# Patient-specific quality assurance for proton depth dose distribution using a multi-layer ionization chamber in a single-ring wobbling method

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## Abstract

The use of a multi-layer ionization chamber, Zebra, in patient-specific quality assurance (QA) for proton depth dose distributions in a single-ring wobbling method is investigated. The depth dose distributions measured using Zebra are compared with those calculated using the treatment planning system (TPS), XiO-M, and measured using an ionization chamber with a motorized water phantom system. Because the TPS only provides point doses, the average doses are calculated using in-house software. The detector size-corrected depth dose distributions are obtained by determining the average of the dose distributions from the TPS over a cylindrical region similar to the size of the Zebra detectors. The calculated depth dose distributions from the cases with a simple compensator shape are in good agreement with those obtained from the TPS without performing volume averaging; however, a 15% difference was shown when compared with those from the cases with a complex compensator shape. Then, the measurements are compared with the detector size-corrected depth dose distributions, showing an improved agreement within 3% for the highly steep dose gradient regions. Although there are some field size limitations, the Zebra system is a useful device for the fast measurement of patient-specific QA for depth dose distributions in wobbled proton beams. However, careful consideration is required for complex dose distribution fields, because the measurements obtained using Zebra cannot be directly compared to the depth dose distributions from the TPS owing to the finite detector size of the Zebra chamber.

**Keywords** Proton beam · Multi-layer ionization chamber · Percentage depth dose · Quality assurance

## 1 Introduction

In radiation therapy, the dose distribution calculated by a treatment planning system (TPS) should be verified to ensure that the correct dose is delivered to the target. For proton beams, the measurement and verification of the depth dose distributions is important because protons have a well-defined range of penetration in a material. Therefore, an accurate and quick verification of the planned doses is challenging, particularly for protons. The depth dose distribution along a beam central axis is typically measured using an ionization chamber and a motorized water phantom dosimetry system [1]. This method is currently considered to be the gold standard because of its high reliability and stability. However, a long period of time is required to set up the instrument and to measure the distributions. In addition, a lengthy quality assurance (QA) process limits the time available for patient treatment. Hence, a more efficient means of obtaining depth dose distributions should be evaluated. To reduce the time required to measure the depth dose distributions and the amount of monitor unit, a multi-layer ionization chamber (MLIC) could potentially provide more efficient measurements.

There are existing studies on MLIC development, performance tests of the MLIC, and the usefulness of the MLIC in periodical QA [2–7]; however, no studies have evaluated its application in patient-specific QA. Recently, pencil beam scanning (PBS) has been used instead of conventional and simple passive scattering proton therapy (PSPT) [8].

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However, there are no reports on the verification of MLIC usefulness in patient-specific QA for PBS and PSPT.

The Zebra MLIC system (IBA dosimetry, Schwarzenbruck, Germany) was originally developed as a tool for machine QA; therefore, it is unknown whether the Zebra system could also be used for patient-specific QA. In this study, we investigate the potential use of the Zebra system for patient-specific QA for proton depth dose distributions in PSPT. The double scattering technique is the most common and traditional scattering technique [9]; however, the wobbling method is also widely used in Japan as an alternative scattering technique [10–12]. Here, the latter method is used, in particular, the single-ring wobbling method, because it is simpler compared with other wobbling methods in particle beam therapy [13].

## 2 Materials and methods

### 2.1 Description of proton therapy system

At the Southern Tohoku Proton Therapy Center (STPTC) in Japan, proton therapy with a proton treatment system (Hitachi, Kashiwa, Japan) was instituted in 2008, and to date, more than 4700 patients with various tumors have been treated with wobbled proton beams. The proton therapy system at the STPTC uses a synchrotron that can accelerate protons up to 235 MeV. This system comprises an ion source, a 3-MeV radiofrequency quadrupole linear accelerator, a 235-MeV synchrotron, a high-energy beam transport line, two gantry irradiation rooms, and one irradiation room for the horizontal beam. The proton kinetic energies regularly used in clinical practice are 150, 210, and 230 MeV. The proton beam delivery system includes beam-wobbling magnets, a lead scatterer, main dose monitor, ridge filter, range shifter, backup monitor, flatness monitor, block collimator, multileaf collimator, and range compensator. The ridge filters are installed downstream of the main dose monitor to produce spread-out Bragg peaks (SOBP) with lengths ranging from 2 to 14 cm in increments of 1 cm. The wobbler system comprises two dipole magnets, and the scattering elements create a broad, flattened beam at the final aperture. This method is known as the single-ring wobbling method [10–13]. A commercially available TPS, XiO-M (Elekta, Stockholm, Sweden), is used to calculate the dose distributions. All treatments are planned using a pencil beam algorithm. The stopping power ratio is approximated based on the effective density measured using computed tomography (CT) images with an appropriate CT number conversion.

## 2.2 Measurements with ionization chamber and motorized water phantom dosimetry system

The measurement of the percent depth dose (PDD) distributions for QA of the clinical proton beams is most commonly performed using an ionization chamber with a motorized water phantom dosimetry system. For the monthly QA procedure at the STPTC, the PDD measurements for wobbled proton beams are performed using an Advanced Markus chamber (Type 34045) (PTW, Freiburg, Germany) in a specialized motorized water phantom dosimetry system (Toyo Medic, Tokyo, Japan).

## 2.3 Measurements with Zebra

The Zebra MLIC system comprises 180 parallel plate ionization chambers (with a diameter of 2.5 cm, an electrode thickness of 1 mm, and an air gap of each electrode of 1 mm) layered longitudinally with a spacing of 2 mm, covering up to 33 cm of the water equivalent thickness. This system can measure and analyze single Bragg peaks and SOBP distributions with a high spatial resolution and a sampling time of 10 ms. The resolution can be further increased by performing two measurements: one with a 1-mm build up and one without. Then, considering the shift in the depth axis, the two measurements are combined. The exterior of the Zebra system is shown in Fig. 1.

The manufacturer recommends performing a uniformity recalibration for the chambers before each use to compensate for variations in the individual channel sensitivities. Here, the uniformity recalibration is performed using a single Bragg peak beam from one of the scattering beam lines with an energy of 230 MeV because 230 MeV is not used in clinical practice. Then, basic functional tests, such



**Fig. 1** Overview of the experimental setup of the Zebra system in the gantry irradiation room

as a linearity check, a reproducibility check, an accuracy check, and a field-size sensitivity check, are performed similar to those used by Dhanesar et al. [4]. A linearity check was performed with physical dose ranging from 0.1 to 10 Gy for a 210-MeV unmodulated beam with a field size of 100 mm × 100 mm. In particular, readings for different applied physical dose were compared for four arbitrarily chosen chambers (1st, 50th, 100th, and 120th channels) in the Zebra. To verify the reproducibility, the Zebra was irradiated repeatedly with a 210-MeV modulated beam with a field size of 100 mm × 100 mm. Short-term (within a day) and long-term (over a period for 4 months) reproducibilities were tested by ten repeated measurements on the same four chambers. To verify the accuracy, the degrader, with thickness in the range of 0–3 mm, was inserted, and it was tested whether the range could be properly evaluated accordingly. The distal depths of 90%, 80%, and 20% were used as evaluation indicators. For the field-size sensitivity check, the Zebra was irradiated by a 210-MeV modulated beam with various field sizes, and the results were compared with those obtained using an Advanced Markus chamber in a motorized water phantom dosimetry system.

## 2.4 Evaluation of patient-specific QA for proton depth dose distribution using Zebra system

The potential use of the Zebra system for patient-specific QA, particularly for the measurement of the depth dose distributions, is investigated by exposing the Zebra system to actual treatment fields generated with wobbled proton beams. Here, ten fields with a simple range compensator shape and ten fields with a complex range compensator shape used with PSPT are examined. We determined whether a simple or a complex range compensator shape is appropriate by visually inspecting the shape and dose distributions obtained by TPS. Note that the meaning of "simple" or "complex" in this study is the difference in the dose distribution near the beam central axis where the detectors exists. In complex cases, the compensator has a steeper slope at the beam central axis than in the simple cases. This results in the considerable dose variation toward the off-central direction in the vicinity of the distal end. Therefore, the dose is non-uniform in the Zebra detector, and the dose averaging is necessary. The depth dose distributions measured using the Zebra system are compared with those calculated using the TPS and measured using the motorized water phantom. Because the TPS only provides point doses, large discrepancies could be observed between the calculated and measured results, especially for the complex compensator shape. Therefore, the average doses are calculated using in-house MATLAB (MathWorks, Natick, MA, USA) software. The detector size-corrected depth dose distributions are obtained by determining the average of the dose distributions from the TPS over a cylindrical region similar to the effective size of the Zebra detectors. In particular, we exported DICOM-RT data from the treatment planning system and set the cylindrical region with a diameter of 2.5 cm and a height of 1 mm in multiple layers on the beam axis to arithmetically average the dose of each area. This averaging method was applied regardless of the shape of the dose distribution.

## 3 Results and discussion

The results of the examined basic functional tests are similar to those reported by Dhanesar et al. [4]. The results of the linearity and reproducibility checks are summarized in Table 1. It was confirmed that the linear fit for all four data sets yielded the coefficient of determination, $R^2$, of 0.999, and the maximum deviation of the reproducibility of all data was less than 1%. The results of the accuracy check are summarized in Table 2. The results agree with an accuracy of at least 0.1 mm. The results of the field size sensitivity obtained in this study are shown in Fig. 2. The field sizes considered are 10 cm × 10 cm, 10 cm × 18 cm, 18 cm × 10 cm, and 18 cm × 18 cm (vertical × horizontal lengths, respectively) and are compared with those measured using the motorized water phantom. Although the manufacturer recommends a field size of 10 cm × 10 cm in the Zebra system, larger field sizes are often used in clinical practice. Therefore, a large field size should be evaluated for the Zebra measurements. Figure 2 shows that the agreement is less favorable for field sizes of 18 cm × 10 cm and 18 cm × 18 cm than that of those measured using the motorized water phantom. These results indicate that a noticeable difference exists in the measured depth dose distributions when the aperture is inserted vertically with a field height of 18 cm. Furthermore, the agreement is less favorable when the field height is greater than 12 cm. Although the details of this cause are unknown, these measurements suggest that when the field height is greater than 12 cm, some electronics of the Zebra system are irradiated. Therefore, the Zebra could potentially be used for

**Table 1** Linearity and reproducibility of test results. Coefficient of determination, $R^2$, for the response of the 1st, 50th, 100th, and 120th chambers of the Zebra with respect to physical doses (upper column). Maximum deviation of the reproducibility of the 1st, 50th, 100th, and 120th chambers of the Zebra for ten repeated measurements over a period of 4 months (lower column)

|  | Channel | | | |
|---|---|---|---|---|
|  | 1st | 50th | 100th | 120th |
| $R^2$ | 0.999 | 0.999 | 0.999 | 0.999 |
| Maximum deviation (%) | 0.56 | 0.77 | 0.63 | 0.48 |

**Table 2** Accuracy test results. Depth at distal dose of 90%, 80%, and 20% were measured with an inserted degrader. The thickness was varied from 0 to 3 mm. All units are in mm

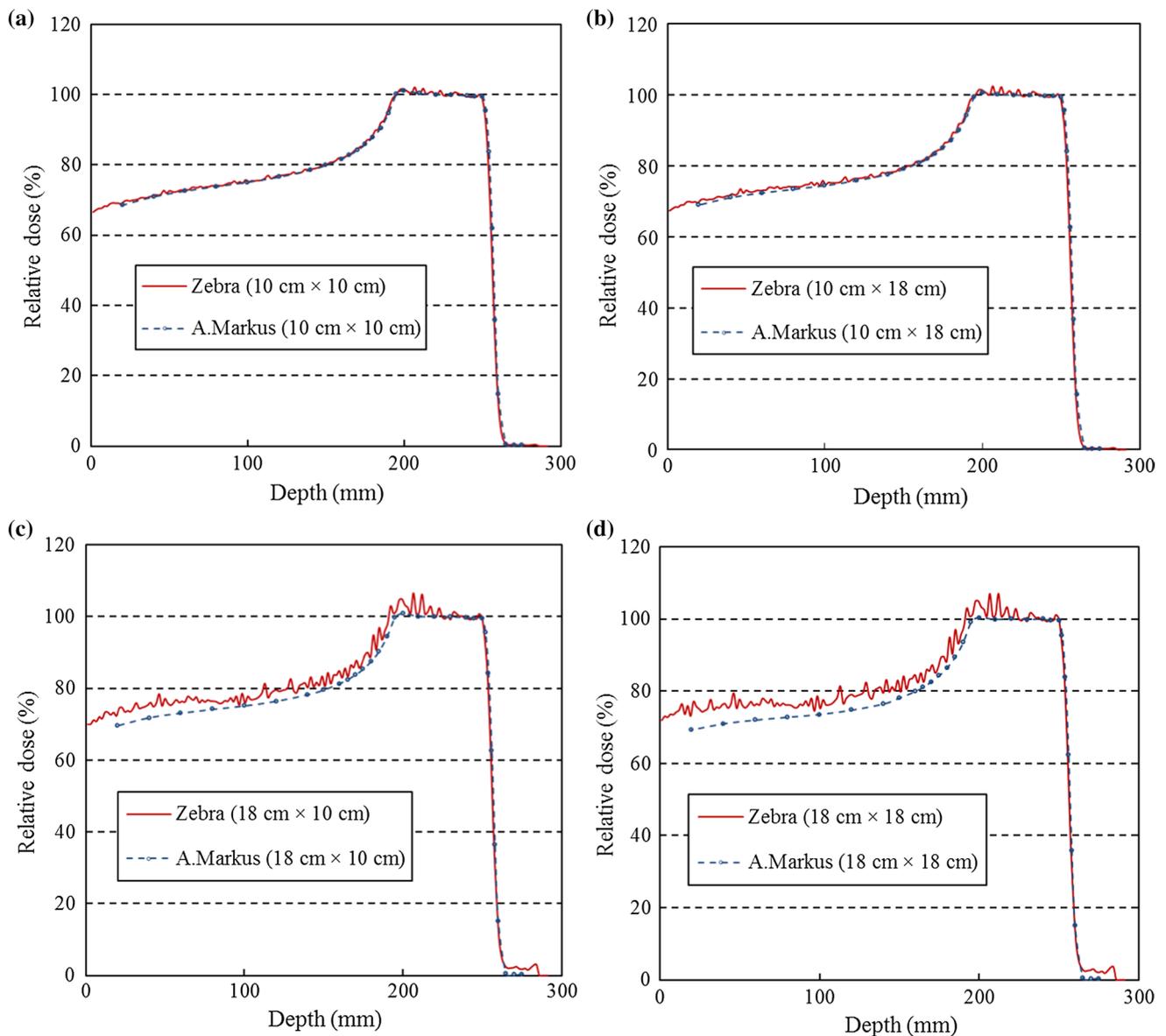| | Degrader thickness (mm) | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 0.5 | 1 | 1.5 | 2 | 3 |
| 150 MeV | | | | | | |
| Distal range (20%) | 145.5 | 145.0 | 144.5 | 143.9 | 143.4 | 142.4 |
| Distal range (80%) | 142.8 | 142.3 | 141.8 | 141.3 | 140.8 | 139.8 |
| Distal range (90%) | 142.3 | 141.8 | 141.3 | 140.8 | 140.3 | 139.3 |
| 210 MeV | | | | | | |
| Distal range (20%) | 264.0 | 263.5 | 236.0 | 262.5 | 262.0 | 261.0 |
| Distal range (80%) | 259.6 | 259.0 | 258.5 | 258.0 | 257.5 | 256.5 |
| Distal range (90%) | 258.7 | 258.1 | 257.6 | 257.1 | 256.6 | 255.6 |



**Fig. 2** Depth dose distributions measured with the Zebra system and the Advanced Markus (A. Markus) chamber using the motorized water phantom for field sizes: **a** 10 cm×10 cm, **b** 10 cm×18 cm, **c** 18 cm×10 cm, and **d** 18 cm×18 cm

measuring the depth dose distributions when the abovementioned conditions are avoided.

Figure 3 shows the measured and calculated depth dose distributions at the beam central axis for three example fields with the simple range compensator shape plans. These cases are in good agreement with the calculated TPS depth dose distributions without volume averaging, with at most a 3% difference in the entire region. Figure 4 compares the three example fields with the complex range compensator shape plans. In the highly steep dose gradient regions, which often appear particularly in advanced head and neck cancer treatment plans with an irregularly shaped range compensator, the maximum difference between the dose measured using the Zebra and the TPS dose was approximately 15%, and the maximum difference of the 90% distal depth was 4.6 mm. To confirm that this is because of the detector size effect, the Zebra measurements were compared with the detector size-corrected depth dose distributions. In most cases, the agreement between the Zebra measurements and the averaged TPS dose distributions was within 3%, and the 90% distal range difference was less than 1 mm for the highly steep

dose gradient regions. The TPS dose averaging resulted in the improvement of 12% dose and approximately 4 mm of 90% distal range.

Although the Zebra system is routinely used for machine QA in proton bean therapy [4], to our knowledge, its use in patient-specific QA for proton beam therapy has not been reported. In addition, there are few reports regarding patient-specific QA for the single-ring wobbling method, which is widely used as a passive scattering method, especially in Japan [10–12]. In this study, we examined the feasibility of using the Zebra system for verifying patient-specific depth dose distributions in the single-ring wobbling method. Although the field size is limited, especially the field height, the Zebra system can measure the depth dose distributions for patient-specific QA. Hence, the Zebra can be a useful device in clinical practice because it measures the entire depth dose distribution for each patient field in less than 10 s.

A complex range compensator shape is occasionally adopted, especially for the head and neck or thoracic target, because these regions are highly heterogeneous. However,
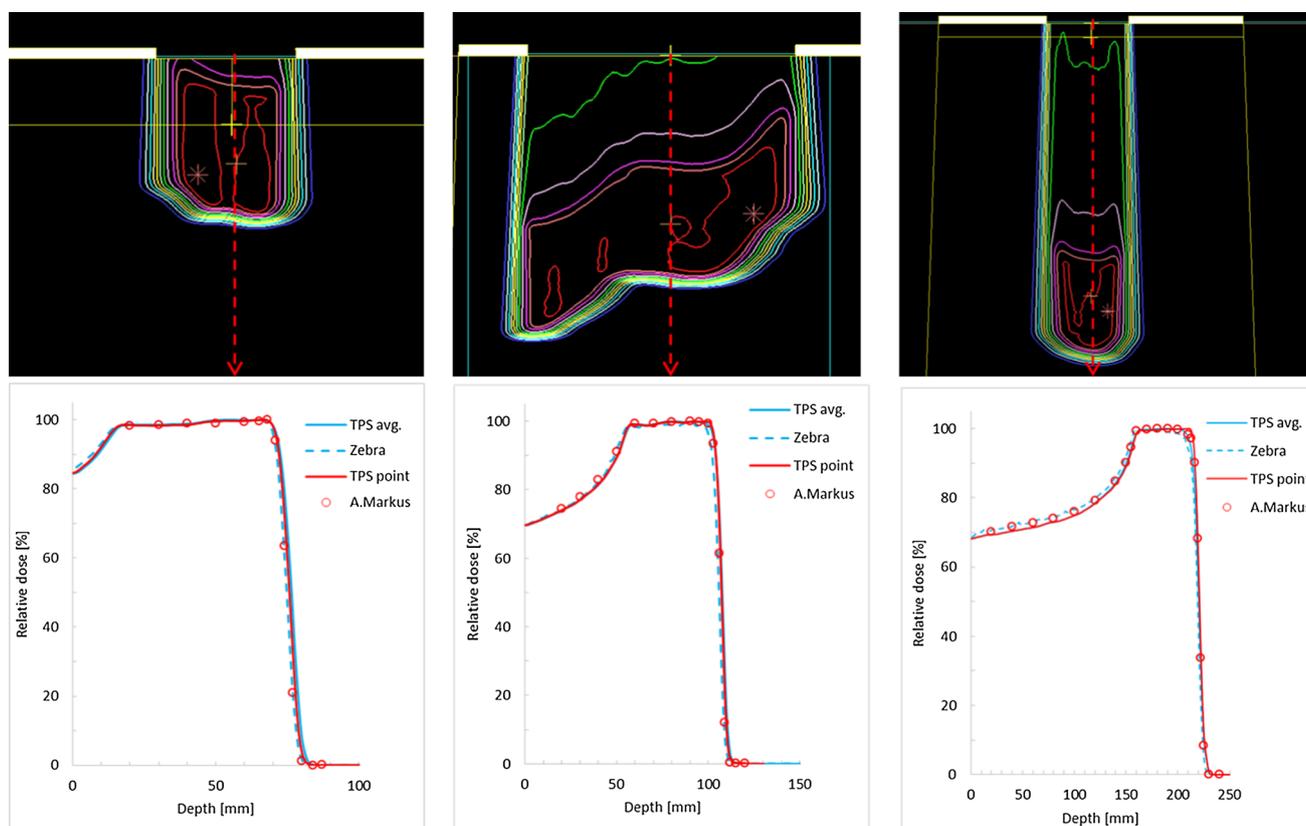


**Fig. 3** Depth dose distributions of three example fields with a simple range compensator shape plan. The upper figures show the dose distributions of the QA plan in the sagittal plane. The isodose levels shown in each figure are 100%, 95%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, and 10%. The lower figures show the depth dose distributions obtained by the TPS calculated point dose, TPS dose averaged over a cylindrical region with a diameter of 2.5 cm, Zebra measurement, and Advanced Markus measurement. Each depth dose distribution is normalized at the maximum dose
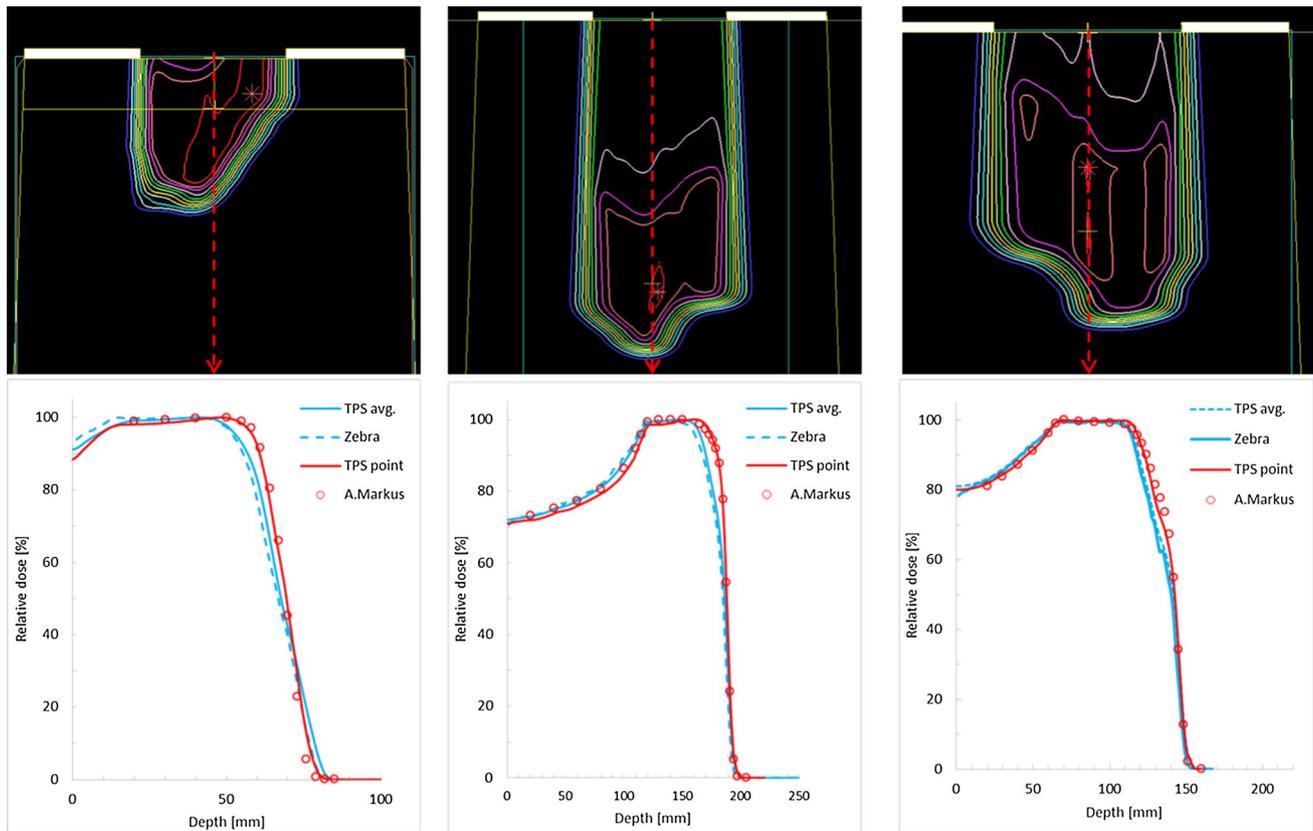
**Fig. 4** Depth dose distributions of three example fields with a complex range compensator shape plan. The upper figures show the dose distributions of the QA plan in the sagittal plane. The isodose levels shown in each figure are 100%, 95%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, and 10%. The lower figures show the depth dose distributions obtained by the TPS calculated point dose, TPS dose averaged over a cylindrical region with a diameter of 2.5 cm, Zebra measurement, and Advanced Markus measurement. Each depth dose distribution is normalized at the maximum dose

a compensator smear is always adopted for creating a range compensator to maintain the robustness of the treatment plan and the gentle dose distribution. In contrast, in intensity-modulated proton therapy (IMPT), complex dose distributions are routinely provided [14]. Currently at the STPTC, the introduction of IMPT technologies and a patient-specific QA procedure are under investigation. Although a motorized water phantom is a reliable method, it is time-consuming to routinely use in clinical practice. Therefore, the Zebra system could be used in patient-specific QA for depth dose distribution in IMPT in the future. In addition to this study, which provides the basic characteristics of the Zebra system in patient-specific QA for depth dose distribution with a single-ring wobbling method, further experiments are required to use the Zebra system in IMPT.

## 4 Conclusion

Although there are some field size limitations, the Zebra system is a useful device for the fast measurement of patient-specific QA for depth dose distribution in wobbled proton beams. However, careful consideration is particularly needed for complex dose distribution fields because the Zebra patient field measurements cannot be directly compared to the depth dose distribution from the TPS owing to the finite detector size of the Zebra chamber. Hence, in those cases, the TPS doses should be averaged over a region that represents the size of the Zebra detectors.

## Compliance with ethical standards

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