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Validation of secondary dose calculation system with manufacturer-provided reference beam data using heterogeneous phantoms

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Abstract

The Mobius3D (M3D) system (Mobius Medical Systems) is a second-check dosimetry system. We investigated the dose calculation accuracy of this system using heterogeneous phantoms with reference beam data provided by the manufacturer using simple and patient plans. We compared the dose distributions between M3D and the treatment planning system, as well as the measurements in solid water phantoms, heterogeneous phantoms, and patient plans for Varian and Elekta accelerators. The M3D results agreed well with the measurements in the solid water phantoms for the simple plans. However, the accuracy of M3D appeared to depend on the type of accelerator, as indicated by the slight differences in the dose measurements. Furthermore, the M3D dose measurements differed by 5–10% in the lung and bone regions. Regarding the patient plans, we confirmed that M3D is reasonably accurate as a second-check system, despite the slight accelerator type-dependent dose difference.

Keywords Quality assurance · Volumetric modulated arc therapy · Dose verification · Second-check dosimetry system · Reference beam data

1 Introduction

Independent verification of both the monitor units and the dose distributions delivered to a patient using a linear accelerator (Linac) has long been a fundamental component of quality assurance in the field of radiation oncology [1]. Such verification relies on secondary independent calculations that can be performed either manually or using commercial software. They are typically based on measured or reference beam data provided by an accelerator manufacturer and generated using a water phantom. The use of manufacturer-provided reference beam data is advantageous from a third party perspective, as well as from the perspective of time efficiency. However, the calculation accuracies of these verification systems and the reference beam data must be confirmed.

The Mobius3D (M3D) system (Mobius Medical Systems, Houston, TX, USA) is a second-check dosimetry system that performs a full dose recalculation from the computed tomography (CT) dataset of the patient, using treatment parameters exported from the primary treatment planning system (TPS). Similar to other commercial TPSs, M3D is equipped with a convolution–superposition algorithm for dose calculation [2]. In addition, M3D is equipped with a reference beam data for each Linac system. Therefore, it is not necessary for users to acquire the beam data. The accuracy of both the reference beam data and the dose calculations is important for a dose verification system. Previously, Nelson et al. [3] used open fields and patient plans to evaluate the fundamental accuracies of manufacturer-provided reference beam data. However, this analysis was limited to photon beams produced by Varian accelerators. Moreover, no previous analysis has involved multiple accelerator vendors, complex plan types, or heterogeneous materials. Although some authors [4, 5] have reported the evaluation and clinical implementation of the M3D system, no study has considered the dose calculation accuracy of this system using heterogeneous phantoms.

The present study investigated the dose calculation accuracy of the M3D system using simple and patient plans for volumetric modulated arc therapy (VMAT), including the doses of heterogeneous materials. These M3D-calculated

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dose distributions were then compared with the distributions obtained via ionization chamber measurements and the TPS.

Fig. 2 Comparison of the dose distributions calculated using the M3D system, the TPS, and the ionization chamber measurements in a solid water phantom, obtained using the Clinac iX 6-MV, Clinac iX 15-MV, synergy 6-MV, and Synergy 10-MV accelerator/beam energy configurations

2 Materials and methods

We used a Synergy® (Elekta, Stockholm, Sweden) Linac with Agility multileaf collimator (MLC) for 6- and 10-MV photon beams and a Clinac iX (Varian Medical Systems, Palo Alto, CA, USA) Linac with Millennium 120 MLC for 6- and 15-MV photon beams. The TPS dose calculations were performed using Pinnacle[3] ver. 9.10 (Philips Radiation Oncology Systems, Madison, WI, USA), which is equipped with a superposition calculation algorithm. For both the Pinnacle[3] and M3D systems, a calculation grid size of 2.0 mm × 2.0 mm × 2.0 mm was used for all the plans. Right Speed RT (GE Healthcare, Chicago, USA) with a 2.5 mm slice thickness was used to obtain the planning CT. The beam data and CT-ED table for each Linac system were already installed in the M3D. We only performed the adjustment of dosimetric leaf gap and, input it (the values for Clinac iX and Synergy were 0.5 mm and 0.7 mm, respectively).

2.1 Phantom plans

The dose calculation accuracy of the M3D system in the phantoms was evaluated by comparing the dose calculations for simple plans with ionization chamber measurements and TPS-calculated doses. Figure 1a–c shows three types of solid water and heterogeneous phantoms, which had overall phantom sizes of 300 mm × 300 mm × 200 mm and 300 mm × 300 mm × 250 mm, respectively. The heterogeneous lung model is comprised of five layers, corresponding to solid water (thickness 50 mm), lung (60 mm), solid water (30 mm), lung (60 mm), and solid water (50 mm) regions (Fig. 1b). The bone model comprised four layers, corresponding to solid water (50 mm), lung (50 mm), bone (50 mm), and solid water (100 mm) regions (Fig. 1c). For the TPS, we calculated the dose distributions for a virtual phantom. For measurement, we used the solid water phantom RMI-457 (relative electron density 1.018), the lung phantom LN-300 RMI-455 (relative electron density 0.293), and the bone phantom Bone SB3 RMI-450 (relative electron density: 1.696) (GAMMEX, Biebertal, Germany).

For the solid water phantom, all the photon beams were used to irradiate the open field sizes of 10×10–300×300 mm^2 at a source-to-surface distance of 900 mm. The isocenter (I.C.) was located at a depth of 100 mm in the solid water phantom (see Fig. 1a). We also planned parallel–opposed beams in two- (AP–PA direction) and four-beam (AP–PA, R–L direction) configurations with a 50×50 mm^2 field for the solid water phantom. For the heterogeneous phantom, we irradiated open field sizes of 30×30, 50×50, and 100×100 mm^2 at a source-to-surface distance of 1000 mm. For each phantom, all the dose profiles were acquired along the white arrows depicted in Fig. 1. A cylindrical ionization chamber (PTW31002, 0.125 cc; PTW, Freiburg, Germany) was used to obtain point-dose measurements in the phantoms. For this, the phantoms were inserted into the built-in cavities of PTW 31002. The distance between the measurement points was 10 mm. For heterogeneous measurements, the absorbed dose to heterogeneous media D_{inhomo} can be represented by the following equation:

$$D_{\text{inhomo}} = N_{\text{D, w}}^{60\text{Co}} \times M_{\text{inhomo}} \times \frac{D_{\text{inhomo}}^{\text{MC}}}{D_{\text{water}}^{\text{MC}}}. \quad (1)$$

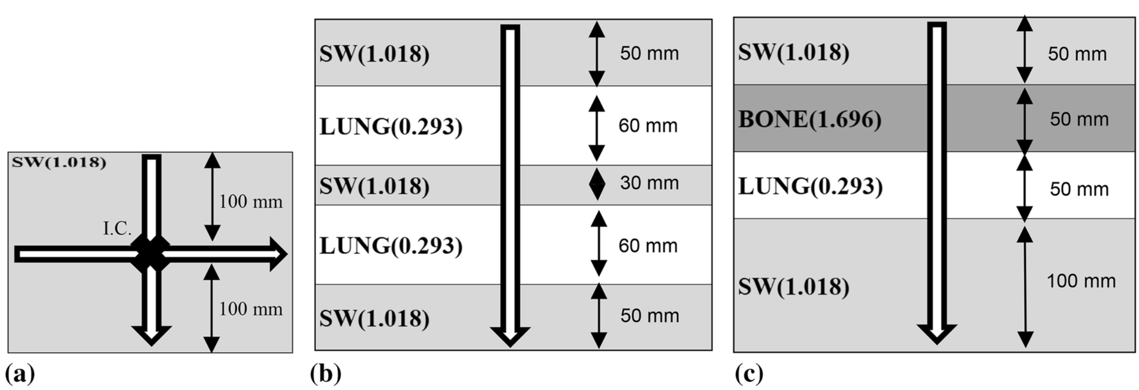
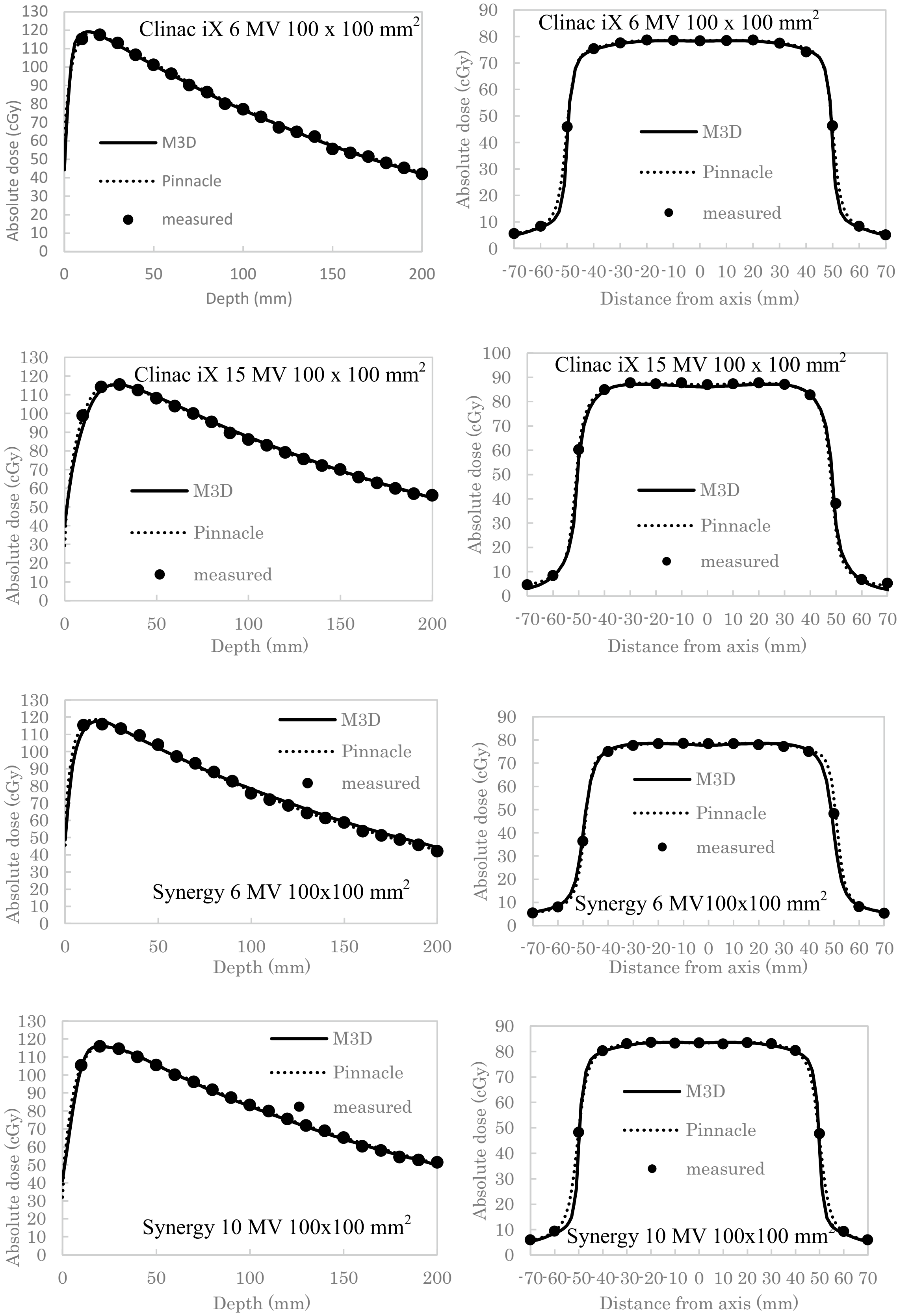


Fig. 1 Schematics of the three types of phantoms used in this study (the dimensions of the schema are not to scale): **a** solid water (SW), **b** lung model (LUNG), and **c** bone model (BONE). Dose profiles were acquired along the beam axis and the horizontal plane at I.C. depth (white arrows). The values in parentheses indicate the relative electron densities



Clinac iX 6 MV 100 x 100 mm²
M3D
Pinnacle
measured
Absolute dose (cGy)
Depth (mm)
Clinac iX 6 MV 100 x 100 mm²
M3D
Pinnacle
measured
Absolute dose (cGy)
Distance from axis (mm)
Clinac iX 15 MV 100 x 100 mm²
M3D
Pinnacle
measured
Absolute dose (cGy)
Depth (mm)
Clinac iX 15 MV 100 x 100 mm²
M3D
Pinnacle
measured
Absolute dose (cGy)
Distance from axis (mm)
M3D
Pinnacle
measured
Synergy 6 MV 100x100 mm²
Absolute dose (cGy)
Depth (mm)
M3D
Pinnacle
measured
Synergy 6 MV100x100 mm²
Absolute dose (cGy)
Distance from axis (mm)
M3D
Pinnacle
measured
Synergy 10 MV 100x100 mm²
Absolute dose (cGy)
Depth (mm)
M3D
Pinnacle
measured
Synergy 10 MV 100x100 mm²
Absolute dose (cGy)
Distance from axis (mm)

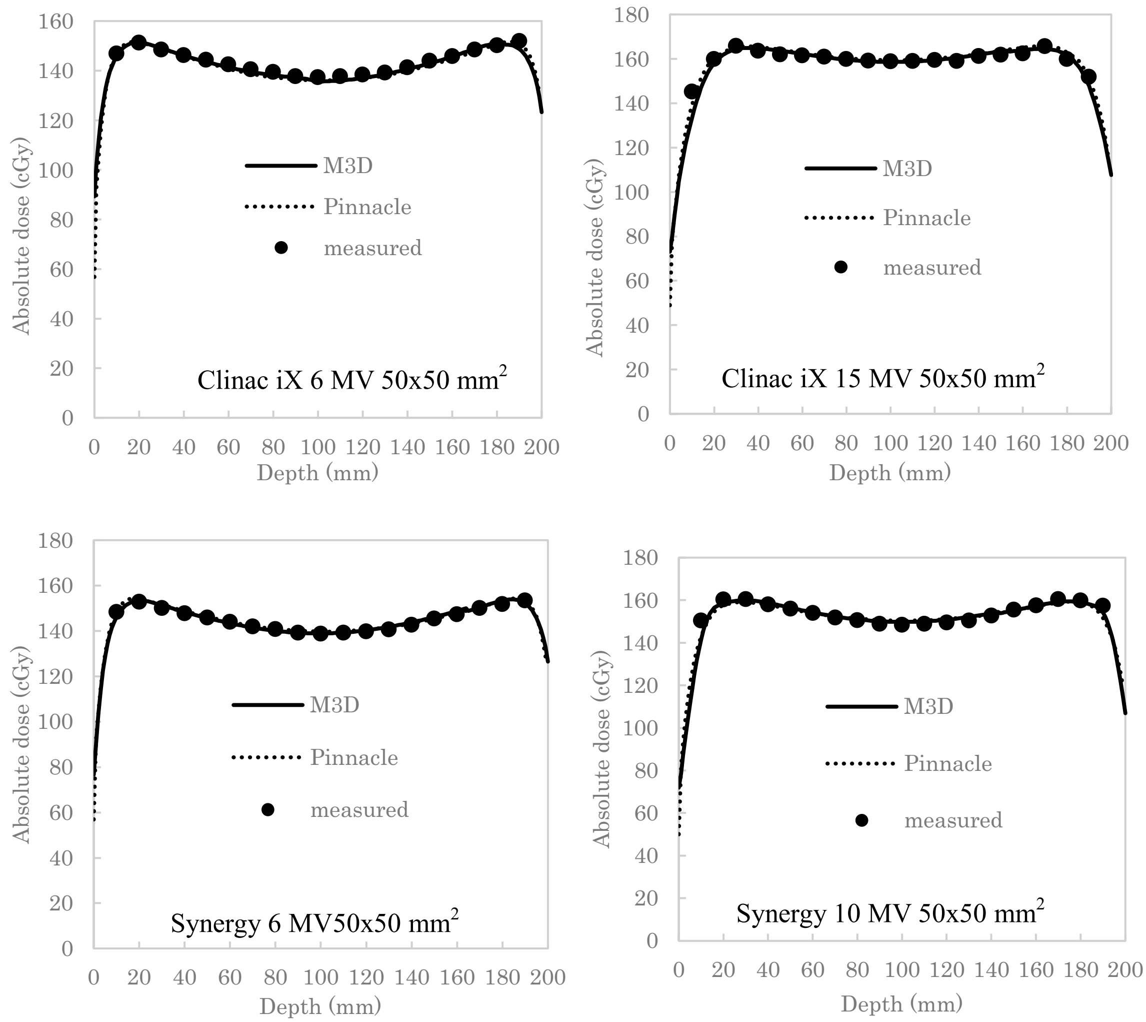


Fig. 3 Comparison of the two-beam parallel–opposed plan dose distributions in a solid water phantom, calculated using the M3D system, TPS, and measured doses from the ionization chamber. Accelerator/beam energy configurations of Clinac iX 6-MV, Clinac iX 15-MV, Synergy 6-MV, and Synergy 10-MV were used

Here, *M* is the measured ionization and the suffixes inhomo, w, and MC represent the heterogeneous media, water, and Monte Carlo calculation, respectively [6]. Finally, we compared the dose profiles between the M3D system, TPS, and ionization chamber measurements as a reference for each phantom. The dose differences were normalized by measuring the beam axis.

2.2 Patient plans

The accuracy of the M3D was also evaluated by comparing the dose calculations obtained using this system and the clinical VMAT plans with actual patient data calculated by the TPS. This portion of the study utilized clinical VMAT treatment planning data from 12 plans corresponding to the brain, neck, whole neck, esophagus, prostate, and pelvis for every two plans. All the patients were treated with a 6-MV beam regardless of the accelerator system. For evaluation, we performed a three-dimensional (3D) gamma analysis for the body structure. The criteria for this analysis were the dose differences of 5%/3 mm, 3%/3 mm, and 2%/2 mm (5%, 3%, and 2% of the prescribed dose, respectively) and the distance-to-agreement (in mm); the threshold was 10% of the prescribed dose. All the dose differences that were used were normalized with the dose of the beam axis.

All the plans were previously evaluated using an ArcCHECK diode array detector, version 2.2 (Sun Nuclear, Melbourne, FL, USA), and they satisfied our hospital criteria (gamma passing rates: > 95%, 3%/1-mm). The center of ArcCHECK was set to the Linac isocenter and was irradiated by the composite beams for each plan. The absolute dose of ArCHECK was calibrated according to the vendor recommendations before irradiation. We carried out the

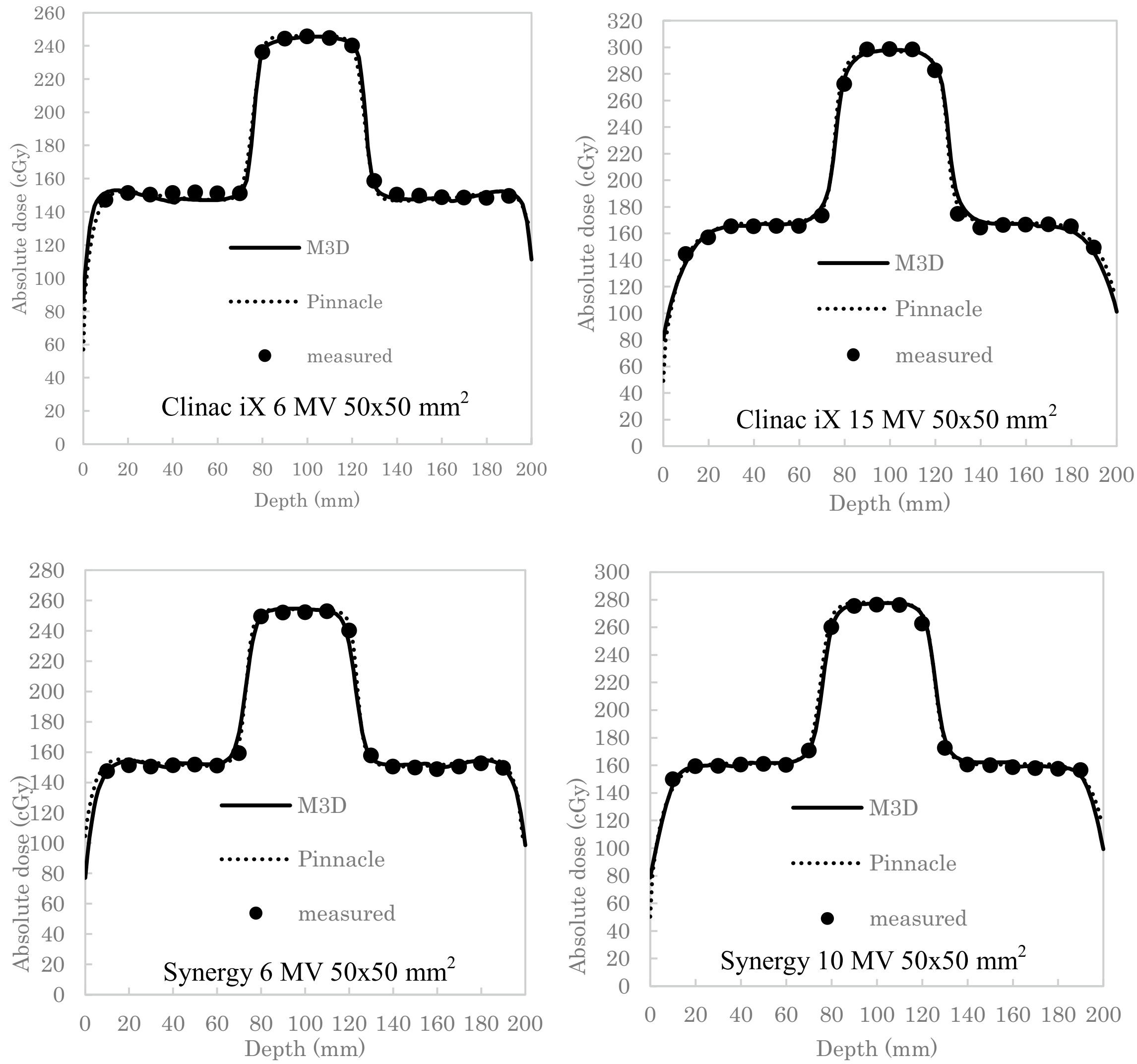


Fig. 4 Comparison of the four-beam plan dose distributions in a solid water phantom, calculated using the M3D system, TPS, and measured doses from the ionization chamber. Accelerator/beam energy configurations of Clinac iX 6-MV, Clinac iX 15-MV, Synergy 6-MV, and Synergy 10-MV were used

verification to compare the gamma evaluation between a popular approach and the M3D.

3 Results

3.1 Phantom plans

Figure 2 compares the dose profiles of 100×100 mm^2 fields of the Clinac iX 6-MV, Clinac iX 15-MV, Synergy 6-MV, and Synergy 10-MV Linac/beam energy configurations. The average differences between the M3D system calculations and the ionization chamber measurements were within 1% for each beam energy. In addition, Pinnacle TPS showed a good agreement with the measurement within 1%. The maximum difference in the dose measurements—4%—occurred at the penumbra of the radiation field with the Synergy 6-MV beam. Considering the measurement uncertainty, we used a 100×100 mm^2 field, which yielded typical results for all fields. The differences between the measurements obtained using the ionization chamber and those calculated with the M3D system were larger in the penumbra and build-up regions of the field than in other areas. Apparently, the differences between the reference beam data provided by the manufacturer and the ionization chamber measured doses were larger when the Synergy accelerator was used, compared with that when Clinac iX was used.

Figures 3 and 4 present the depth dose profiles in the AP–PA direction for the 50×50 mm^2 field and parallel–opposed two- and four-beam plan configurations at a

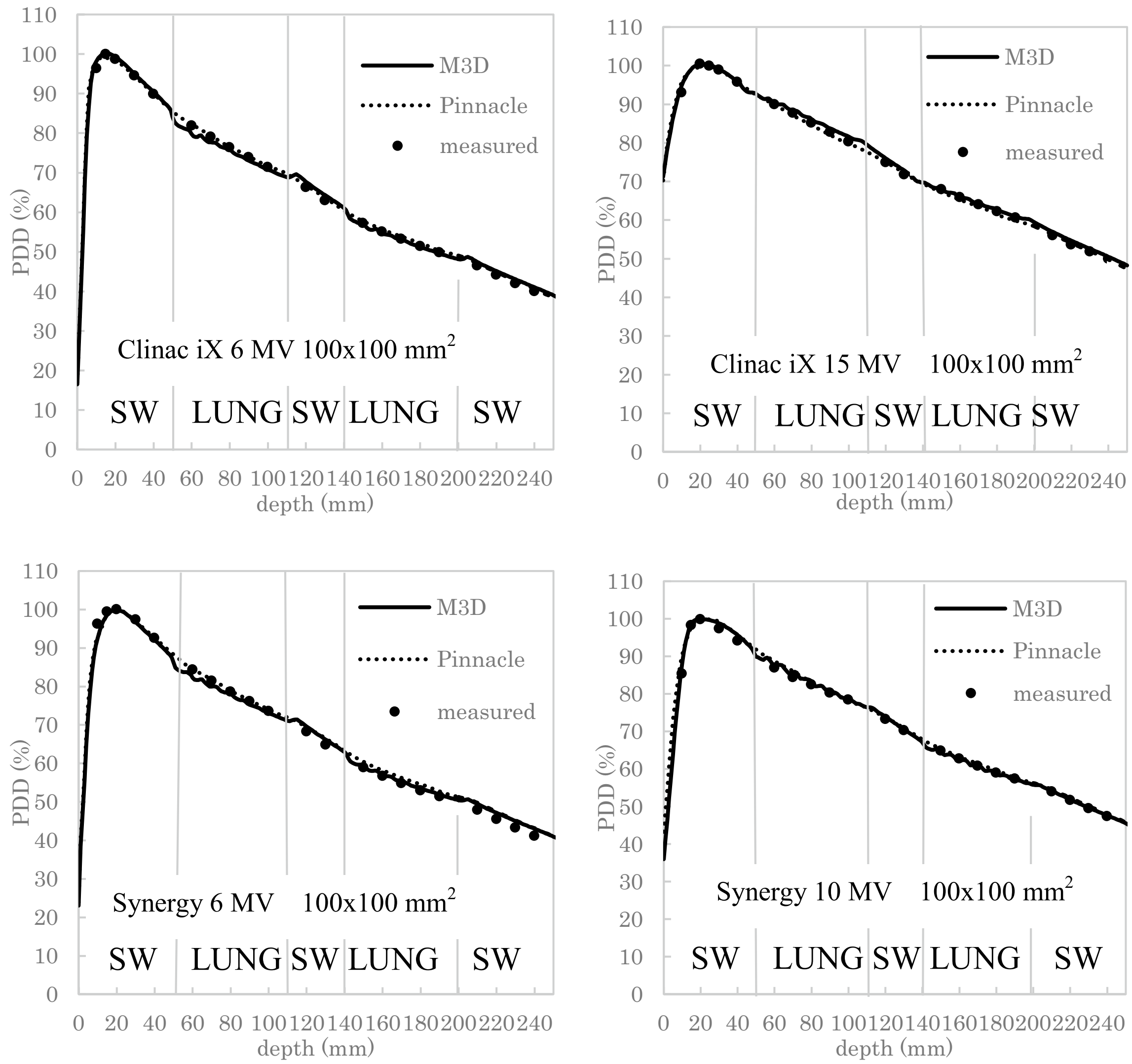


Fig. 5 PDD curves of a lung model phantom measured using an ionization chamber, calculated using both the M3D system and the TPS. Accelerator/beam energy configurations of Clinac iX 6-MV, Clinac iX 15-MV, Synergy 6-MV, and Synergy 10-MV were used

depth of 100 mm, obtained using the M3D system, the TPS, and ionization chamber measurements. The M3D-calculated and TPS dose profiles agreed with the ionization chamber measurements within a variance of 4% for all accelerator types, beam energies, and configurations. However, in the build-up and build-down regions of the fields, there was an increase in the differences between the M3D and ionization chamber measurements, especially when the Synergy accelerator was used.

Figures 5 and 6 compare the percentage depth dose (PDD) curves for the lung and bone models obtained with the following accelerator/beam energy configurations: Clinac iX 6-MV, Clinac iX 15-MV, Synergy 6-MV, and Synergy 10-MV. Except for the build-up and build-down, lung, and bone regions, the M3D-calculated and TPS dose profiles agreed with the ionization chamber measurements within 3%. At all beam energies, the dose differences between the M3D calculations and the ionization chamber measurements were greater in the lung and bone regions than in the solid water phantom. In particular, the difference between the M3D calculations and the ionization chamber measurements was larger in the boundary regions of the lung and bone models, relative to water. The maximum dose differences between the M3D calculations and ionization chamber measurements were 7% and 10% for the lung and bone models, respectively. For both types of accelerators, a lower beam energy yielded larger differences in the doses to the lung and bone regions. In addition, the dose distributions calculated using the M3D system in the lung and bone regions exhibited considerable increases and decreases.

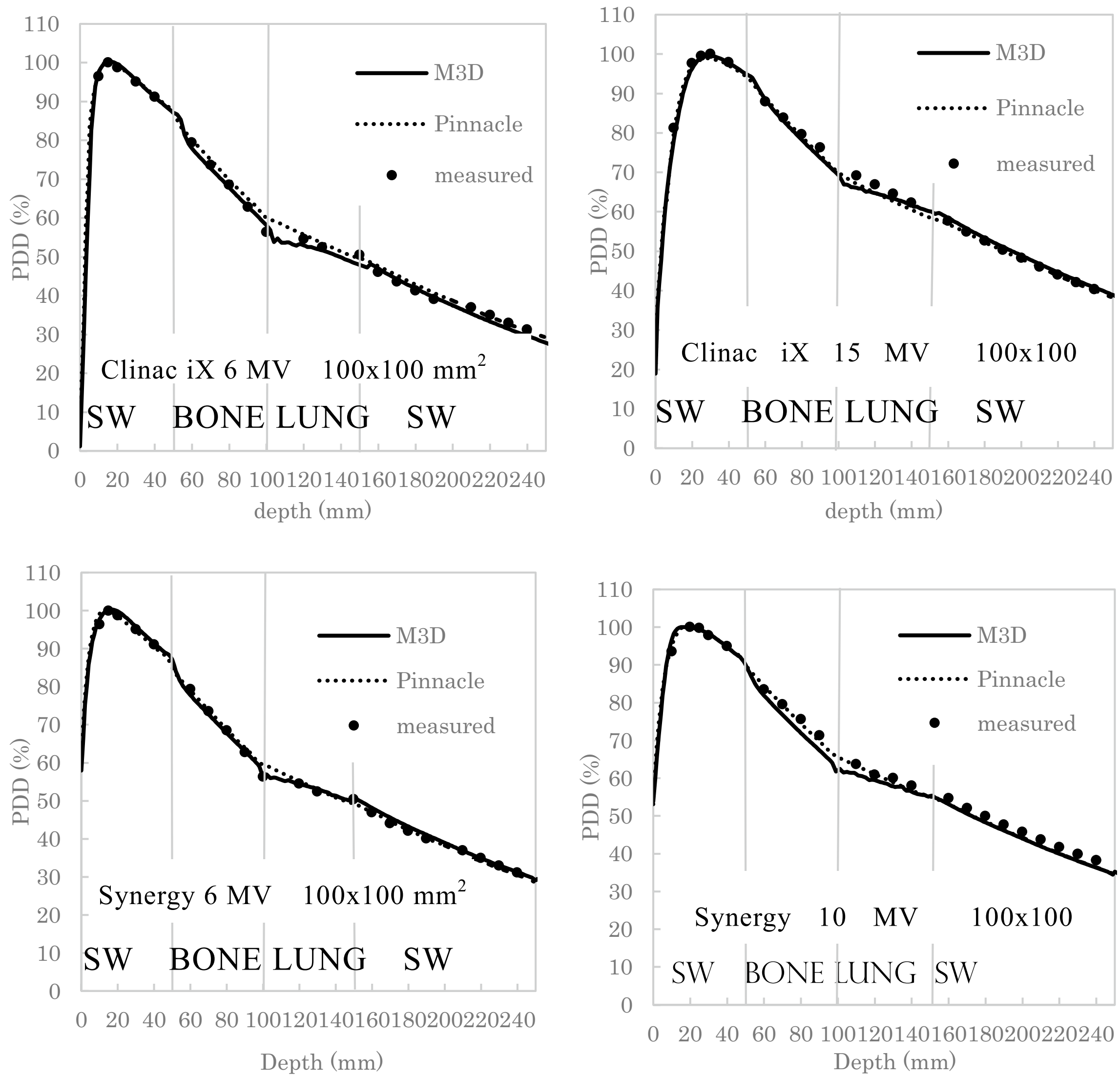


Fig. 6 PDD curves of a bone model phantom measured using an ionization chamber, calculated using both the M3D system and the TPS. Accelerator/beam energy configurations of Clinac iX 6-MV, Clinac iX 15-MV, Synergy 6-MV, and Synergy 10-MV were used

3.2 Patient plans

We evaluated the treatment plans devised for the same patients using two Linac systems and verified the doses using the ArcCHECK system. Table 1 lists the percentages of the M3D- and ArcCHECK-calculated dose points for patient cases with gamma values of <1 (i.e., γ of 5%/3-mm <1), relative to the TPS. Here, the 5%/3-mm criterion yielded a perfect gamma passing rate. However, we observed differences when the 2%/2-mm criterion was applied. As in the phantom study, data obtained using the Synergy accelerator exhibited a lower gamma passing rate.

Figure 7 presents the TPS and M3D dose distributions for the case where the whole neck was treated using the Synergy 6-MV beam. This case had the poorest gamma passing rate. The central regions of both the horizontal and vertical dose profiles, which comprised an air duct, exhibited large differences from the TPS-calculated doses. As in the phantom study, the dose calculations of the M3D system were uncertain in the anatomical regions with low densities.

4 Discussion

We investigated the fundamental accuracy of 3D dose distributions calculated from the reference beam data using the M3D system. Thus, we confirmed that this system can provide a reasonable level of accuracy for a second dosimetric check. However, our results indicate that the M3D system

Table 1 Percentage of dose points calculated by the TPS with gamma (γ) values < 1 relative to doses calculated using the M3D system for VMAT plans of the brain, neck, whole neck, esophagus, prostate, and pelvis

Site	Accelerator	%points $\gamma < 1$		
		5%/3 mm	3%/3 mm	2%/2 mm
Brain	Clinac iX			
	M3D	100	100	99.2
	ArcCHECK	100	99.9	99.1
	Synergy			
	M3D	100	100	99.7
	ArcCHECK	100	100	99.2
Neck	Clinac iX			
	M3D	100	99.9	98.4
	ArcCHECK	100	100	97.2
	Synergy			
	M3D	100	99.9	95.3
	ArcCHECK	100	99.9	98.1
Whole neck	Clinac iX			
	M3D	100	99.9	97.7
	ArcCHECK	100	99.9	96.4
	Synergy			
	M3D	100	99.8	96.8
	ArcCHECK	100	99.9	96.9
Esophagus	Clinac iX			
	M3D	100	100	99.4
	ArcCHECK	99.9	98.1	99.1
	Synergy			
	M3D	100	100	96.2
	ArcCHECK	100	99.2	99.1
Prostate	Clinac iX			
	M3D	100	100	99.5
	ArcCHECK	100	100	99.9
	Synergy			
	M3D	100	100	97.7
	ArcCHECK	100	100	99.8
Pelvis	Clinac iX			
	M3D	100	99.9	97.9
	ArcCHECK	100	100	96.8
	Synergy			
	M3D	100	99.9	96.9
	ArcCHECK	100	99.9	96.1

and reference beam data should not be used for situations that require a highly accurate dose verification.

The solid water phantom analysis indicated that the M3D system provided an acceptable second dosimetric check. Previously, Nelson et al. [3] reported that the average dose differences between the M3D system and ionization chamber measurements of water phantoms were within 1% for PDD curves and dose profiles from the Varian accelerators, although larger dose differences were observed at smaller field sizes. In particular, the superposition algorithm cannot perform small-field calculations, owing to the complete lack of lateral electron equilibrium [7]. These results are consistent with our findings.

Further, we reported that the Elekta Synergy accelerator yielded larger dose differences than the Varian accelerator. However, this difference is not sufficient to affect clinical practice [8]. As the maximum dose differences were observed at the field penumbra, adjustments to the multileaf collimator and jaws may reduce or resolve this discrepancy. In addition, it includes a geometric uncertainty of the ionization chamber measurement because the diameter of the ionization chamber is 5.5 mm. Furthermore, the M3D system and the simple open-field plan tended to yield similar results for both two- and four-beam treatment plans. The differences between the M3D and TPS dose were attributed to the larger dose differences of the Synergy. This indicates the importance of good agreement between the reference beam and the actual beam data. M3D users must pay attention to the difference between the reference beam data used in the M3D and the beam data adopted in their own facilities.

For the heterogeneous lung and bone model phantoms, dose distributions calculated using the M3D system differed considerably from the measured doses in the lung and bone regions, respectively. Mcdonald et al. [4] compared the doses accuracies calculated using the M3D system and the Acuros XB calculation algorithm, which is considered to be one of the most accurate commercially available dose calculation algorithms. Similar to our findings, the authors reported dose differences between the M3D system and Acuros XB, in both the lung and bone regions. The differences were attributed to the nature of the M3D. This system is based on superposition and uses only correct electron densities based on a water-based dose kernel, without considering the elemental compositions of different materials [7]. However, even if the M3D system was equipped with a collapsed-cone convolution/superposition calculation algorithm, the calculated doses would differ from those obtained using the Pinnacle TPS, which also uses a superposition calculation algorithm. Thus, we presume that the observed differences in the dose calculation are caused by inter-system differences in calculation efficiency such as calculation time and directions [9].

Previously, Fontenot et al. [5] used the 5%/3-mm criterion in a gamma analysis of the M3D system and reported a high passing rate for patient plans. In our study, we applied several criteria for gamma analysis and demonstrated the potential of M3D under stricter criteria. In a previous comparison of the dose calculation accuracy between the M3D and the COMPASS systems, Clemente-Gutiérrez F et al. [10] suggested applying both the 3%/3-mm and 2%/2-mm criteria to the gamma passing rate. We note that even for

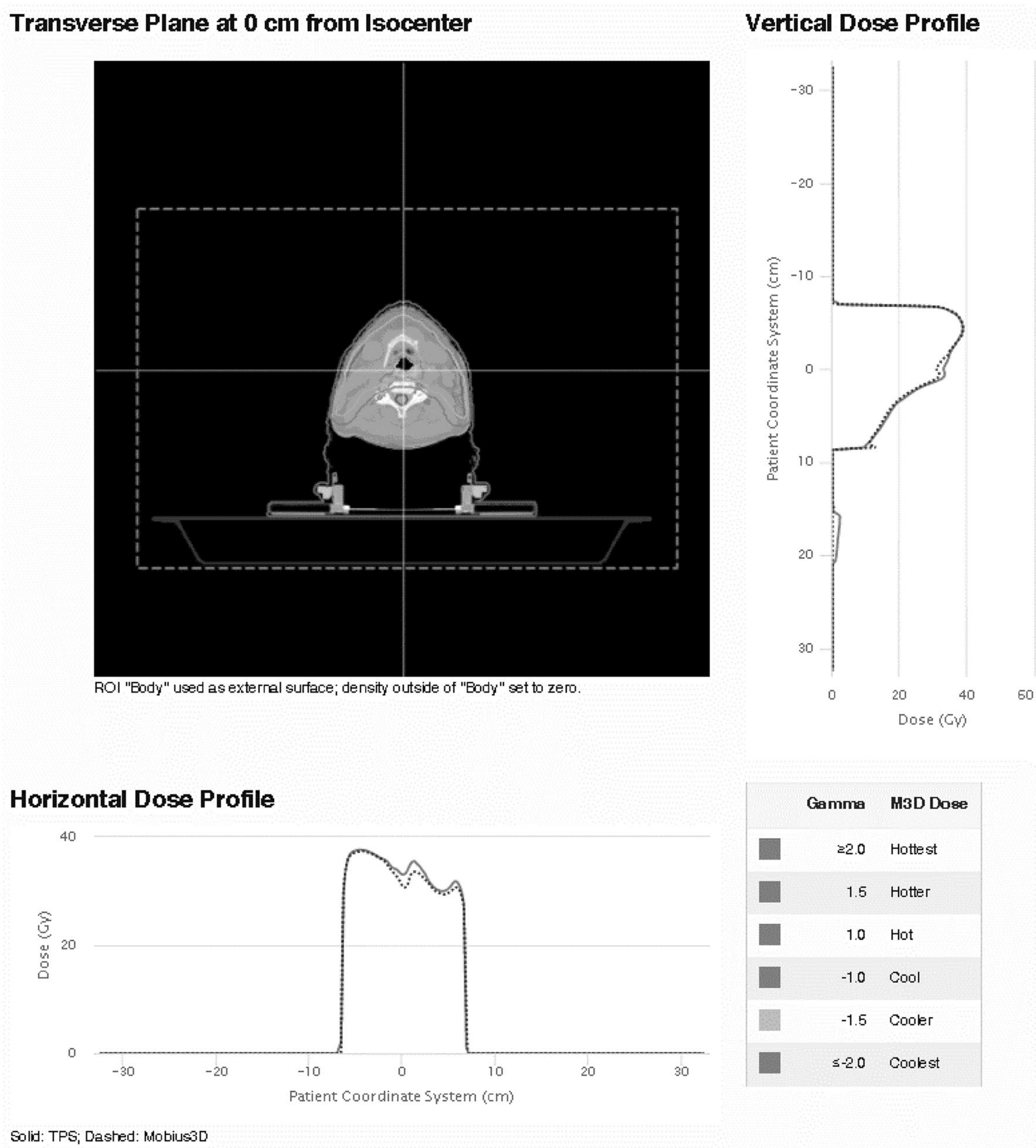


Fig. 7 Dose distributions calculated using the TPS (solid lines) and the M3D system (dashed lines) for the scanning of the whole neck with the Synergy 6-MV beam. This case had the poorest gamma passing rate

patient plans, agreement between the reference beam data and the actual beam data affected the gamma passing rate, as Synergy-derived patient plans had a lower gamma passing rate under the 2%/2-mm criterion.

For the planning of the whole neck, the differences in the M3D and the TPS dose profiles led to the inability of the former to calculate a complex dose distribution for VMAT. In particular, the M3D system yielded inaccurate data for the doses of the air-filled regions, which typically require a robust dose calculation algorithm [11]. Therefore, the M3D system appears to be unsuitable for highly accurate dose calculations in anatomical regions filled with air. Therefore, although the M3D system is acceptable for a second dosimetric check, it is not more accurate than the TPS.

5 Conclusions

We investigated the dose calculation accuracy of the M3D system using heterogeneous materials and manufacturer-supplied reference beam data, simple plans, and patient plans for clinical VMAT. For the simple plans, the reference beam data exhibited good agreement with the dose measurements obtained in a solid water phantom. However, the calculations using the reference beam data differed slightly from the ionization chamber measurements, depending on the type of accelerator used. For patient plans, we confirmed that the M3D system is reasonably accurate for second dosimetric checks, although we observed slight differences between accelerators produced by different manufacturers. In the lung and bone regions, the calculations generated using the M3D system differed by 10% from the doses measured in the ionization chamber. In conclusion, the M3D system is a useful clinical dose verification tool; however, its accuracy level is unacceptable for dosimetric scenarios that require highly accurate calculations.

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Compliance with ethical standards

Conflict of interest All authors have no conflicts of interest to disclose.

Ethical approval All procedures in studies involving human participants were performed in accordance with the ethical standards of Kumamoto University Hospital, and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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