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Evaluation of patient-specific quality assurance in spot-scanning proton therapy using 2D ionisation chamber array

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Original Article

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Abstract

Purpose: This study aimed to report the outcomes of patient-specific quality assurance (QA) in spot-scanning proton therapy using a two-dimensional ionisation chamber array and investigate the relationship between gamma passing rate and plan parameters.
Materials and methods: Patient-specific QA was performed and evaluated by gamma analysis using a 3% dose difference and 2-mm distance-to-agreement with 172 treatment plans in the head and neck, breast, chest, abdominal and pelvic regions. The outcomes of patient-specific quality assurance regarding the gamma passing rate of the treatment sites, monitor unit (MU) per spot, measurement depth, range shifter, number of spots, energy layer and target volume were analysed.
Results: No significant difference ($p = 0{\cdot}10$) in the gamma passing rates between the treatment sites. The gamma passing rate was >98% in all the regions. The overall result of patient-specific QA with the gamma evaluation was $99{\cdot}1 \pm 1{\cdot}6$%. For the MU per spot, range shifter and measurement depth, the gamma passing rate was >98%. The gamma passing rate of the number of spots, energy layer and target volume was >97%.
Conclusion: Patient-specific QA measurements showed that the gamma passing rate was >98% and was independent of the treatment site, MU per spot, range shifter, number of spots, energy layer and target volume but depend on measurement depth ($p < 0{\cdot}05$). A gamma index of 3%, 2 mm forms reasonable criteria for patient-specific QA in spot-scanning proton therapy.

Introduction

Proton therapy is an advanced radiotherapy technique that provides highly conformal dose distribution. It can improve tumor control by sparing normal tissues and reducing side effects and secondary cancers.[1] This can be achieved using passive scattering and spot scanning.[2–4] Currently, the most common delivery technique is spot scanning owing to its convenience and ability to reduce the intensity of the dose from the component (compensator and aperture) compared to passive scattering.[5] Magnetic deflection is used to position the individual spots laterally within an energy layer. The depth of the irradiation is achieved by changing the energy.[2,4] However, certain spot-scanning characteristics, particularly the finite range, can create difficulties in verification because when the density had changed, the finite range will have drastically changed too.[3]

Patient-specific quality assurance (QA) is an important process in radiotherapy. It verifies the dose distributions between the dose calculated by the treatment planning system and the measured dose to ensure the delivered dose from the machine in order to avoid errors that may occur with the patients during treatment. Most methods for patient-specific quality assurance involve measurements using an ionisation chamber array followed by two-dimensional (2D) or three-dimensional (3D) gamma analysis.[2,3,6]

In proton therapy, a 2D ionisation chamber array is the detector, which is the most commonly used for patient-specific QA in many studies.[2,7,8] The 2D ionisation chamber array is suitable for routine verification of patient-specific dose distributions of proton therapy beams.[7] For patient-specific QA in proton therapy, there is no consensus criterion. There are only end-to-end verification criteria with criteria of 3%, 3 mm and 95% of gamma passing rate.[9] Outcomes of patient-specific QA for spot-scanning proton therapy have shown that 3%, 3 mm with a 90% gamma passing rate is a reasonable action level for 2D comparisons of dose planes in spot-scanning proton therapy.[8] In a previous study, the characteristics of 2D ionisation chamber array for patient-specific QA were tested and showed effective performance in spot-scanning proton therapy with criteria of 3%, 2 mm.[10] Although there are studies investigating 2D ionisation chamber array for patient-specific quality assurance in spot-scanning proton therapy,

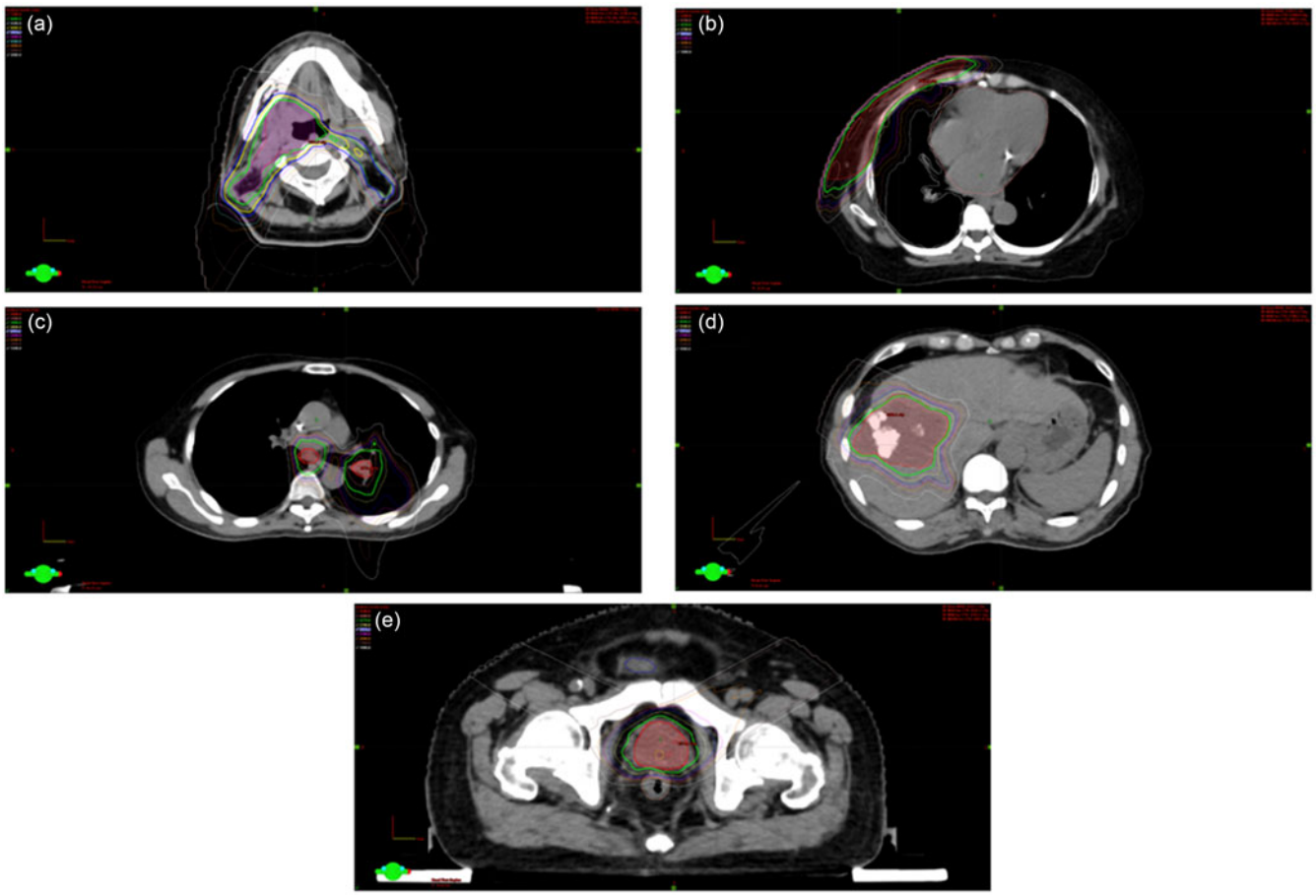

Figure 1. An example of treatment plans for (a) head and neck, (b) breast, (c) chest, (d) abdomen and (e) pelvis region.

but there are few studies that report the outcomes of patient-specific QA.[8] Moreover, there are many factors that may affect the gamma passing rate.[8,11,12] This study reports the outcomes of patient-specific QA in spot-scanning proton therapy using a 2D ionisation chamber array and investigates whether treatment site and plan parameters affect gamma passing rate.

Materials and Methods

From March to November 2023, we performed patient-specific QA for 172 treatment plans and 542 treatment fields. The plans were planned for proton technique with Varian Eclipse treatment planning system, version 16·1 (Varian Medical Systems) in five treatment sites including the head and neck, breasts, chest, abdomen and pelvis with the depth of 2–20 cm and the use of range shifters 2, 3 and 5 cm and without range shifter for all genders and ages and exclude the plans that were planned for other techniques. The energy layer, number of spots and target volume of each field were recorded. An example of treatment plans is illustrated in Figure 1.

Dose was delivered using a Varian ProBeam Compact spot scanning system (Varian Medical Systems, Palo Alto, California, USA), which uses the spot-scanning technique and comprises a superconducting cyclotron, beam transport and energy selection system. The beam selection system can range from 70 to 220 MeV. The gantry can fully rotate 360°. The maximum field size was 30 × 40 cm^2. This technology allows fast-dose delivery and layer switching.[13–15] The PTW OCTAVIUS Detector 1500XDR array (PTW-Freiburg, Freiburg, Germany) was used for measurement. It is a 2D detector array used for dosimetry measurements with detectors arranged in a checkerboard design. It comprises 1405 vent ionisation chambers and has an area of 27 × 27 cm^2. The vented plane-parallel ion chambers are 4·4 mm × 4·4 mm × 3·0 mm in size. The chamber volume was 0·06 cm^3. The area density above the chamber volume was 0·8 g/cm^2. The reference point was located 7·5 mm below the array surface. The detector resolution for dose and dose rate was 0·1 mGy and 0·1 mGy/min, respectively.[16,17]

Verification plans creation

All verification plans were created according to the patient treatment plans with Varian Eclipse treatment planning system using the same proton fluence for each field which the treatment plans were developed using multi-field optimisation technique (MFO). The treatment plan was robustly optimized using 5 mm setup uncertainty and 3·5% range uncertainty. The analytical dose algorithm was Proton Convolution Superposition (PCS) version 16·1.

Patient-Specific QA setup

The measurement device was placed in a Virtual Water phantom (Standard Imaging Inc., Middleton, WI, USA) with a 3-cm backscatter slab phantom in the isocentre plane. The effective

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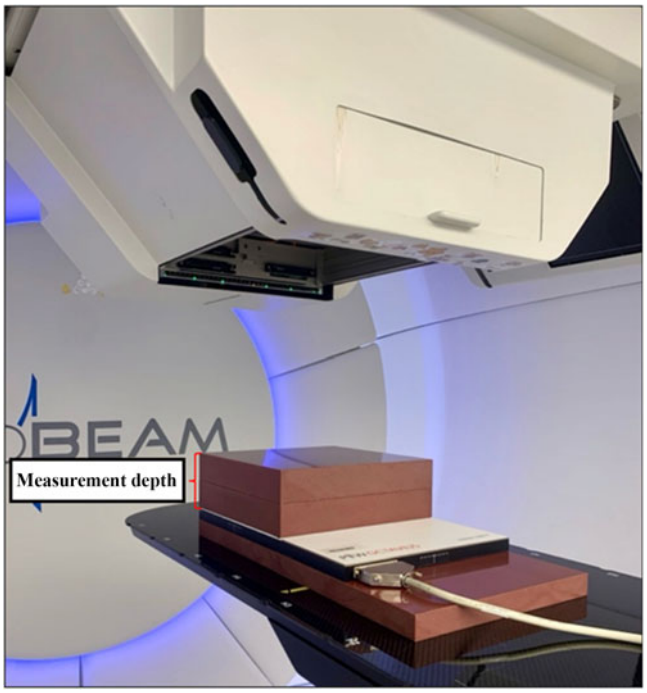

Figure 2. The patient-specific QA setup for each plan.

measurement point was selected as the measurement depth which was the same depth as nearly the middle of the target depth and under the same conditions as those in the actual treatment plans. There was the use of polycarbonate range shifter and snout size same as the actual plans. The gantry was set to 0° and evaluated using the perpendicular composite method at one measurement depth for each plan. The setup for patient-specific QA is illustrated in Figure 2.

Measurement

First, the PTW OCTAVIUS 1500XDR was activated with pre-irradiation at 400 cGy, 10-cm depth and a field size of 28 × 28 cm^2 and calibrated with 200 cGy, 2-cm depth and a field size of 10 × 10 cm^2 before start patient-specific QA in each day. The measured dose of each verification plan was compared with the calculated dose using the gamma index criteria of 3%, 2 mm, which is an absolute global gamma evaluation and a 10% dose threshold using the VeriSoft program version 8·0. The gamma passing rate of each plan was recorded as mean value and standard deviation.

Analyzation

The dataset of monitor unit (MU) per spot, measurement depth, range shifter, number of spots, energy layer and target volume for each plan were recorded and analyzed. We compared the gamma passing rate according to the treatment sites, MU per spot, measurement depth, range shifter, number of spots, energy layer and target volume. This study was approved by Institutional Review Board (IRB) of the Faculty of Medicine, Chulalongkorn University (IRB731/66).

Statistical analysis

The data were normal distribution with *p-value* more than 0·05. The data of gamma passing rate between each treatment site, MU per spot, measurement depth, range shifter thickness, number of spots range, energy layers range and target volume were examined in term of mean and standard deviation (SD) and evaluated by one-way analysis of variance (ANOVA). The data of correlation between target volume and plan parameters were evaluated by linear regression. A *p-value* less than 0·05 was considered statistically significant.

Results

Table 1 shows the gamma passing rate from the patient-specific QA for each treatment site in terms of mean and standard deviation. The most common sites were the abdomen and head and neck, with 50 and 44 plans, respectively. There was no significant difference ($p = 0{\cdot}10$) between the treatment sites. Overall, the gamma passing rate was 99·1 ± 1·6%.

Table 2 shows the gamma passing rates of the different categories of MU per spot, measurement depth and range shifter thickness. In most cases, we used 1 MU per spot with 129 plans. The minimum and maximum gamma passing rates were 99·1% and 99·4%, respectively. There was no significant difference ($p = 0{\cdot}93$) between the different categories of MU per spot.

The most common measurement depth was 5 cm, with 71 plans. The gamma passing rate was within the range of 98·3–100% in each measurement depth. There was a significant difference ($p = 0{\cdot}04$) between the measurement depths. The difference occurs with 5 pairs; (1) 2 cm and 5 cm, (2) 2 cm and 8 cm, (3) 5 cm and 20 cm, (4) 8 cm and 15 cm and (5) 8 cm and 20 cm which *p-value* was less than 0·002 by Bonferroni methods.

There was no significant difference ($p = 0{\cdot}07$) in the gamma passing rates between cases with and without range shifters within the range of 98·9–99·7% which is illustrated in Table 2. In most cases, there appeared to be no use for a range shifter. In the cases that used the range shifter, the 3-cm range shifter was most commonly used.

Figure 3a shows the results for gamma passing rate for a number of spots grouped by range. The average gamma passing rate among different ranges was more than 99% and there is no difference ($p = 0{\cdot}73$). The minimum gamma passing rates had the number of spots >10,000 spots and an energy layer more than 80 layers shown in Figure 3b. The gamma passing rate between different ranges showed no significant difference ($p = 0{\cdot}83$).

The gamma passing rate showed no difference ($p = 0{\cdot}71$) between various target volumes. Most cases had small target volume of 600 cm^3. The average gamma passing rate was more than 98% in Figure 3c. In Figure 4a–c, the number of fields, number of spots and energy layer unrelated to the target volume with the values show a similarity and the results showed that each region had various target volumes.

The results show that the efficacy of patient-specific QA remains consistent across treatment sites, MU per spot, range shifter, number of spots, energy layer and target volume. This underscores a universal approach to QA across diverse treatment scenarios.

Discussion

The gamma index criterion for patient-specific QA in proton therapy has not been defined. In many studies, the researchers used criteria of 3%, 3 mm with 90% and 95% of gamma passing rate which in the earliest stage it is the criteria for intensity-modulated radiation therapy (IMRT) QA[18] and found that it provides high

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Table 1. Summary of the gamma passing rate from patient-specific QA of each treatment site

Treatment site	No. of plans	No. of fields	No. of spots	Energy layers	Target volume (cm^3)	Gamma passing rate (%)
Head and neck	44	148	5011 ± 5570	69·7 ± 50·5	307·4 ± 528·1	99·4 ± 1·2
Breast	19	40	8018 ± 5545	39·7 ± 11·3	873·0 ± 462·9	99·6 ± 0·7
Chest	29	113	7166 ± 6652	68·3 ± 40·0	422·7 ± 625·5	98·9 ± 2·0
Abdomen	50	174	11,365 ± 11,340	65·8 ± 34·9	375·0 ± 603·7	98·7 ± 2·0
Pelvis	30	67	4857 ± 4888	35·8 ± 18·7	402·0 ± 750·6	99·3 ± 1·3
Total	172	542	7527 ± 8218	59·1 ± 39·3	425·8 ± 626·0	99·1 ± 1·6

Table 2. Summary of the gamma passing rate from patient-specific QA of each MU per spot, each measurement depth and each range shifter thickness

		No. of plans	No. of fields	Gamma passing rate (%)	*p-value*
MU per spot	**1**	129	431	99·1 ± 1·6	
	3	14	35	99·4 ± 1·0	
	5	15	41	99·1 ± 1·4	
	10	14	35	99·1 ± 2·4	
	Total	172	542	99·1 ± 1·6	0·93
Measurement depth (cm)	**2**	18	44	99·8 ± 0·3	
	3	31	102	99·5 ± 1·6	
	5	71	236	99·0 ± 1·8	
	8	27	89	98·3 ± 1·6	
	10	11	36	99·0 ± 1·7	
	15	12	31	99·7 ± 0·4	
	20	2	4	100·0 ± 0	
	Total	172	542	99·1 ± 1·6	< 0·05
Range shifter (cm)	**Without range shifter**	103	340	98·9 ± 1·6	
	2	2	7	99·7 ± 0·4	
	3	38	122	99·4 ± 1·9	
	5	29	73	99·6 ± 1·1	
	Total	172	542	99·1 ± 1·6	0·07

gamma passing rate[2,7,8,12] and is a reasonable criterion.[8] If the gamma passing rate passes the tighter criterion, another criterion will pass too. Therefore, in this study, the criteria of 3% and 2 mm were used. It is commonly used for patient-specific QA in intensity-modulated radiation therapy.[19] From a study on the characteristics of the PTW OCTAVIUS 1500XDR for patient-specific QA in spot-scanning proton therapy with the criteria of 3% and 2 mm to define that PTW OCTAVIUS 1500XDR can be used for patient-specific QA, the confidence limit of the gamma passing rate was 95·7%.[10] From our statistical analysis, we found no significant difference ($p = 0{\cdot}10$) between the treatment sites, which allowed us to calculate the confidence limit for the overall plans. The results show an effective results as same as the study from Chan MF et al.[2] which using radiochromic film and MatriXX PT in patient-specific QA found that with the criteria 3%, 2 mm, the gamma passing rate was 98·2 ± 0·5% and 97·3 ± 0·9%, respectively.

The gamma passing rate from patient-specific QA resulting in 165 of the 172 treatment plans was >95·7%, and every measurement had a high gamma passing rate value (>90%). Arjomandy et al.[7] reported that the dose distribution may be different because of the size of the high-dose gradient and the beam output, while Mackin et al.[8] reported many factors, such as a steep dose gradient (transverse to the measured plane) and the Eclipse dose calculation, which systematically gives a higher dose value than the measurement in regions proximal to the spread-out Bragg peak. In this study, we observed daily quality assurance. The output signal was practicable; thus, the failure may have occurred because the steep dose gradients of the proton beams contributed to a gamma passing rate <95·7% including the field size of the target which was bigger than the detector or was very small. For example, some head and neck fields in craniospinal radiotherapy (CSI) case have the field size bigger than the detector, and some fields were very small which cause the gamma passing rate fell below the expected threshold. The report from Liu C et al.[12] found that the results from criteria of 2%, 2 mm have the same conclusion from criteria of 3%, 3 mm, so the tighter criterion could reasonable for the use of 2D patient-specific QA.

In this study, MU per spot and plans with or without a range shifter did not affect the patient-specific QA, while there was no significant difference in the gamma passing rate value. The number

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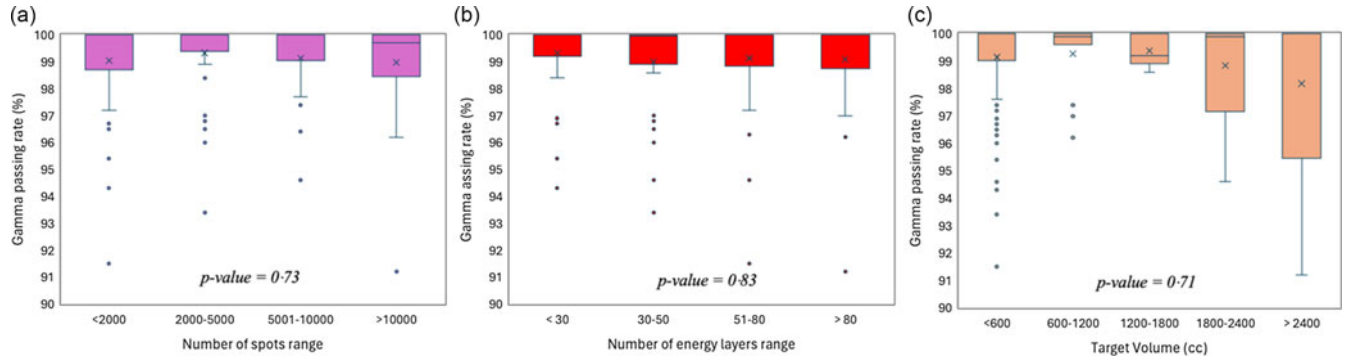

Figure 3. Box-and-whisker plot of gamma passing rate for (a) number of spots range, (b) number of energy layers and (c) target volume.

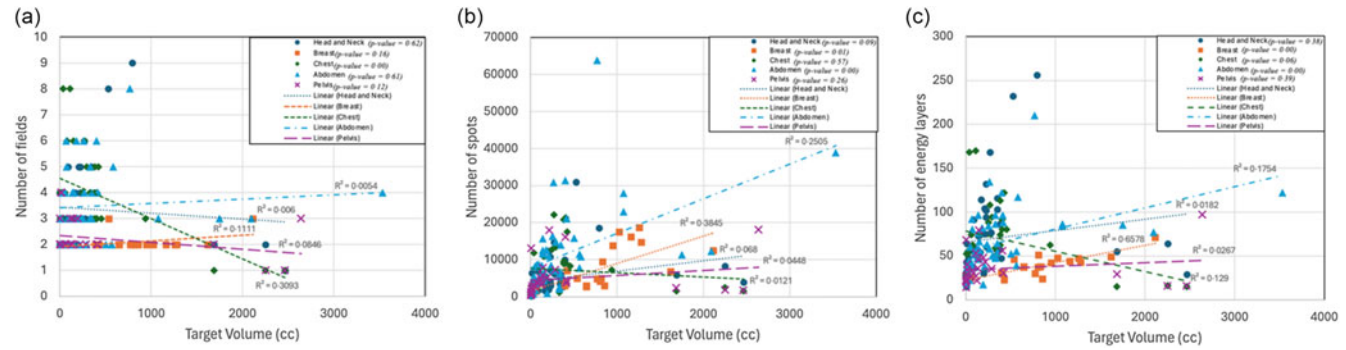

Figure 4. Correlation between target volume and (a) number of fields, (b) number of spots range and (c) number of energy layers.

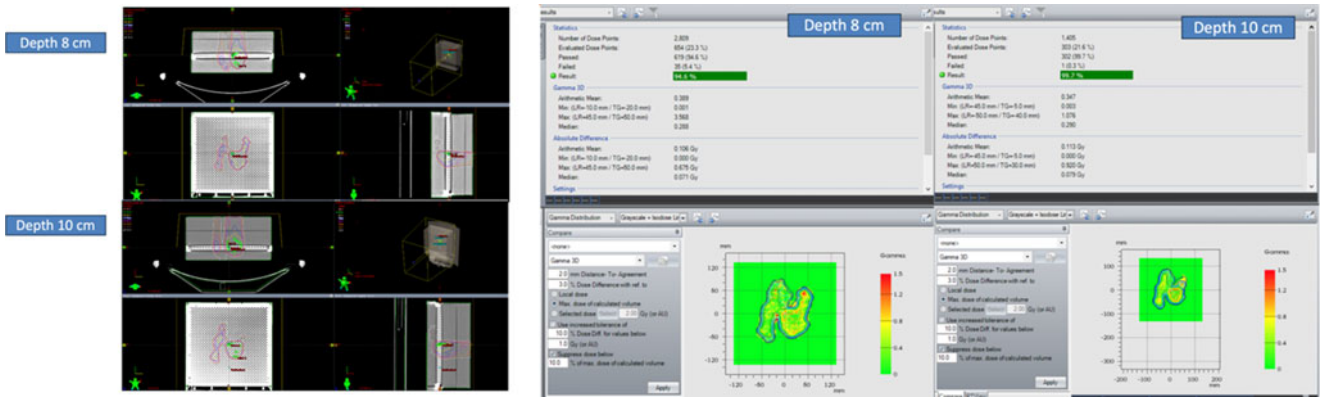

Figure 5. Gamma passing rate from one plan in different depth.

of spots and energy layers also led to almost no difference in the gamma passing rate, but there was a significant difference between different measurement depths ($p = 0{\cdot}04$) so the measurement depth selection was important in patient-specific QA. If the measurement depth selection was wrong, such as it was too shallow or too deep, the gamma passing rate was also wrong and the results will fail because of the steep dose gradient. For example, Figure 5 shows the gamma passing rate of the same treatment plan but with different depth, the depth which was close to the center could impact the high gamma passing rate.

As per the results, the target volume was unrelated to the number of fields, number of spots and energy layers. These values did not change with the target volume which R^2 was nearly zero, but the type of target, region and nearby region (organs at risk) should be considered. In the breast and abdomen region, *p-value* was less than 0·05 for correlation with number of spots and energy layers and in the chest for number of fields. The large number of spots and energy layers could be chosen for the large target volume with the positive correlation illustrated in Figure 3a–c. For a number of fields, Figure 3a shows a low negative correlation which the small number of fields could be chosen for the large target volume. The gamma passing rate showed no significant difference between the target volume regions ($p = 0{\cdot}71$). In further study, it could be studied with the tighten criterion such as 2%, 2 mm and

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other plan parameters such as dose rate which did not set directly in TPS and did not study to investigate the effect on patient-specific QA in proton therapy to define criteria for the error detection and define the error that can occur with the proton beam delivery.

Conclusion

Patient-specific QA measurements using a PTW OCTAVIUS 1500XDR array showed that the gamma passing rate at our institute was >98% and was independent of the treatment site, MU per spot, range shifter, number of spots, energy layer and target volume. Moreover, we found the measurement depth could impact the gamma passing rate. We propose a gamma index of 3%, 2 mm as reasonable criteria for patient-specific QA during spot-scanning proton therapy with 2D detector which has an effective performance.

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Author contributions. Nuttida Rawiwan: methodology, writing – original draft. Nichakan Chatchumnan: methodology, writing – original draft. Manunchaya Vinoinoch: writing – review and editing. Sakda Kingkaew: writing – review and editing. Puntiwa Oonsiri: writing – review and editing. Sornjarod Oonsiri: conceptualisation, supervision, validation, writing – review and editing.

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Competing interests. The authors declare no conflict of interest.

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