Evaluation of output factors of different radiotherapy planning systems using Exradin W2 plastic scintillator detector

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Abstract

This study aims to evaluate the output factors (OPF) of different radiation therapy planning systems (TPSs) using a plastic scintillator detector (PSD). The validation results for determining a practical field size for clinical use were verified. The implemented validation system was an Exradin W2 PSD. The focus was to validate the OPFs of the small irradiation fields of two modeled radiation TPSs using RayStation version 10.0.1 and Monaco version 5.51.10. The linear accelerator used for irradiation was a TrueBeam with three energies: 4, 6, and 10 MV. RayStation calculations showed that when the irradiation field size was reduced from 10×10 to 0.5×0.5 cm^2, the results were within 2.0% of the measured values for all energies. Similarly, the values calculated using Monaco were within approximately 2.0% of the measured values for irradiation field sizes between 10×10 and 1.5×1.5 cm^2 for all beam energies of interest. Thus, PSDs are effective validation tools for OPF calculations in TPS. A TPS modeled with the same source data has different minimum irradiation field sizes that can be calculated. These findings could aid in verification of equipment accuracy for treatment planning requiring highly accurate dose calculations and for third-party evaluation of OPF calculations for TPS.

Keywords: plastic scintillator; radiation therapy; small irradiation field; output factor

Introduction

In recent years, radiotherapy technology has advanced remarkably, giving rise to high-precision radiotherapy approaches such as stereotactic radiosurgery, stereotactic body radiation therapy, intensity-modulated radiation therapy, volume-modulated arc therapy, Vero4DRT, and tomotherapy. These radiotherapy methods are the results of combining small irradiation fields from standard-sized irradiation field sizes. Therefore, the output factor (OPF) and dosimetry techniques for large to small irradiation fields of the radiation therapy planning system (TPS) are important [1]. In a TPS, the user applies the measurement conditions specified by the manufacturer using detectors with different characteristics, such as ionization chambers, semiconductor detectors, and diamond detectors, from different manufacturers and of various sizes. Based on the measurement results, the manufacturer performs photon beam modeling for the TPS. The OPF irradiation field sizes for photon beam data used for modeling in many TPS range from 40×40 to 2.0 × 2.0 cm^2. Therefore, dose calculations for irradiation fields smaller than 2.0 × 2.0 cm^2 are based on TPS simulation calculations utilizing photon beam data measured with the detectors owned. Therefore, even if the TPS is modeled using the same photon beam data, the characteristics of its dose calculation appear with decreasing irradiation size. In other words, the practical irradiation field size limit is different. To perform more accurate radiation therapy, understanding the dose calculation characteristics at the OPF due to the irradiation field size for each TPS and controlling the accuracy are clinically important. To perform this control, the selection of a radiation detector for appropriate OPF acquisition must be considered. In contrast, ionization chambers, which are typical commercially available radiation detectors, require caution in calculating the OPF for small irradiation field sizes because the values measured for each type and size of detector are different [1]. The calculation of OPF for small irradiation field sizes is because charged particle equilibrium is not established and the line quality changes; moreover, the sensitivity of the detector varies with the size of the sensitive volume of the detector and its composition density [1].

The OPF is obtained from standard to small irradiation field sizes using an ionization box up to the size of the irradiation field where volume averaging works. For smaller irradiation fields, a small detector (such as dosimetry diodes, diamond detectors, liquid scintillators, and organic scintillators) is employed [2]. The power coefficients obtained from the small detector measurements are re-normalized to the smallest field size for which an ionization chamber is utilized. This method is referred to as the daisy-chain strategy [2]. Another method for calculating the OPF in small irradiation fields is combining large area parallel plane ionization chambers and a chromodynamic film. In 2017, the International Atomic Energy Agency (IAEA) published Technical Report Series No. 483 (IAEA TRS-483), providing recommendations for small irradiation field measurements and values [3].

IAEA TRS-483 defined the field output correction factors ($k^{fclin,fmsr}_{\mathrm{Qclin,Qmsr}}$) for the OPF calculation for each detector [4]. In this report, we focus on the Exradin W1 plastic scintillator detector

(PSD; Standard Imaging Inc., Middleton, WI, USA) with a field output correction factor of 1.0. The Exradin W1 PSD has a generally low signal-to-noise ratio, high spatial resolution, flat energy dependence, small size, and very low detector-induced radiation field perturbation, and it is considered by many researchers to be a valuable water-equivalent detector for use in small beam dosimetry applications [1, 4–11].

Studies have been published on the variability of OPF measurements between different TPSs, which used various treatment devices such as linear accelerators and cyberknives and detectors such as various ionization chambers and semiconductors [12,13]. However, to the best of our knowledge, there have been no studies on the evaluation of OPF between calculation and measurement data using different TPSs and plastic scintillators. Although the characteristic measurements required by manufacturers are the same, different facilities use different measurement detectors for modeling. Modeling techniques for measured photon beams also vary among TPS manufacturers.

The purpose of this study was to investigate the calculation characteristics of the OPF values obtained using the Exradin W2 PSD, an updated model of the Exradin W1 PSD, by adopting them as references and comparing them with the OPF calculation results of a TPS modeled using photon beam data measured at our institution.

The PSD used in our study was an Exradin W2 PSD (Standard Imaging Inc., Middleton, WI, USA), an updated version of Exradin W1 PSD (Standard Imaging) and the most commercially available PSD in the world. Many researchers have reported that Exradin W1 PSD is a useful water-equivalent detector for small-field verification and measurement tasks [1, 5–8, 14–16]. Exradin W2 PSD is a model with an added beam scanning capability [9], and it has desirable characteristics such as water resistance, tissue equivalence, direct reading, dose, dose rate dependence, energy independence, angle dependence, response characteristics, and minimal radiation damage [7, 9]. However, when measured using an Exradin W2 PSD, the detector scintillation signal is superimposed by the Cerenkov radiation generated in the illuminated portion of the scintillator and optical fiber [10, 17]. This effect is remedied by a correction method called the spectral method, which has been extensively discussed in previous studies [4, 10, 11, 18, 19]. Thus, Exradin W2 PSD is the best commercially available small-field detector.

Materials and Methods

Dosimetry system setup

The dosimetry systems used in this study were an Exradin W2 PSD (Standard Imaging Inc.) and a BeamScan water phantom (PTW, Freiburg, Germany). The Exradin W2 PSD was connected to the BeamScan water phantom, and dosimetry was performed using the MAX SD potentiometer, developed and supplied by the manufacturer specifically for PSD (Fig. 1). The Exradin W2 PSD consists of a plastic scintillation fiber, based on polystyrene and acrylonitrile butadiene styrene (ABS) plastic, and an optical fiber that transmits the light generated in the scintillator to a shielded optical enclosure inside the MAX SD electromagnetic meter (Fig. 2a) [9]. The Exradin W2 PSD has detectors with two sizes of fibers: a W2-1×1 detector (diameter, 1.0 mm; length, 1.0 mm; volume, 0.0008 cm^3) and a W2-1×3 detector (diameter, 1.0 mm; length, 3.0 mm; volume, 0.0024 cm^3; Fig. 2b). In this study, the highly sensitive W2-1×3 detector was used [9, 19].

Charles et al. [21] also suggested that OPF measurements with small irradiation field sizes require a very careful experimental approach that includes dosimetry field size measurements simultaneously with each OPF measurement. Therefore, in this study, we used the scanning capability of the Exradin W2 PSD to measure the cross-axis profile in the tank simultaneously with each OPF measurement using the BeamScan water phantom. Careful attention was paid to an accurate and reproducible experimental setup and methodology [9].

Cherenkov radiation effect correction and dose calibration were performed using 30 × 30 × 30 cm^3 Solid Water HE (Gammex, Middleton, WI, USA) according to the manufacturer's recommended method. Several studies have reported this calibration; thus, it was omitted [7, 20, 22, 23]. The linear accelerator used was the TrueBeam (Varian Medical System, Palo Alto, CA, USA) photon beam. For the validation of this study, photon beams energies of 4, 6, and 10 MV were selected, and the range selection of the dose rate was 240–600 MU/min. The geometric conditions of the BeamScan water phantom were set up to a source-to-surface distance (SSD) of 90 cm. This condition was consistent with the introduction of the TPS. Field size definitions included the 100 cm source detector distance and 90 cm SSD, as specified by the TPS vendor.

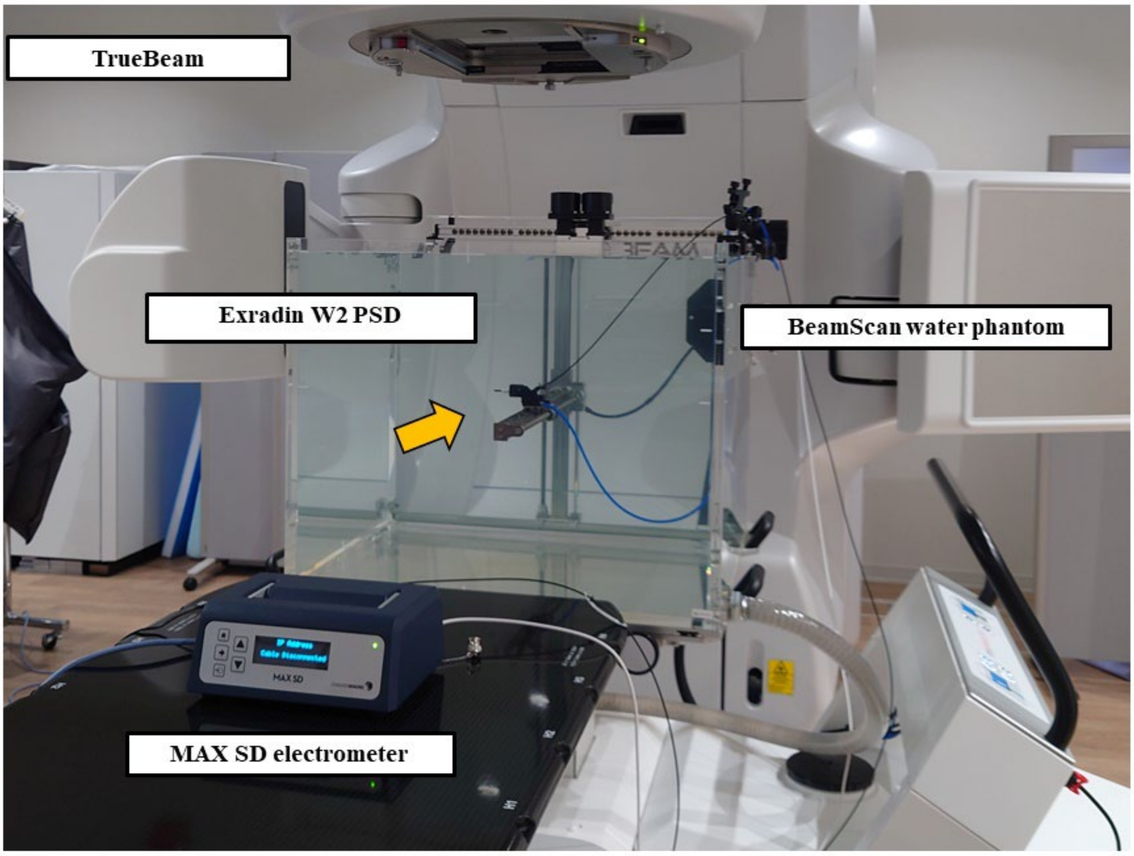

Fig. 1 Exradin W2 PSD and MAX SD electrometer combination

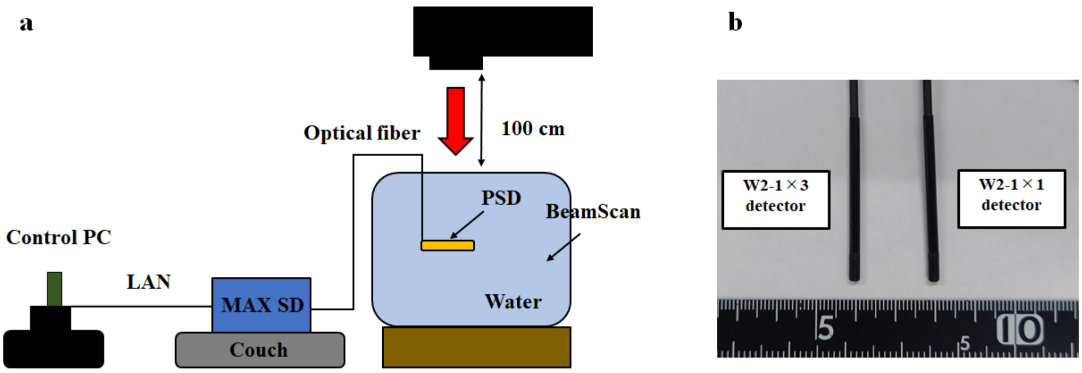

Fig. 2 (a) BeamScan water phantom setup and Exradin W2 PSD configuration. (b) W2-1×3 and W2-1×3 detectors. PSD, plastic scintillator detector.

Plastic scintillator detector (Exradin W2 PSD)

A small field dosimetry evaluation of the Exradin W2 PSD was reported by Galavis et al. [9]. We used a TrueBeam (Varian Medical System, Palo Alto, CA, USA) to evaluate the Exradin W2 PSD dosimetry in the range between the reference field size (10 × 10 cm^2) and small irradiation field size (0.5 × 0.5 cm^2). The performance of the Exradin W2 PSD was evaluated by scanning and measuring the percent depth dose (PDD) in a range of irradiation field sizes from large to small.

The geometric conditions of the BeamScan water phantom were set to those of a 90 cm SSD. These conditions were consistent with the introduction of the TPS. The field size definitions included the 100 cm source-to-detector distance and 90 cm SSD, as specified by the TPS vendor. The used photon beam energy was 6 MV, and the measured irradiation field sizes were 10 × 10, 7.0 × 7.0, 5.0 × 5.0, 3.0 × 3.0, 2.0 × 2.0, 1.0 × 1.0, 0.7 × 0.7, and 0.5 × 0.5 cm^2.

The PDD measurements using Exradin W2 PSD (irradiation field sizes, 10 × 10 and 0.5 × 0.5 cm^2) were compared with the measurements of the ionization chamber (Semiflex 3D type 31021; PTW) and chromodynamic film (Gafchromic film EBT-3; Ashland ISP Advanced Materials, Wayne, NJ, USA). The ionization chamber measurement conditions were a photon beam energy of 6 MV, a dose rate of 600 MU/min, and an irradiation field size of 10 × 10 cm^2. The geometric conditions with a 90 cm SSD ionization chamber setting were effective centers. The used ionization chamber, Semiflex 3D type 31021, has a recommended minimum measurable field size of 2.0 × 2.0 cm^2. Therefore, the irradiation field size of 0.5 × 0.5 cm^2 was not measured [24]. Scanning measurements were made with a BeamScan water phantom. The PDD measurements using Exradin W2 PSD (irradiation field sizes 0.5 × 0.5 cm^2) were compared with the measurements obtained using the chromodynamic film (Gafchromic film EBT-3). The measurement conditions for the chromodynamic film were a photon beam energy of 6 MV, dose rate of 600 MU/min, and field size of 0.5 × 0.5 cm^2. The geometric conditions were set at an SSD of 90 cm. The phantom used was a 30 × 30 × 30 cm^3 Solid Water HE. The measured chromodynamic films were stored in a dark room at low temperature for approximately 24 h and then analyzed using DD-SYSTEM version 31.7 (R-Tech Inc., Tokyo, Japan).

As there have been reports on the temperature dependence of Exradin W2 PSD, the water temperature was maintained at 22–23 °C during the measurement period in our study, and large temperature fluctuations were avoided [7, 9].

Short- and long-term system reproducibility of the Exradin W2 PSD measurements was considered using the beam scanning capability of the Exradin W2 PSD. The measurement conditions consisted of an irradiation field size of 10 × 10 cm^2 and measurement of the PDD. The geometric condition of the beam-scanning water phantom was set at 90 cm SSD. This condition was consistent with the photon beam data acquisition conditions when the treatment planning system was installed. The measurement periods were 8 hours, 1 day, 1 week, and 1 month.

OPF measurement

The conditions for OPF measurement using the Exradin W2 PSD were based on IAEA TRS-483 [4]. Photon beam energies of 4, 6, and 10 MV; dose rates of 250–600 MU/min; and field sizes of 10 ×10, 9.0 × 9.0, 8.0 × 8.0, 7.0 × 7.0, 6.0 × 6.0, 5.0 × 5.0, 4.0 × 4.0, 3.0 × 3.0, 2.0 × 2.0, 1.5 × 1.5, 1.0 × 1.0, 0.9 × 0.9, 0.8 × 0.8, 0.7 × 0.7, 0.6 × 0.6, and 0.5 × 0.5 cm^2 were used. The geometric conditions were a 90 cm SSD and 100 cm source-to-target distance (STD). The linear accelerator used for irradiation was a TrueBeam. The phantom used was a BeamScan water phantom (PTW). The water temperature was maintained at 22–23 °C during the measurement period.

The OPF was derived from the measurements by applying the following equations:

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

$$k^{fclin,fmsr}_{Qclin,Qmsr} = 1.0. \qquad (2)$$

Here $\Omega^{fclin,fmsr}_{Qclin,Qmsr}$ is the field OPF, $\frac{M^{fclin}_{Qclin}}{M^{fmsr}_{Qmsr}}$ is the ratio of the detector readings, f_{clin} is the clinically targeted non-reference field, and f_{msr} indicates the treatment device-specific reference field.

For TrueBeam (Varian Medical System, Palo Alto, CA, USA), fmsr equals a conventional 10 cm × 10 cm reference field.

The detector-specific field output correction factor for small irradiation field measurements is then indicated by $k^{fclin,fmsr}_{Qclin,Qmsr}$, the value of which was applied as described in IAEA TRS-483.

OPF calculation

The conditions for calculating OPF with TPS are photon beam energies of 4, 6, and 10 MV; a dose rate of 250–600 MU/min; and an irradiation field size of 10 × 10, 9.0 × 9.0, 8.0 × 8.0, 7.0 × 7.0, 6.0 × 6.0, 5.0 × 5.0, 4.0 × 4.0, 3.0 × 3.0, 2.0 × 2.0, 1.5 × 1.5, 1.0 × 1.0, 0.9 × 0.9, 0.8 × 0.8, 0.7 × 0.7, 0.6 × 0.6, and 0.5 × 0.5 cm^2. The geometric conditions were a 90 cm SSD and 100 cm STD. The phantom used was a virtual phantom (30 × 30 × 30 cm^3) created by the TPS.

The OPF calculation was derived from the following equation:

$$\Omega^{fclin,fmsr}_{Qclin,Qmsr} = \frac{M^{fclin}_{Qclin}}{M^{fmsr}_{Qmsr}}. \qquad (3)$$

The TPS used for the dose calculations used RayStation version 10.0.1 (RaySearch Laboratories, Stockholm, Sweden) and Monaco version 5.51.10 (Elekta CMS, Maryland Heights, MO, USA). The linear accelerator employed for both dose calculations was TrueBeam. The beam data for the dose calculations were identical but modeled by each TPS manufacturer. RayStation utilized the clinical dose calculation algorithm collapsed cone convolution (CCC), with a calculation grid size of 1.0–3.0 mm. For dose assessment, a simulated evaluation region of interest (ROI) was placed in the sensitive area of the Exradin W2 PSD with a collection volume of 0.00236 cm^3 (=0.00236 cc) and diameter of 1.0 mm × L3.0 mm to obtain mean doses. The Monaco dose calculation was then performed using the clinical Monte Carlo algorithm: the X-ray voxel Monte Carlo.

The statistical uncertainty at the time of calculation was 0.1%. To obtain the point dose considering the Monte Carlo uncertainty, the evaluation point is set at a mean dose of radius 0.25 cm and volume 0.081 cm^3 to avoid volume effects.

Selecting an exceedingly small grid size is usually effective for dosimetry of small irradiation fields. However, the selection of a fine grid size has a trade-off relationship with the length of treatment planning time [25, 26]. Therefore, we determined a practical irradiation field size when the grid size was varied from 1.0 to 3.0 mm and the OPF calculation results were set to an allowable error of 2.0%.

Results

Performance evaluation

The PDD measured with the plastic scintillator is shown in Fig. 3a. The beam energy was 6 MV, and the irradiation field sizes were 10 × 10, 7.0 × 7.0, 5.0 × 5.0, 3.0 × 3.0, 1.5 × 1.5, 1.0 × 1.0, 0.7 × 0.7, and 0.5 × 0.5 cm^2. A field size of 0.5 × 0.5 cm^2 is the smallest field size that can be created with TrueBeam. The smallest field size of the PDD could be measured using the Exradin W2 PSD. Fig. 3b compares the results of the chromodynamic film, ionization chamber, and Exradin W2 PSD. The irradiation field size was 10 × 10 cm^2, and the photon beam energy was 6 MV. The compared range was 20 cm deeper than the depth of the maximum dose. The dose differences between the chromodynamic film and Exradin W2 PSD were within 1.0% for all the depths. In the ionization chamber, there was a 1.2% phase difference with the chromodynamic film at all depths. The Exradin W2 PSD was shown to be consistent with the results of the chromodynamic film and ionization chamber measurements at the reference irradiation field size of 10 × 10 cm^2. Fig. 3c presents the results of the measurements for the Exradin W2 PSD and chromodynamic film with an irradiation field size of 0.5 × 0.5 cm^2. The beam energy was 6 MV. The compared range was 20 cm deeper than the depth of the maximum dose. The dose differences between the chromodynamic film and Exradin W2 PSD were within 3.1% for all depths. The Exradin W2 PSD showed measurability with the smallest irradiation field size of 0.5 × 0.5 cm^2 that can be obtained with TrueBeam. The short- and long-term stability of the correlations are plotted in Fig. 3d, which shows the correlation data at the start of the experiment for 8 hours, 1 day, 1 week, and 1 month. The measurement error at an interval of approximately 8 hours, 1 day, 1 week, and 1 month from the start of the measurement was 0.8%, 0.4%, 1.0%, and 1.0%, respectively. The Exradin W2 PSD showed very stable measurements. The comparisons were made with a beam energy of 6 MV, field size of 10 × 10 cm^2, and PDD. The room temperature during the measurement period was in the range of 22–23 °C, and large fluctuations were avoided.

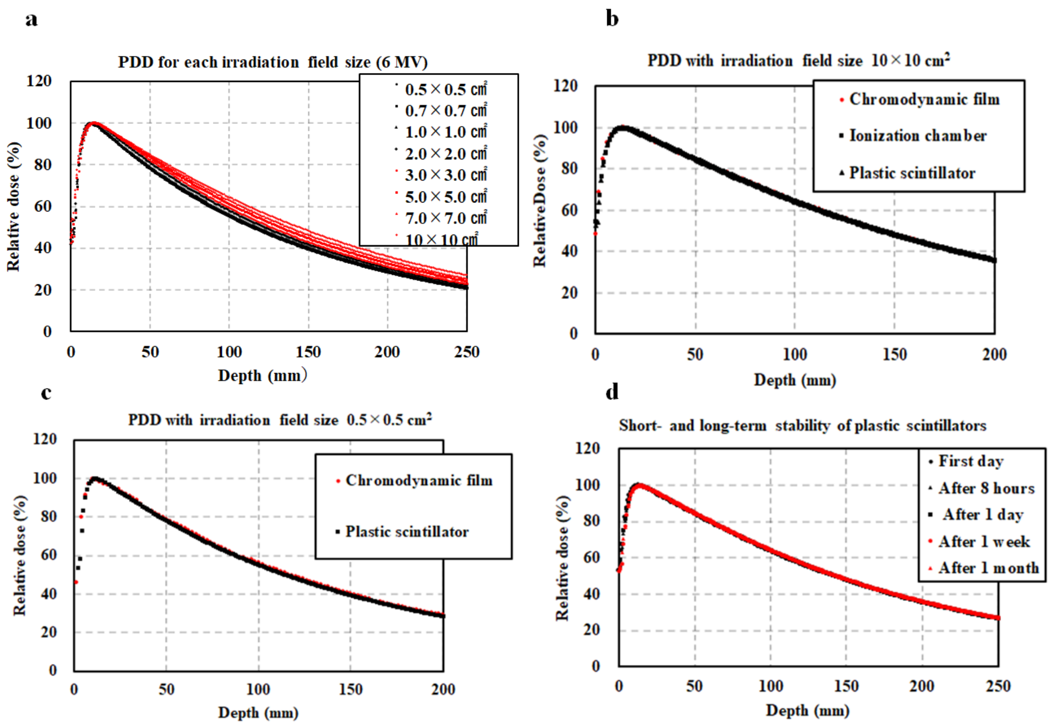

Fig. 3 (a) PDD measurement results for each irradiation field size at a photon beam energy of 6 MV with the Exradin W2 PSD. (b) PDD measurement results with each detector (chromodynamic film, ionization chamber, and Exradin W2 PSD) for an irradiated field size of 10 × 10 cm^2 with a photon beam energy of 6 MV. (c) PDD measurement results with each detector (chromodynamic film and Exradin W2 PSD) for an irradiated field size of 0.5 × 0.5 cm^2 with a photon beam energy of 6 MV. (d) Results of short- and long-term stability of measurements using the Exradin W2 PSD: comparison of PDD measurements with a photon beam energy of 6 MV and an irradiated field size of 10 × 10 cm^2. PDD, percentage depth dose

RayStation OPF

Table 1 lists the OPFs measured and calculated with the Exradin W2 PSD, RayStation, and Monaco at photon beam energies of 4, 6, and 10 MV. The grid size was calculated at 1.0 mm. The measured values are the averages of five measurements. Fig. 4 plots the measured OPF of the Exradin W2 PSD at a typical photon beam energy of 6 MV versus the calculated OPFs of RayStation and Monaco. The RayStation OPF calculations are within 2.0% of the Exradin W2 PSD measurements used as references in this study under conditions of 4 MV energy for irradiated field sizes ranging from 10 × 10 to 0.5 × 0.5 cm^2. The maximum error for the irradiated field size in the range from 10 × 10 to 0.5 × 0.5 cm^2 was 1.9%. For energies of 6 MV, the comparison error between the Exradin W2 PSD measurements and RayStation calculations was within 2.0% for irradiated field sizes in the range from 10 × 10 to 0.5 × 0.5 cm^2. The maximum error for irradiation field sizes in the range from 10 × 10 to 0.5 × 0.5 cm^2 is 1.5%.

For a photon beam energy of 10 MV, the comparison error between the Exradin W2 PSD measurement and the RayStation calculation is within 2.0% for field sizes in the range from 10 × 10 to 0.5 × 0.5 cm^2. The maximum error for irradiation field sizes in the range from 10 × 10 to 0.5 × 0.5 cm^2 is 1.0%. Therefore, according to the practical definition, with an OPF uncertainty tolerance of 2.0%, the practical definition of an irradiation field in RayStation is a field size ≧ 0.5 × 0.5 cm^2, in agreement with the theoretical definition, at photon beam energies of 4, 6, and 10 MV.

We evaluated, calculated and measured the OPF by changing the calculation grid size of RayStation. Therefore, we determined a practical irradiation field size when the grid size was varied from 1.0 to 3.0 mm and the OPF calculation results were set to an allowable error of 2.0%.

Table 2 presents a comparison of the OPF measured by the Exradin W2 PSD with the OPF calculated using the RayStation by grid size at photon beam energies of 4, 6, and 10 MV in terms of pass rates. Fig. 5 shows a comparison of OPF measured by the Exradin W2 PSD with the OPF calculated using the RayStation by grid size at a typical photon beam energy of 6 MV. At a photon beam energy of 4 MV, practical field sizes within 2.0% error are obtained with a field area ≧ 0.5 × 0.5 cm^2 for a grid size of 1.0 mm and a field area ≧ 1.5×1.5 cm^2 for a grid size of 2.0 mm. The irradiation field was ≧ 2.0 × 2.0 cm^2.

At a photon beam energy of 6 MV, practical field sizes within 2.0% error are ≧ 0.5 × 0.5 cm^2, ≧ 0.5 × 0.5 cm^2, and ≧ 1.5 × 1.5 cm^2 for grid sizes of 1.0, 2.0, and 3.0 mm, respectively. At a photon beam energy of 10 MV, practical field sizes within 2.0% error are ≧ 0.5 × 0.5 cm^2, ≧ 0.7 × 0.7 cm^2, and ≧ 1.5 × 1.5 cm^2 for grid sizes of 1.0, 2.0, and 3.0 mm, respectively.

Monaco OPF

Table 1 lists the comparative error between the Exradin W2 PSD and Monaco OPF values. The error is 2.0% for the irradiation field size range from 10 × 10 to 1.5 × 1.5 cm^2 at a photon beam energy of 4 MV. The maximum error for the measured irradiation field range from 10 × 10 to 0.5 × 0.5 cm^2 is 22.3%. At a photon beam energy 6 MV, the comparison error between the Exradin W2 PSD measurement and Monaco calculation is within 2.0% at irradiation field sizes from 10 × 10 to 1.5 × 1.5 cm^2. The maximum error for irradiation field sizes from 10 × 10 to 0.5 × 0.5 cm^2 is 26.5%. At a photon beam energy of 10 MV, the comparison error between the Exradin W2 PSD measurement and Monaco calculation is within 2.0% for irradiation field sizes from 10 × 10 to 1.5 × 1.5 cm^2. The maximum error is 42.0% for irradiation field sizes from 10 × 10 to 0.5 × 0.5 cm^2. Therefore, according to the practical definition, with an OPF uncertainty tolerance of 2.0%, the practical irradiation field size for Monaco is ≧ 1.5 × 1.5 cm^2 at photon beam energies of 4, 6, and 10 MV.

The Monaco dose calculation uses a Monte Carlo algorithm, and due to its characteristics, the choice of grid size has a greater impact on the dose calculation time than other calculation algorithms. Therefore, knowing the practical irradiation field size by selecting the grid size is clinically meaningful. We obtained the practical irradiation field size by varying the grid size from 1.0 to 3.0 mm and assuming an allowable error of 2.0% in the OPF calculation results. The calculation uncertainty was set at 0.1%.

Table 3 shows a comparison of the OPF measured by the Exradin W2 PSD with the OPF calculated by the Monaco by grid size at photon beam energies of 4, 6, and 10 MV in terms of pass rates. Fig. 6 presents a comparison of the OPF measured by the Exradin W2 PSD with the OPF calculated by the Monaco by grid size at a typical photon beam energy of 6 MV. At a photon beam energy of 4 MV, practical field sizes within 2.0% error are $\geqq$ 1.5 × 1.5 cm^2, $\geqq$ 1.5 × 1.5 cm^2, and $\geqq$ 1.5 × 1.5 cm^2 for grid sizes of 1.0, 2.0, and 3.0 mm, respectively. At a photon beam energy of 6 MV, practical field sizes within 2.0% error are $\geqq$ 1.5 × 1.5 cm^2, $\geqq$ 1.5 × 1.5 cm^2, and $\geqq$ 1.5 × 1.5 cm^2 for grid sizes of 1.0, 2.0, and 3.0 mm, respectively. At a photon beam energy of 10 MV, practical field sizes within 2.0% error are $\geqq$ 1.5 × 1.5 cm^2, $\geqq$ 2.0 × 2.0 cm^2, and $\geqq$ 2.0 × 2.0 cm^2 for 1.0, 2.0, and 3.0 mm, respectively.

Table 1 Pass rate comparison between measured and calculated OPFs for each photon beam energy

Field size (cm^2)	Photon beam energy														
	4 MV					6 MV					10 MV				
	OPF			Pass rate (%) for PSD		OPF			Pass rate (%) for PSD		OPF			Pass rate (%) for PSD	
	PSD	RayStation	Monaco	RayStation	Monaco	PSD	RayStation	Monaco	RayStation	Monaco	PSD	RayStation	Monaco	RayStation	Monaco
0.5	0.47	0.47	0.37	−0.2	22.3	0.47	0.47	0.34	−1.2	26.5	0.42	0.42	0.25	1.0	42.0
0.6	0.56	0.55	0.45	1.9	19.6	0.55	0.55	0.43	1.0	22.0	0.48	0.48	0.32	−0.7	33.6
0.7	0.61	0.61	0.53	−0.2	12.3	0.60	0.60	0.50	−1.3	15.8	0.54	0.54	0.39	−0.4	27.8
0.8	0.66	0.65	0.59	1.5	10.4	0.64	0.65	0.56	−0.4	12.7	0.58	0.58	0.45	0.0	22.3
0.9	0.68	0.68	0.64	0.4	6.4	0.67	0.68	0.62	−1.5	7.2	0.61	0.61	0.50	−1.0	17.2
1.0	0.71	0.70	0.68	1.0	4.5	0.70	0.70	0.66	−0.3	5.9	0.64	0.64	0.56	−0.9	12.5
1.5	0.76	0.75	0.76	1.1	0.7	0.77	0.77	0.76	0.6	1.0	0.74	0.74	0.73	0.2	2.0
2.0	0.78	0.78	0.79	1.5	−0.5	0.80	0.79	0.79	1.3	1.2	0.80	0.79	0.79	0.8	1.3
3.0	0.82	0.82	0.82	0.9	0.4	0.84	0.84	0.84	0.6	0.9	0.86	0.86	0.86	0.2	0.1

4.0	0.86	0.85	0.86	1.0	−0.2	0.87	0.87	0.86	0.5	1.0	0.89	0.89	0.89	0.2	−0.1
5.0	0.89	0.88	0.89	0.9	0.3	0.90	0.89	0.89	0.8	1.4	0.92	0.91	0.92	0.3	0.2
6.0	0.92	0.91	0.92	0.8	0.2	0.93	0.92	0.92	0.8	1.3	0.94	0.94	0.93	0.2	0.4
7.0	0.94	0.94	0.94	0.6	0.6	0.95	0.94	0.94	0.5	1.0	0.96	0.96	0.95	0.1	0.5
8.0	0.96	0.96	0.97	0.4	−0.3	0.97	0.97	0.96	0.2	0.6	0.97	0.97	0.97	−0.1	0.7
9.0	0.98	0.98	0.99	0.2	−0.4	0.99	0.98	0.98	0.1	0.8	0.99	0.99	0.98	0.0	0.3
10.0	1.00	1.00	1.00	0.0	0.0	1.00	1.00	1.00	0.0	0.0	1.00	1.00	1.00	0.0	0.0

OPF, output factor; PSD, plastic scintillator detector.

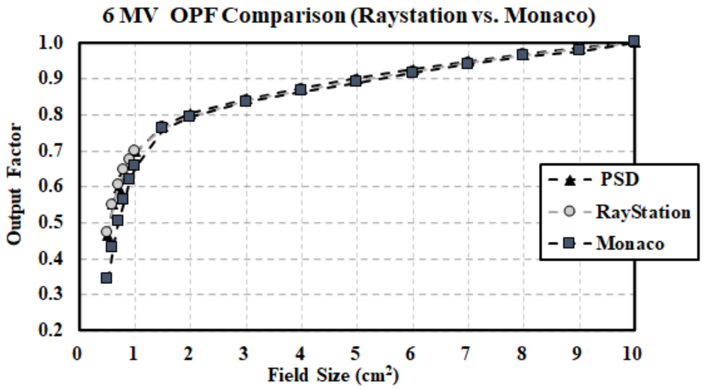

Fig. 4 Exradin W2 PSD measurements, RayStation calculations, and Monaco calculations at a photon beam energy of 6 MV. OPF, output factor; PSD, plastic scintillator detector

Table 2 Pass rates of RayStation calculation results in measured values

Field size (cm^2)	RayStation pass rate (%) Photon beam energy 4 MV Grid size 1.0 mm	4 MV Grid size 2.0 mm	4 MV Grid size 3.0 mm	6 MV Grid size 1.0 mm	6 MV Grid size 2.0 mm	6 MV Grid size 3.0 mm	10 MV Grid size 1.0 mm	10 MV Grid size 2.0 mm	10 MV Grid size 3.0 mm
0.5	−0.2	**7.1**	**24.3**	−1.2	**6.4**	**24.0**	1.0	**8.7**	**24.7**
0.6	1.9	**10.9**	**21.1**	1.0	**9.9**	**20.3**	−0.7	**6.4**	**17.1**
0.7	−0.2	**4.5**	**14.9**	−1.3	**3.2**	**13.7**	−0.4	**3.8**	**13.8**
0.8	1.5	**4.9**	**12.6**	−0.4	**2.8**	**10.5**	0.0	**3.0**	**10.5**
0.9	0.4	**2.8**	**8.4**	−1.5	0.8	**6.4**	−1.0	1.2	**6.7**
1.0	1.0	**2.7**	**6.6**	−0.3	1.4	**5.3**	−0.9	0.8	**4.8**
1.5	1.1	1.5	**2.1**	0.6	1.1	1.8	0.2	0.8	1.9
2.0	1.5	1.7	1.7	1.3	1.6	1.6	0.8	1.1	1.4
3.0	0.9	1.2	1.0	0.6	1.1	0.8	0.2	1.2	0.7
4.0	1.0	1.2	1.0	0.5	0.9	0.7	0.2	0.5	0.3
5.0	0.9	1.1	0.9	0.8	1.0	0.9	0.3	0.5	0.4
6.0	0.8	0.8	0.8	0.8	0.8	0.8	0.2	0.3	0.2
7.0	0.6	0.6	0.6	0.5	0.6	0.6	0.1	0.1	0.1
8.0	0.4	0.4	0.4	0.2	0.3	0.3	−0.1	0.0	−0.1
9.0	0.2	0.2	0.2	0.1	0.2	0.2	0.0	0.0	0.0
10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Pass rate ≧ 2.0% is indicated by boldface.

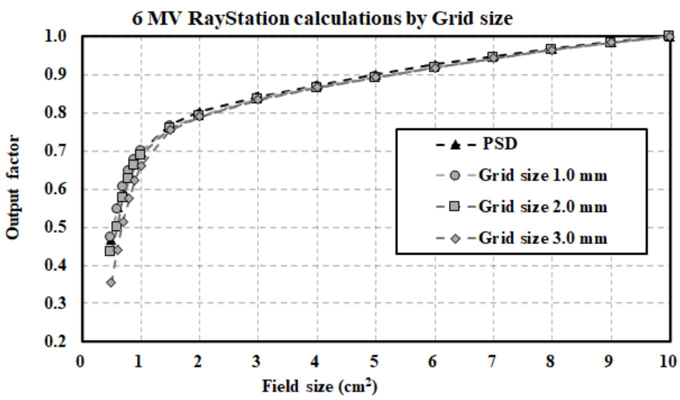

Fig. 5 Comparison between measured OPF of the Exradin W2 PSD and calculated OPF of RayStation by grid size at a photon beam energy of 6 MV. OPF, output factor; PSD, plastic scintillator detector

Table 3 Pass rates of Monaco calculation results in measured values

Field size (cm^2)	Monaco pass rate (%)								
	Photon beam energy								
	4 MV			6 MV			10 MV		
	Grid size 1.0 mm	Grid size 2.0 mm	Grid size 3.0 mm	Grid size 1.0 mm	Grid size 2.0 mm	Grid size 3.0 mm	Grid size 1.0 mm	Grid size 2.0 mm	Grid size 3.0 mm
0.5	**22.3**	**24.8**	**29.1**	**26.5**	**27.6**	**31.6**	**42.0**	**43.3**	**45.5**
0.6	**19.6**	**21.5**	**24.1**	**22.0**	**23.3**	**26.5**	**33.6**	**34.7**	**36.6**
0.7	**12.3**	**14.8**	**17.0**	**15.8**	**16.2**	**18.5**	**27.8**	**29.0**	**30.5**
0.8	**10.4**	**6.5**	**14.1**	**12.7**	**11.2**	**14.4**	**22.3**	**22.6**	**25.0**
0.9	**6.4**	**7.9**	**9.4**	**7.2**	**7.0**	**9.8**	**17.2**	**16.9**	**18.1**
1.0	**4.5**	**6.0**	**7.3**	**5.9**	**6.1**	**8.5**	**12.5**	**12.7**	**13.5**
1.5	0.7	0.0	0.6	1.0	–0.2	0.5	2.0	**2.6**	**3.0**
2.0	–0.5	–0.1	–0.1	1.2	–0.1	0.2	1.3	0.7	0.1
3.0	0.4	0.3	0.5	0.9	–0.8	0.2	0.1	0.4	–0.4
4.0	–0.2	0.5	0.4	1.0	–0.5	0.3	–0.1	0.7	–0.5
5.0	0.3	1.6	0.8	1.4	–0.2	0.4	0.2	0.2	–0.7
6.0	0.2	0.9	1.1	1.3	–0.2	0.4	0.4	0.0	0.1
7.0	0.6	0.3	0.6	1.0	–0.4	0.1	0.5	0.7	–0.1
8.0	–0.3	0.2	0.3	0.6	0.1	0.1	0.7	0.2	–0.4
9.0	–0.4	0.0	0.7	0.8	–0.1	0.0	0.3	0.3	–0.1
10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Pass rate ≧ 2.0% is indicated by boldface.

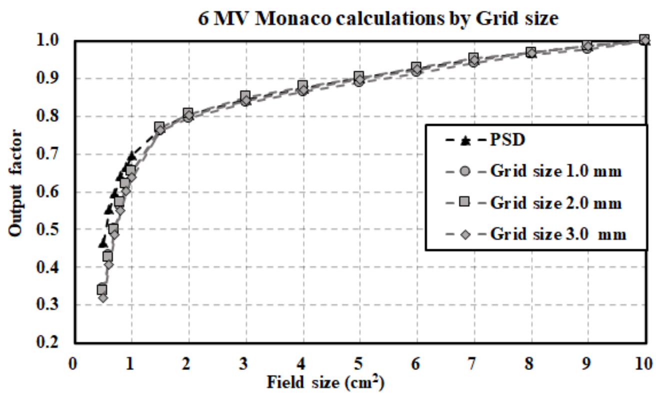

Fig. 6 Comparison between measured OPF of the Exradin W2 PSD and calculated OPF of Monaco by grid size at a photon beam energy of 6 MV. OPF, output factor; PSD, plastic scintillator detector

Discussion

In this study, using the Exradin W2 PSD, the dosimetry characteristics of the OPF of a TPS modeled with beam data including the OPF from 40 × 40 to 0.5 × 0.5 cm^2 using ionization chambers of diverse sizes were verified. Several researchers have reported that the Exradin W1 PSD, the predecessor of the plastic scintillator used for verification, can accurately evaluate the OPF and PDD in an energy-dependent manner (≤1.0%) [7, 9, 23, 27]. In other words, the Exradin W1 PSD has a correction factor of 1.0 for small irradiation fields in IAEA TRS-483 and can measure a wide range of irradiation field sizes with only one type of detector. In addition, because the Exradin W2 PSD is almost equivalent to water, it can be used for OPF measurement without disturbing the radiation field and without using correction factors other than the volume average effect [4, 28].

The Exradin W2 PSD is an upgraded version of the Exradin W1 PSD with additional scan measurement capabilities and improved temperature response. We demonstrated these findings in PDD measurements with a photon beam energy of 6 MV and field sizes of 10 × 10 cm^2 and 0.5 × 0.5 cm^2 by comparing them with results from ionization chamber dosimeters and chromodynamic films. The results demonstrate that the Exradin W2 PSD performs well as a 0.5 × 0.5 cm^2 OPF validation tool, which is the minimum irradiation field size that can be formed with TrueBeam from its reference irradiation field size (10 × 10 cm^2). It also demonstrated good long-term and short-term system stability.

The OPF calculation performance was evaluated using a RayStation with the Exradin W2 PSD. When the OPF calculation results were within the tolerance of 2.0%, the practical irradiation field size was ≧ 0.5 × 0.5 cm at photon beam energies of 4, 6, and 10 MV. Although the OPF values below 2.0 × 2.0 cm^2 were simulated, the calculated values were in good agreement in RayStation. This situation was the case for the photon beam data used for beam modeling, with field sizes ranging from 40 × 40 to 2.0 × 2.0 cm^2, obtained using three unusual types of ionization chambers. The OPF correction factor of IAEA TRS-483 for small irradiation fields was not applied.

The results of this study suggest that the practical field size may be modified by the range of photon beam data measurements, method, and type and combination of data acquisition detectors. The results reported by Charles et al. [21] indicate that careful experimental methods and precise alignment of detector installations are required. The Exradin W2 PSD has a simple measurement procedure and can cover a range of large to small irradiation fields. The Exradin W2 PSD is considered suitable for evaluating TPS OPF calculations.

In a TPS, the computational grid size is an important factor influencing the dose calculation results, and the smaller the computational grid size, the smaller the effect of the volume-averaging effect; therefore, the results are improved [25, 26, 29]. For example, an irradiation field of 0.5 × 0.5 cm^2 with a computational grid size of 2.0 mm occupies a larger part of the irradiation field than a computational grid size of 1.0 mm. Moreover, when the computational grid size is 3.0 mm, the effect becomes exceptionally large (Fig. 7). However, a disadvantage exists in that the dose calculation time increases proportionately as the computational grid size becomes smaller. Therefore, in clinical practice, we believe that the computational grid size should be as small as possible within an acceptable time. Consequently, regarding the OPF calculated by changing the calculation grid size from 1.0 mm to 2.0 mm or 3.0 mm, the practical irradiation field size under the condition of a tolerance of 2.0% or less is $\geqq 1.5 \times 1.5$ cm^2 for 4 MV, $\geqq 0.9 \times 0.9$ cm^2 for 6 MV, and 0.9×0.9 cm^2 for 10 MV. When the grid size is 3.0 mm, the field size is $\geqq 2.0 \times 2.0$, $\geqq 1.5 \times 1.5$, and $\geqq 1.5 \times 1.5$ cm^2 at photon beam energies of 4, 6, and 10 MV, respectively. In this study, we demonstrated the practical irradiation field size when the grid size was changed from 1.0 to 3.0 mm. Use of this item as a factor in treatment planning with the RayStation is clinically significant.

The performance of the OPF calculation by Monaco was evaluated using the Exradin W2 PSD, demonstrating that the practical small irradiation field when the OPF calculation results are within a tolerance of 2.0% is $\geqq 1.5 \times 1.5$ cm, in line with the theoretical definition for photon beam energies from 4 to 10 MV. The field sizes of the photon beam data used for beam modeling ranged from 40×40 to 2.0×2.0 cm^2 formed with the same TrueBeam as the RayStation. The statistical uncertainty in the calculations was 0.1%, and the average dose to volume was used to calculate the OPF. The dose calculated by Monaco by X-ray voxel Monte Carlo simulation may vary depending on the location and volume of the ROI at the measurement point. Therefore, in this study, the conditions of the measurement point were determined based on discussions with the manufacturer.

As Monaco uses Monte Carlo to calculate doses, the effect of increased calculation time due to grid size is larger than those of other dose calculation algorithms such as CCC and superposition. Therefore, understanding the practical irradiation field in OPF by grid size is clinically significant. The results show that the practical irradiation field for OPF calculated by changing the grid size from 1.0 mm to 2.0 mm or 3.0 mm with a tolerance of 2.0% or less is $\geqq 1.5 \times 1.5$ cm^2 at a photon beam energy of 4 MV when the grid size is 2.0 mm. At 10 MV, the field size is $\geqq 2.0 \times 2.0$ cm^2. At a grid size of 3.0 mm, the appropriate field size is $\geqq 1.5 \times 1.5$, $\geqq 1.5 \times 1.5$, and $\geqq 2.0 \times 2.0$ cm^2 at photon beam energies of 4, 6, and 10 MV, respectively. In this study, the practical irradiation field size was demonstrated when the grid size was varied from 1.0 to 3.0 mm. From the results, we believe that Monaco experiences a small effect of grid size on the error of the OPF calculations in the Exradin W2 PSD when the tolerance is 2.0%. This finding suggests that the use of Monaco in treatment planning is clinically meaningful.

The OPFs calculated using two different TPSs modeled with the same beam data were validated by comparing them with the OPF measured by the Exradin W2 PSD. The results demonstrate that even TPSs modeled with the same beam data have different limits of practical irradiation fields based on the calculation results (Table 1). Performance of a TPS cannot be compared only in terms of the accuracy of OPF calculation, because many factors such as inhomogeneity correction affect the dose calculation in clinical treatment planning. Nonetheless, when focusing only on the calculated OPF value, there was a clear difference between RayStation and Monaco in terms of practical field size limits for clinical use. In this regard, Simon K. Goodall [30] et al. found that the Monte Carlo calculated distribution contains statistical noise, which reduces the dependence on single voxel dose. They report that while the average dose to a small target volume minimizes the effect of noise, significant volume averaging occurs in small fields [30]. Therefore, recommend that the optimal spherical volume of interest of the detector be installed and evaluated. By implementing the above methodology, the agreement between measurements and Monaco dose calculations can be significantly increased. In Monaco, the effect of the grid size on the dose calculation was smaller than that of RayStation. This characteristic can be attributed to the smaller evaluation ROI size in Monaco. Fig. 7 shows the radiation fluence and volume effects for each grid size. We believe that the effect will change when the size of the evaluation ROI is varied.

We believe that this study will be useful for future verification of equipment accuracy for treatment planning that requires highly accurate dose calculations and for third-party evaluation of OPF calculations for TPS. However, further research is needed for Monaco to establish the appropriate volume of interest for the Exradin W2 PSD in the measurement of small irradiated fields and differences when using detectors other than PSDs.

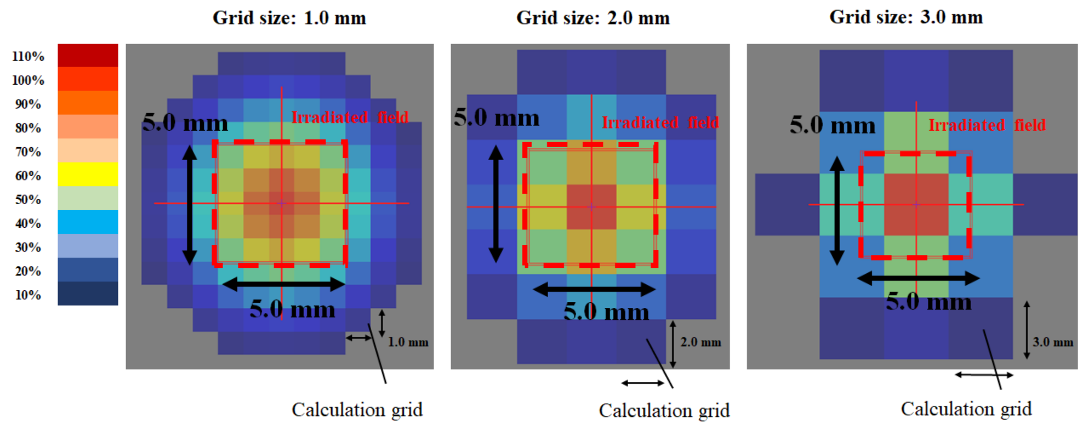

Fig. 7 Radiation fluence and volume effect for each calculated grid size (shown in Monaco calculations)

Conclusion

This study demonstrated the effectiveness of the Exradin W2 PSD in validating the OPF of a TPS. The range of practical irradiation field sizes for OPF calculations differed even for TPSs modeled with the same photon beam data. We believe that characterizing the TPS at the OPF for each irradiation field size using the Exradin W2 PSD and controlling the accuracy are clinically important.

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