker. CC13 is the standard chamber for clinical use in water phantoms and for output factor measurements. CC01 detector is the conventional ionization chambers for measurements of small fields and of ranges with high dose gradients, e.g. stereotactic radiosurgery fields. The EDGE detector delivers flatter profiles, sharper resolution, and the real beam picture for treatment planning. Compared to ion chambers, EDGE detectors gives approximately 100 times more signal even though it is over 6000 times smaller in volume. The blue phantom was positioned at a source-to-surface distance (SSD) of 100 cm.

3. Thermoluminescent dosimeter (TLD)

Thermoluminescent dosimeter (TLD)-100 (LiF) chips are applied to compare the output factors according to the field size with a solid phantom. The Harshaw 5500 Automatic TLD Dosimetry reader (Harshaw/Bicon, Solon, Ohio, USA) is used to read the radiation dose absorbed by individual TLD elements. The dosimeters were annealed in a PTW-TLDO (Physikalisch-Technische Werkstatten, Freiburg, Germany) Harshaw oven.

4. Gafchromic EBT2 film

Owing to the difficulties of dosimetry, such as the CPE (charged particles equilibrium), partial blocking of the beam source, steep dose gradients of the dose distribution and perturbation of the detectors in a small fields (<3×3 cm^2), Gafchromic EBT2 films (International Specialty Products, Wayne, NJ) are used frequently to verify the radiation dose.

Gafchromic EBT2 films are self-developing with several improvements. EBT2 films have several characteristics compared to the previously used the radio-chromic film. They contain a yellow marker dye to minimize the response difference caused by coating anomalies and have a wide of range for energies from 50 keV into the MeV range.

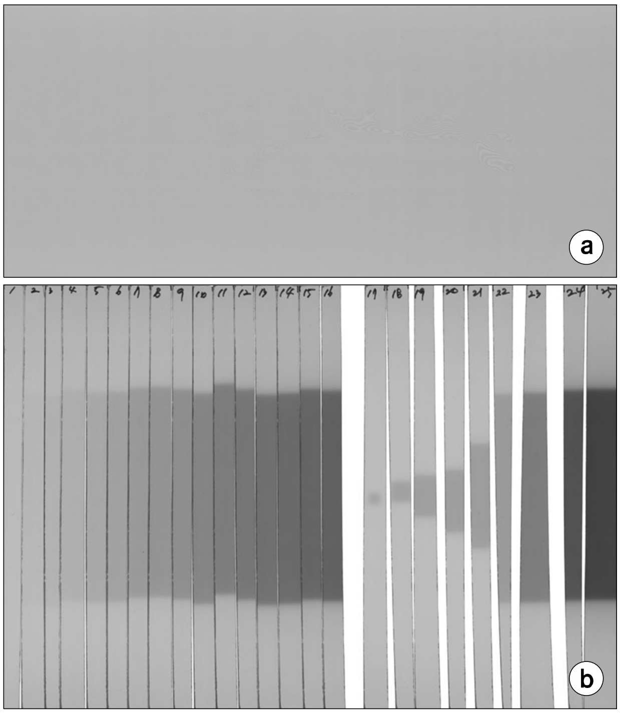

Fig. 3. Photograph of the Gafchromic EBT2 films for the dose calibration. (a) Background film; (b) Cut-calibration film (#1～#16, #24, #25: 0, 10, 20, 30, 50, 70, 100, 120, 150, 200, 250, 300, 350, 400, 450, 500, 700, and 1000 cGy, respectively; #17～#22 (exposed film for output factors in each field): 5×5, 10×10, 20×20, 30×30, 50×50, and 100 mm×100 mm, respectively. #23 is a re-measurement of #11.

The Gafchromic EBT2 films were also scanned with an Epson 10000XL flatbed scanner (Seiko Epson Corp., Nagano, Japan) according to recommendations of the Gafchromic EBT2 film's manufacturer (ISP Corporation, Wayne, NJ). An Epson Expression 10000XL scanner is used widely for EBT2 dosimetry. The scan option was selected with 48 bit color to scan in RGB mode, a spatial resolution of approximately 75 dpi and "No Color Correction-with turn off all image adjustment features". The scanned images were calibrated in the range from 0 to 1000 cGy (0, 10, 20, 30, 50, 70, 100, 120, 150, 200, 250, 300, 350, 400, 450, 500, 700, and 1000 cGy) in the red, green and blue channels to analyze the scanned-images using the OmniPro I'mRT Version 1.7 (IBA Dosimetry, Schwarzenbruck, Germany). The 8"×10" film was used for the background and calibration. The EBT2 film was cut in the vertical direction at intervals of approximately 17 mm, as shown in Fig. 3b. Fig.

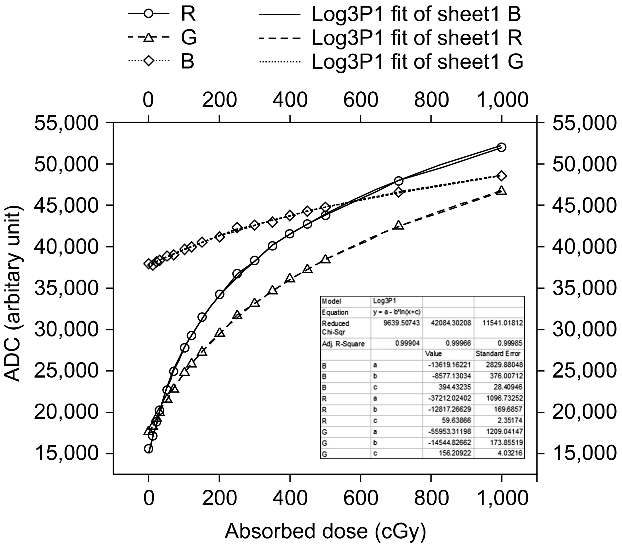

Fig. 4. Calibration curve for the 6 MV photon beam with R, G, B channel (0, 10, 20, 30, 50, 70, 100, 120, 150, 200, 250, 300, 350, 400, 450, 500, 700, and 1000 cGy).

3b was divided in a calibration film and exposed film for the output factor measurements. The EBT2 films were calibrated with #1～#16, #24, and #25 for the 0, 10, 20, 30, 50, 70, 100, 120, 150, 200, 250, 300, 350, 400, 450, 500, 700, and 1000 cGy, respectively, and #17～#22 of the films exposed with 5 mm×5 mm, 10 mm×10 mm, 20 mm×20 mm, 30 mm×30 mm, 50 mm×50 mm and 100 mm×100 mm for the output factor measurements, respectively. #23 of the films was a re-measurement of #11 because of the stopped beam when exposing #11 of the film. A detailed description of the calibration of the EBT2 films was explained in a previous paper.[21] Results of the calibration curve for 6 MV photon energies with R, G and B channel as shown by the Fig. 4.

Fig. 4 indicates the calibration curves for the 6 MV photon energies with R, G and B respectively. Experimental data points were fitted to a Log3P1 model with log function by using the OriginPro 8.5 software.

The fitted curves used by the following log equation as below:

$$y = a - b \times \mathrm{In}(x + c)$$

The related coefficients are a=−37212.0, b=−12817.2, c=59.6 and adjusted R-Square=0.999 for r channel.

Because the red channel is the smallest for an increase of the absorbed dose while increasing the analog-to-digital converter (ADC) values, the red channel was selected for the measurement of the output factor with various field sizes.

Results and Discussion

The output factors were measured using the CC13, CC01, EDGE, TLD, and Gafchromic EBT2 films for photon beam from a 6 MV accelerator with a Novalis Tx linear accelerator. The detectors for the CC13, CC01 and EDGE measured the water phantom, and the output factors for the TLD and Gafchromic EBT2 film were used for the solid phantom (PMMA-Polymethylmethacrylate). All the measured output factors were normalized to a 10×10 cm^2 field size.

The CC13, CC01 and EDGE detectors were measured from 0.5 cm to 10 cm, and the TLD and EBT2 films are measured up to 10 cm. The difference in the output factor between 2×2 cm^2 to 10×10 cm^2 field size was less than 2%, but compared to the EDGE detector there were differences of −55.11, −22.23, −42.32, and −7.91% for the CC13, CC01, TLD, and Gafchromic EBT2 films in the 0.5 cm field size. If the field size is smaller, it can be seen that the variations of the output factor increased according to the detector.

Fig. 5 shows the output factor measured with CC13, CC01, EDGE, TLD and EBT2 film for photon beam from a 6 MV accelerator for field sizes ranging from 0.5×0.5 cm^2 to 10×10 cm^2. Fig. 5 indicates the according to kind of the detector the output factors was significantly different in the below the 2 cm size of the field, but more than size of the 2 cm the output factor was almost the same.

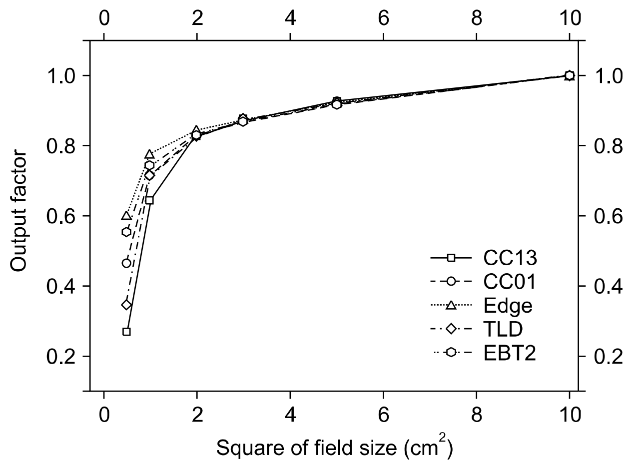

Fig. 5. Output factor measured with CC13, CC01, EDGE, TLD and EBT2 film for photon beam from a 6 MV accelerator for field sizes ranging from 0.5×0.5 cm^2 to 10×10 cm^2.

Das et al. summarized the dosimetry of a small field in non-equilibrium radiation therapy.[13)] The output factors with various detectors such as Scanditronix-SFD, Scanditronix-RFD, Exradin-A16, PTW-Pinpoint, PTW-0.125CC, PTW-0.3CC, PTW-0.6CC, PTW-Markus and Wellhofer-IC4 were reported using photon beam from 6 MV and 15 MV accelerators dmax. The results reported by Das et al. coincided well with the measurements in the small field.

Haryanto et al. reported the output factors measured with different detectors (diode, diamond, pinpoint and ionization chamber) with those simulated using Monte Carlo methods.[18)] The measurements of the photon beam output factor were used in a water phantom at a depth 10 cm with a SSD of 100 cm and a square field ranging from 1 cm to 15 cm. The results of a Monte Carlo simulation reported by Haryanto et al. in a 1×1 cm^2 field size coincided with the output factor of the EDGE detector.

Cranmer-Sargison et al. reported the experimental small field output for the photon beam from a 6 MV accelerator of an IBA stereotactic field diode (SFD), PTW T60008, T60012, T60016 and T60017 field diode on both Varian ix and Elekta Synergy accelerators.[22)] Cranmer-Sargison et al. measured at depths of 1.5, 5.0 and 10.0 cm for square field sizes of 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, and 3.0 cm. Their experimental results were in good agreement with the experimental results for a field size $<$3 cm.

Various detectors have different dosimetric characteristics when used for small photon field measurements. Silicon and diamond detectors have been reported significantly better than ionization chamber in the small fields due to inherent small active volume and in the case of diamonds improved tissue equivalent density. And also, Film dosimetry can be measured with excellent high resolution 2D dose distributions without volume effect.[7)]

Until now, ionization chambers the most widely used to the measurement of the ionization dose, but those are not always suitable where situations of high dose gradients, volume averaging, and lack of electron equilibrium in the dosimetry of small photon fields.

IPEM Report-103[7] pointed out that the deficiencies in the dosimetric accuracy of the measurement have been shown to significantly affect the outcome of quality control in radiotherapy such as, IMRT, Dynamic Conformal ARC (DCA), and RapidARC techniques.

Conclusion

In conclusion, dosimetry of a small field ($<3\times3$ cm^2) has been great challenges in radiotherapy. The small field dosimetry is important in modern radiotherapy because it has been frequently used to remove the tumor with high dose hypo-fractionated stereotactic radiosurgery (SRS) or high dose single fraction SRS with small size target.

Our study shows that the dosimetry for a small photon beam ($<3\times3$ cm^2) should use CC01 or EDGE detectors with a small active volume. The output factors with the EDGE detectors in a small field ($<3\times3$ cm^2) coincided with the Gafchromic EBT2 films.

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Gafchromic EBT2필름과 다양한 검출기를 이용하여 3 cm^2 이하의 소조사면에서 출력비율의 선량검증

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소조사면의 선량검증은 고선량을 1회에 치료하는 정위적방사선수술(Stereotactic radiosurgery, SRS)과 고선량을 소분할 하여 치료하는 소분할방사선치료(hypo-fractionated radiotherapy)에서 작은 크기의 종양을 치료하기 위해서 자주 사용되기 때문에 현대의 방사선치료에서 있어서 매우 중요하다. 그러나, 3 cm^2 이하의 소조사면에 대한 선량검증은 방사선치료에서 있어서 대단한 도전이다. 소조사면의 선량검증은 (a) 측방전자균형(lateral electronic equilibrium)의 부족, (b) 급격한 선량 기울기(steep dose gradient), (c) 선원의 부분적 차폐 때문에 어렵다. 이 연구의 목적은 6 MV 광자선의 3 cm^2 이하의 소조사면에서 출력비율을 다양한 검출기로 측정하고 검증하는 것이다. 출력비율은 CC13 이온함, CC01 이온함, EDGE 검출기, 열발광선량계(thermoluminescence dosimeters, TLD), Gafchromic EBT2 필름을 이용하여 0.5×0.5 cm^2, 1×1 cm^2, 2×2 cm^2, 3×3 cm^2, 5×5 cm^2, 10×10 cm^{2}의 다양한 조사면에서 측정하였다. 출력비율의 차이는 조사면의 크기가 작아질수록 검출기간의 차이는 증가하였다. 본 연구의 결과는 3 cm^2 이하의 소조사면의 선량측정은 CC01 이온함, EDGE 검출기와 같은 작은 크기의 방사부부피(active volume)를 가지는 검출기를 사용해야 한다는 것을 입증하였다. 또한, 3 cm^2 이하의 소조사면에서 EDGE 검출기의 출력비율은 Gafchromic EBT2 필름의 결과와 잘 일치하였다.

중심단어: 소조사면, 출력비율, EDGE 검출기, Gafchromic EBT2 필름