Technology in Cancer Research & Treatment
Volume 20: 1-10

DOI: 10.1177/15330338211033076
journals.sagepub.com/home/tct
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Fast MCsquare-Based Independent Dose Verification Platform for Pencil Beam Scanning Proton Therapy

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Abstract

Purpose: To commission MCsquare (a multi-cores CPU-based dose calculation engine) for pencil beam scanning (PBS) proton therapy, integrate it into RayStation treatment plan system (TPS) to create a dedicated platform for fast independent dose verification. **Method:** A MCsquare-based independent dose verification platform (MC2InRS) was developed to realize automatic dose re-calculation for clinical use, including data preparation, dose calculation, 2D/3D gamma analysis. MCsquare was commissioned based on in-air lateral dose profiles, integrated depth dose, and the absolute dose of different beam energies for Proteus®ONE. MC2InRS was validated with measurement data using various targets and depths in a water phantom. This study also investigated 15 clinical cases to demonstrate the feasibility and effectiveness of MC2InRS platform in clinic practice. **Results:** Between simulation and measurement, the distal range differences at 80% (R80) and 20% (R20) dose levels for each energy were below 0.05 mm, and 0.1 mm, respectively, and the absolute dose differences were below 0.5%. 29 out of 36 QA planes reached a 100% gamma passing rate (GPR) for 2%/2mm criteria, and a minimum of 98.3% gamma was obtained in water phantom between simulation and measurement. For the 15 clinical cases investigated, the average 2D GPR (2%/2mm) was 95.4%, 99.3% for MCsquare vs. measurement, MCsquare vs. TPS, respectively. The average 3D GPR (2%/2mm) was 98.9%, 95.3% for MCsquare vs. TPS in water, and computed tomography (CT), respectively. **Conclusion:** MC2InRS, a fast, independent dose verification platform, has been developed to perform dose verification with high accuracy and efficiency for Pencil Bream Scanning (PBS). Its potential to be applied in routine clinical practice has also been discussed.

Keywords

pencil beam scanning, MCsquare, dose verification, Monte Carlo simulation

Received: November 02, 2020; Revised: May 17, 2021; Accepted: June 11, 2021.

Introduction

Compared to passive scattering, pencil beam scanning (PBS) has a higher beam utilization rate, less neutron production, and usually does not require customized apertures and compensators. It's been used to treat tumors located around critical organs like the oral cavity, bowel, or spinal cord, where tumors are usually shaped irregularly.[1-4] However, complexity always comes with conformality.[5,6] PBS makes exceptionally high demands on the treatment plan system (TPS), accelerator, and irradiation system. For each treatment field, the combinations of spot positions, ranges, and weights have to be determined by TPS to get the optimized fluence map. The fluence map must be converted into machine-readable files, which must be

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correctly interpreted and delivered by the treatment machine. Whether the dose distribution can meet the clinical requirements depends on each scanning point's position accuracy and dose accuracy. Taylor *et al*[7] performed anthropomorphic proton phantom-based measurements to verify various TPS systems' dose calculation accuracy. They found potential deficiencies in proton therapy planning and delivery. Given these factors, independent (secondary) dose verification is critical for PBS to ensure the patient's plan is accurate.[8-10]

Secondary dose calculation has been a routine procedure in conventional radiation therapy. Commercial software, such as RadCalc and IMSure, are available to validate the photon dose calculated by the treatment planning system (TPS).[11,12] Unfortunately, to the best of our knowledge, such a tool has not been introduced to proton therapy as a standard practice. Mackin *et al* reported using a second-check analytical dose calculation engine to improve spot-scanning proton therapy patient-specific quality assurance (PSQA) with their in-house software HplusQA.[13] Since analytical models were used in their treatment planning system (TPS) and HplusQA calculations, some correlation was observed in their study. Compared to analytical algorithms, Monte Carlo (MC) simulations are generally more accurate. However, the conventional MC algorithm's clinical uses are limited due to relatively slow speed.[14,15] Aitkenhead *et al*[16] introduced Gate[17] for dose re-calculation, which costs hundreds of CPU hours. Beltran *et al* showed their in-house GPU-based fast MC algorithm for patient-specific QA, which is much fast but only limited to their single institute usage.[18] This work aims to develop a dedicated platform for rapid, independent dose verification for PBS proton therapy and introduce the entire workflow that can be adapted to other proton therapy clinics.

MCsquare is a multipurpose, CPU-based fast MC algorithm developed by Souris *et al*.[19] Compared with conventional MC codes such as Geant4,[14,20,21] TOPAS,[15] and Fluka,[22] etc. it reduces the simulation time significantly with analogous accuracy. Huang *et al* commissioned MCsquare for a cyclotron-based proton machine universal nozzle and explored its clinical implementations.[23,24] Deng *et al* commissioned MCsquare for a synchrotron-based proton machine and integrated it into their in-house C++-based I/O user interface for second dose calculation.[25] In this study, MCsquare was commissioned and integrated into RayStation (RaySearch Laboratories, Sweden)[26] using the programing language Python (version 2.7). The calculation accuracy and efficiency of MCsquare in RayStation (MC2InRS) were validated by the TPS and measurements using both water phantom and patient data. Both Proteus®Plus and Proteus®ONE beam models were commissioned for clinical use at our institute, and only Proteus®ONE results will be displayed to simplify the report.

Materials and Methods

Commissioning the MCsquare Beam Model

Proteus®ONE is a compact synchrocyclotron system designed by IBA (Ion Beam Applications, Belgium).[27] For this study, our initial benchmark measurements were performed with 33 beam energies (70-225 MeV per 5 MeV step plus 227 MeV) to obtain an MCsquare beam model for Proteus®ONE. Proteus®ONE only has 1 range-shifter thickness available with different sizes, approximately 4.1 cm water equivalent thickness (WET) and density of 1.2 g/cm3, for shallow target treatment. The Beam Data Library (BDL) was implemented as a look-up table, and the source plane is located at 45 cm ahead of the isocenter, which contains parameters that characterize the beam for various energies. The beam parameters were tuned to align the MCsquare simulation with experimental measurements first. The range shifter parameters, including material, density, and WET were then added to build the beam model. The commissioning steps include 1) modeling the beam optics, 2) modeling the beam energy spectrum, and 3) modeling Proteus®ONE output as a function of energy in terms of protons per MU. The detailed methods and procedures can be found in previous publications.[24,28,29]

Integrated depth dose (IDD) was measured by StingRay (IBA Dosimetry, Germany) in the Blue Phantom PT (IBA Dosimetry, Germany) with a 6-cm sampling radius. The energy spectrum is a Gaussian distribution, where the energy spread is defined as a percentage of the mean energy value. The beam parameters for each energy were determined by adjusting the mean energy and energy spread of MCsquare IDD to match the measurement. The fitting parameters were validated by comparing the distal range of 20% (R20) and 80% (R80) dose levels of MCsquare IDD with measured IDD.

Spot profiles in the air were acquired using a scintillation screen/charged-coupled device (CCD) camera detector (Lynx PT—IBA Dosimetry, Germany), at the distances of −40, −20, −10, 0, 10, and 20 cm from the isocenter along the beam direction, with a 0.5-mm spatial resolution. The optical parameters, including spot sigma (the standard deviation of spot position distribution), angular variance (the standard deviation of angular distribution), and sigma-angular correlation (the correlation between spot sigma and angular variance) at the nozzle exit (−45 cm from isocenter), were extracted from the measurement at those 6 different positions. With the optical parameters, a bivariate 2D Gaussian per axis was used to sample particle position and momentum direction; the detailed procedure is described in the previous study.[20]

A PPC05 chamber (Parallel Plate Chamber—IBA Dosimetry, Germany) was used to determine the absolute dose in water with a 10×10 cm^2 field at the effective measurement depths of 2.18 cm, 4.18 cm, 6.18 cm, and 8.18 cm for energies of 70-90 MeV, 95-110 MeV, 115-120 MeV, and 125-227 MeV, respectively. The absolute dosimetry calibration approach proposed by Goma *et al* was used to calculate the number of protons per MU.[30]

Design of Independent Dose Verification Platform

Figure 1 illustrates the design and workflow in the MC2InRS platform. This platform can perform the independent dose calculation for both the QA plan (in water) and the clinical plan

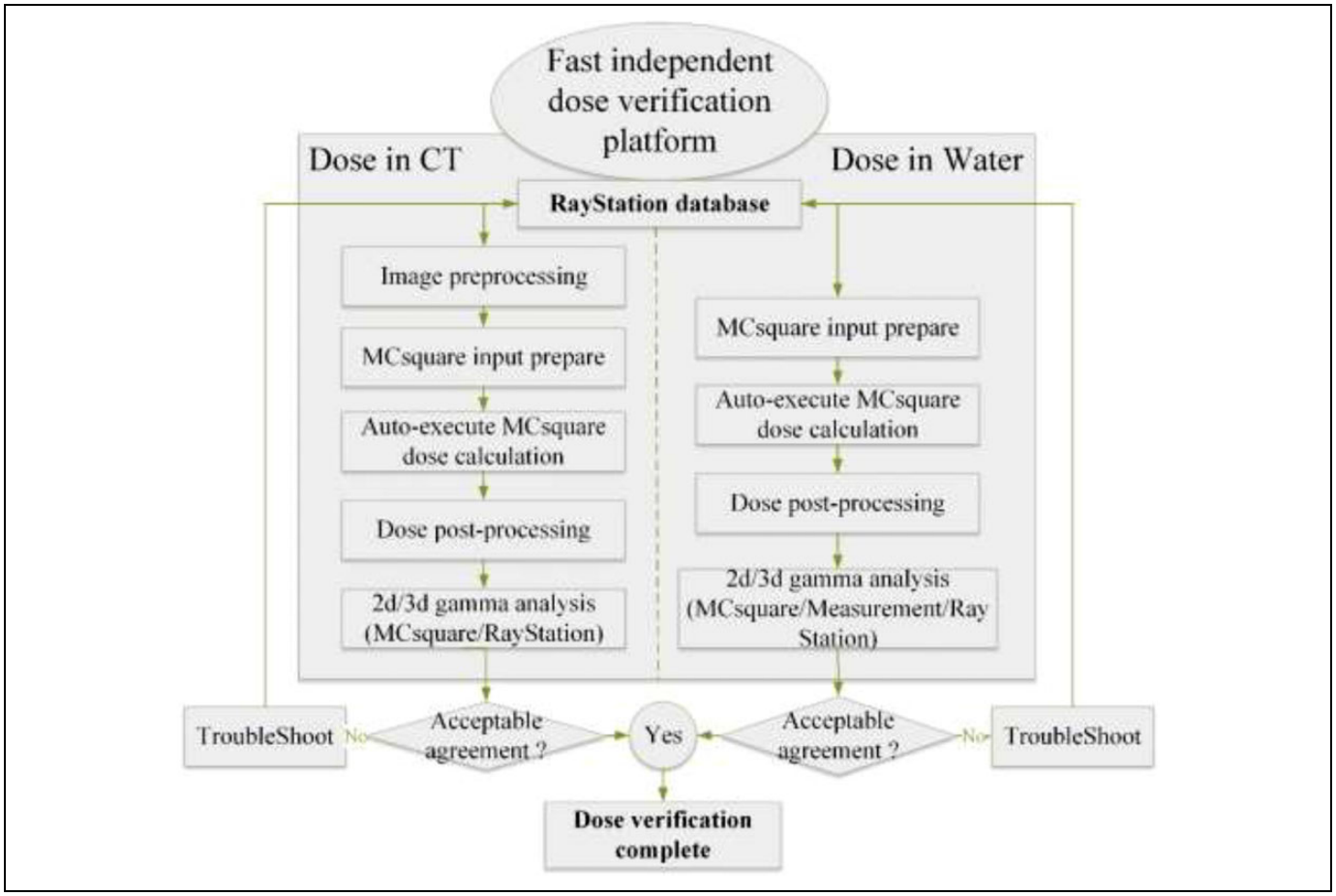

Figure 1. Workflow for PBS independent dose verification using MC2InRS.

(CT). For dose in water, the pre-processing includes creating water phantom virtual CT reference to TPS QA plan dose grid setting, generating config files, and translating the QA plan. The dose grid (size of $150 \times 150 \times 152$ and resolution of $2 \times 2 \times 2$ mm^3) in MCsquare calculation is identified as the input virtual CT. Post-processing writes the output results to DICOM format for the final comparison. For Dose in CT, the pre-processing consists of exporting the original CT files, RT Struct, RT Dose and RT Plan files, generating the input and config files, and translating the RT plan. The dose calculation grid is identical to the original CT resolution. The post-processing includes translating the output result back to DICOM format and resampling using the TPS dose grid setting as a reference. All the above steps are performed automatically in MC2InRS. 2D and 3D gamma analysis is also integrated into MC2InRS for quantitative analysis.

Validation of MC2InRS

Three steps were used to perform end-to-end tests of the MC2InRS platform: 1) comparison of spread-out Bragg peak (SOBP) and lateral dose profiles against measurements, 2) comparison of the simulation results against RayStation results and PSQA measurements, and 3) comparison of the simulation results against RayStation with patient geometries.

Dose comparison with a uniform target in the water. To quantitatively compare the IDD and lateral dose profiles among MCsquare simulations, RayStation calculations, and measurements, a $40 \times 40 \times 40$-cm^3 water phantom was created in RayStation. Uniform targets of $3 \times 3 \times 3$ cm^3, $5 \times 5 \times 5$ cm^3, $7 \times 7 \times 7$ cm^3 were generated at the depths of 5, 10, 15, and 20 cm in the water phantom. In total, 12 targets were created, and 12 treatment plans were optimized accordingly, with the prescription set to a uniform dose of 200 cGy to the targets. SOBP curves and lateral dose distributions were extracted and compared for these plans; gamma analysis at various depths was conducted using the built-in gamma analysis module of the MC2InRS platform.

Comparisons with PSQA water measurements. Currently, our institution's clinical PSQA workflow is to deliver the QA plans to MatriXX^{ONE} placed in a water tank at several different depths. 2D dose distributions at these measurement depths are compared with the TPS results at the same depths. The same method was used in this study to validate the MC2InRS

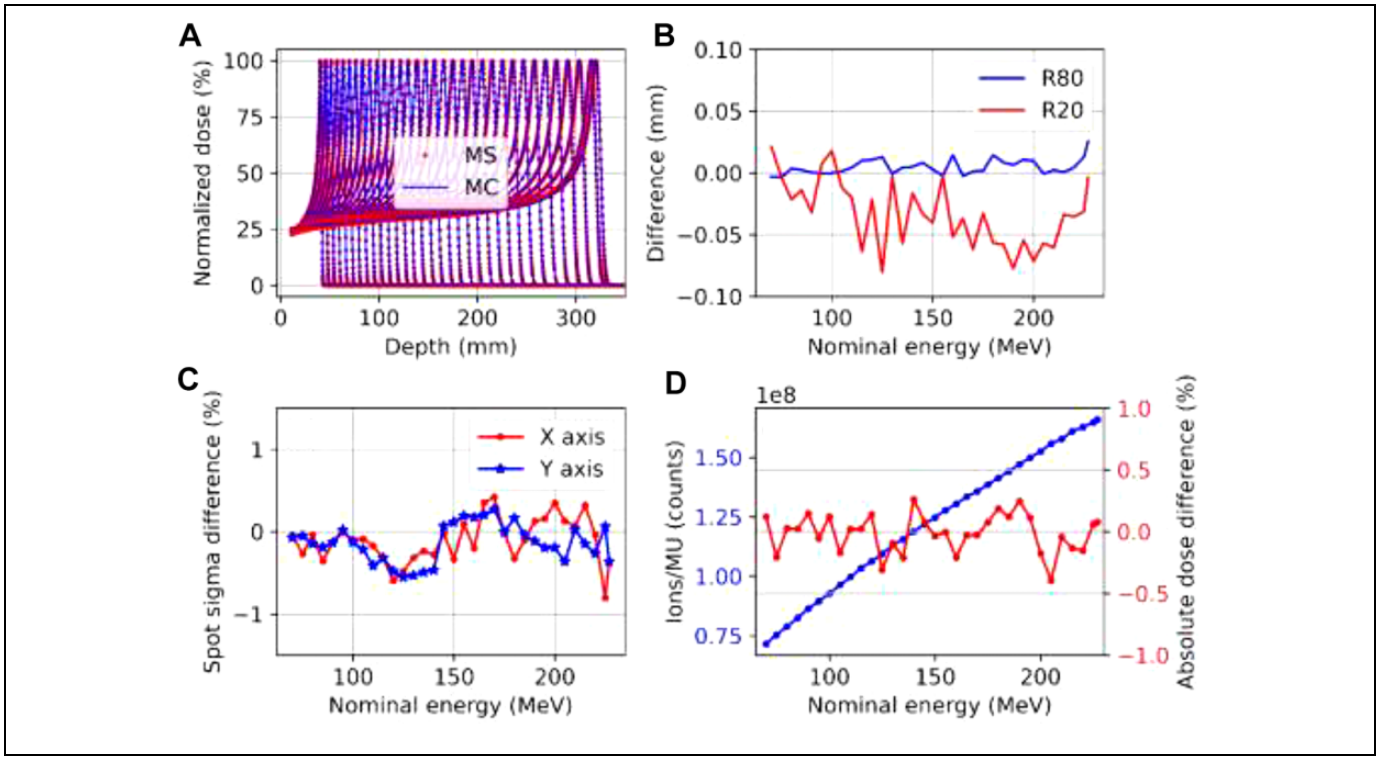

Figure 2. A, IDD curves in water for all 33 proton beam energies tested. Circle points represent measurement data, and the solid lines represent MCsquare simulation results. B, Range differences between measurements and MCsquare simulation for each energy. C, In-air spot sigma difference at isocenter for horizontal (X-axis) and vertical (Y-axis) directions. D, Absolute dose difference between MCsquare and the measurement (Red line) and the number of protons per MU as a function of nominal energy obtained in MCsquare (Blue line). MS indicates measurement; MC, MCsquare.

platform. Both 3%/3mm and 2%/2mm criteria were implemented between measurements and MC2InRS or TPS. All gamma analyses conducted in this study used local gamma criteria with a 10% low dose threshold.

Comparisons with RayStation patient CT calculation. It is relatively simple to validate MCsquare in water. It is more clinically meaningful to validate TPS calculation in CT with patient geometry; however, limited by measurement conditions, this is hard to achieve in measurement. Benefiting from the capacity of the MC2InRS platform, we were able to calculate the dose with patient CT geometries after calibrating the CT Hounsfield unit-to-density/material transformation. Fifteen patients (5 prostate, 5 head and neck (H&N), and 5 craniospinal irradiation (CSI) cases) were retrospectively studied to validate the MC2InRS platform and demonstrate its effectiveness for clinical use. For H&N and CSI cases, the dose was optimized and calculated by the RayStation MC algorithm with 0.5% uncertainty. For prostate cases, a pencil beam algorithm was used in RayStation to do the optimization. The corresponding cases were re-calculated by MC2InRS with 0.5% uncertainty. The clinical practice criterion of 3%/3mm and a tighter 2%/2mm gamma analysis were performed to quantify the dose difference between RayStation and MC2InRS.

Results

Single Spot IDD Curves, Spot Size, and Absolute Dose Difference

Figure 2 shows the beam parameters fitting results from the MCsquare beam model. As shown in Figure 2A, the IDD curves from MCsquare simulations are in good agreement with the measurements. The R80 difference and R20 difference for each energy are below 0.05 mm, 0.1 mm, respectively, as shown by blue and red lines in Figure 2B. The difference in in-air spot sigma at the isocenter from the MCsquare simulation and measurement was less than 1% for all 33 beam energies, as shown in Figure 2C. The absolute dose differences between MCsquare and the measurement were below 0.5%, as shown by the red dots in Figure 2D. The number of protons per MU as a function of nominal energy is shown in Figure 2D blue line.

SOBP and Lateral Profile Validation

Figure 3 shows the SOBP and lateral profile comparisons between the measurement and simulation for various uniform targets in the water phantom. Figure 3A-C shows the SOBP for $3 \times 3 \times 3$ cm^3, $5 \times 5 \times 5$ cm^3 and $7 \times 7 \times 7$ cm^3 targets at depths of 5, 10, 15, and 20 cm, respectively. For all 3 targets, the R80 difference is below 1%, and the distal 80%-20% distance is

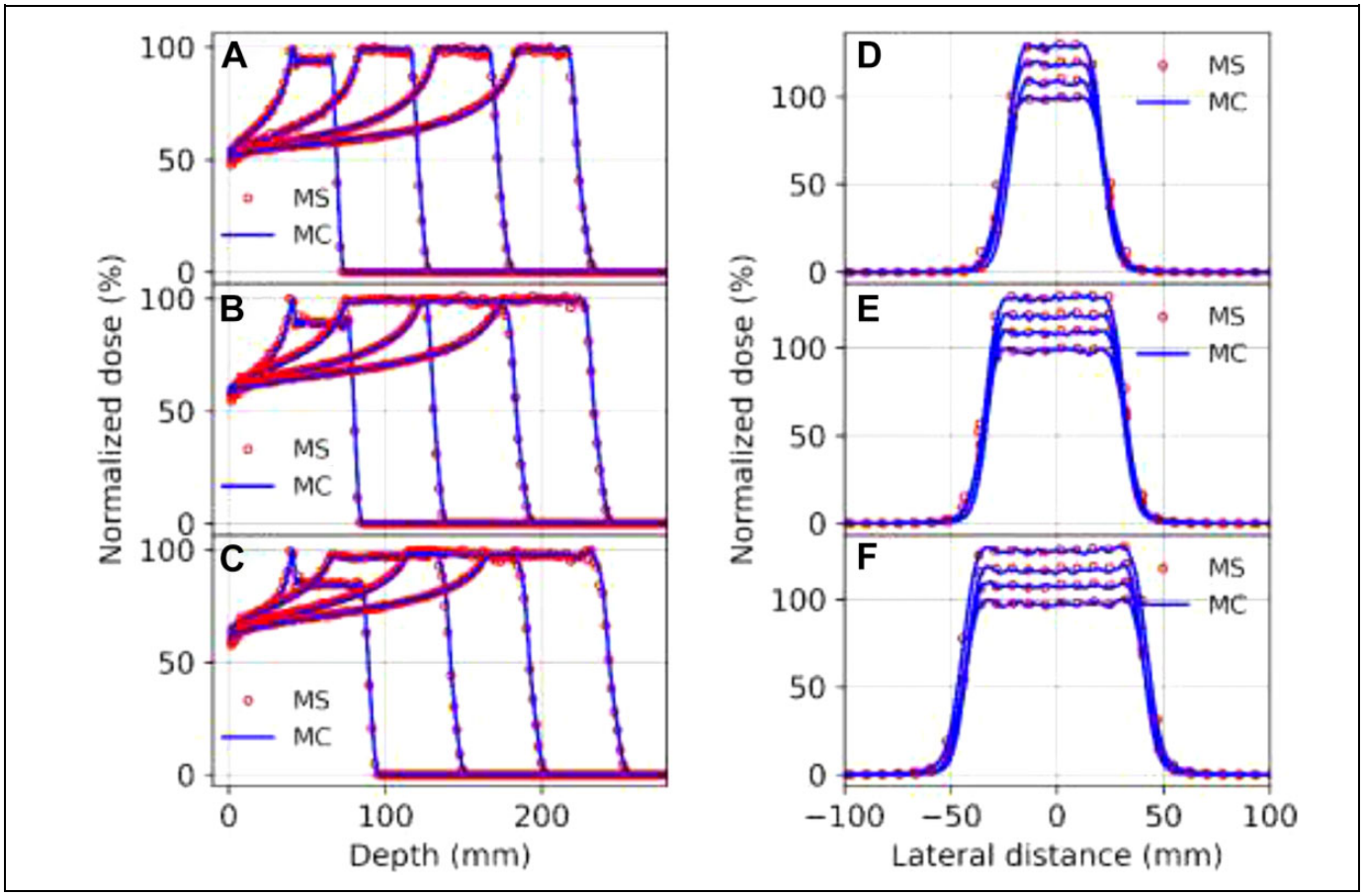

Figure 3. A-C, SOBPs from MCsquare and the measurements for $3 \times 3 \times 3$ cm^3, $5 \times 5 \times 5$ cm^3, and $7 \times 7 \times 7$ cm^3 target at depths of 5, 10, 15, and 20 cm, respectively. D-F, Lateral dose profiles at the horizontal direction target center plane at different depths. The SOBPs or lateral dose profiles from MCsquare and measurement at an identical position or depth were scaled by the same factor. For a clearer view, the lateral dose profiles in (D), (E), and (F) were scaled by a factor of 1.0, 1.1, 1.2, and 1.3 for the depths of 5, 10, 15, and 20 cm respectively. MS indicates Measurement; MC, MCsquare.

below 0.3 mm. A small dip for all 3 targets at a depth of 5 cm is observed, and the SOBP width is less than the planned width. The problem is due to the need for energy layers below 70 MeV, which are unavailable without a range shifter. Figure 3D-F shows the lateral dose distribution for the 3 targets at different depths. The maximum FWHM (full width at half maximum) and lateral penumbra differences are below 1 mm and 0.5 mm, respectively.

Table 1 shows the gamma analysis results at different planes for various uniform targets in the water phantom. The measurement depths were at the entrance surface, mid-surface, and exit surface of the target. The 3D calculation spatial resolution in MC2InRS was $2 \times 2 \times 2$ mm^3, and the corresponding slice was extracted to compare with the measured planar dose. For all planes, gamma passing rates (GPRs) reach 100% at the criteria of 3%/3mm. When setting 2%/2mm as the evaluation standard, 29 out of 36 planes get 100%, and the minimum is 98.3%.

Comparisons With PSQA Measurements in Water

Table 2 shows the PSQA gamma analysis results for all 15 patients. The measured planar dose is regarded as a reference dataset, and MCsquare or RayStation dose is considered to be an evaluation dataset that is interpolated when doing 2D gamma analysis. When comparing 2D or 3D dose from RayStation and MCsquare, RayStation dose is regarded as the reference dose. From the 3D gamma analysis results, the average GPRs are 100% and 98.9% for 3%/3mm, and 2%/2mm criteria, which indicates the dose from MC2InRS is very close to RayStation. The average 2D GPRs for 3%/3mm and 2%/2mm are 99.4% and 95.4% for MC2InRS compared with measurement, which is 99.9% and 99.3% compared with RayStation, respectively. For 2D gamma analysis, most GPRs are 100% for the 3%/3mm criterion, and the worst one is 94.5%. In general, MC2InRS calculation is very consistent with RayStation, the measurement coincidentally varied, and it could be caused by low resolution (7.6 mm) of MatriXX^{ONE} and setup errors.

Comparisons With RayStation 3D Calculation Using Patient CT

Table 3 shows the 3D patient-specific QA gamma analysis results with patient geometry for all 15 patients between

Table 1. Results of 2D Gamma Analysis of MCsquare Versus Measurements for Uniform Targets.[a]

Target	Iso depth (cm)	Measurement depth (cm)	2D GPRs (2%/2 mm)
3 × 3 × 3	5	4,5,6	100,100.100
	10	9,10,11	100,100,100
	15	14,15,16	98.3,100,100
	20	19,20,21	100,100,100
5 × 5 × 5	5	3,5,7	98.3,99.2,100
	10	8,10,12	99,99,100
	15	13,15,17	100,100,100
	20	18,20,22	99,100,100
7 × 7 × 7	5	4,5,8	100,100,100
	10	7,10,13	99.3,100,100
	15	12,15,18	100,100,100
	20	17,20,23	100,100,100

Abbreviation: GPRs, gamma passing rates.
[a]Local gamma criteria with a 10% low dose threshold were applied.

RayStation and MCsquare. Most of the GPRs are above 99% for the 3%/3mm criterion, and the worst one is above 96% and 93.2%% for 3%/3mm and 2%/2mm, respectively. The average GPRs between RayStation and MCsquare are 98.6% and 95.3% for 3%/3mm and 2%/2mm, respectively.

Figure 4 shows the 2D dose distribution maps in 3 planes for CSI patient 3 as an example.

MC2InRS Efficiency Analysis

Table 4 shows the MC2InRS time analysis using the number of protons of 1×10^8 as an example. In this test, statistical uncertainties of 1%, 1.5%, and 2% were reached for prostate, H&N, and CSI cases, respectively, when 1×10^8 protons are simulated for each subject. Since the MC2InRS is integrated into RayStation, all simulations were performed on the RayStation server (System: Microsoft Windows Server 2012; CPU: 2*Intel Xeon E5-2667 v3@3.20 GHz, 16 cores/32 threads in total; Memory: 240 GB; GPU: NVIDIA Quadro K6000&K4200), MCsquare utilized 32 threads of CPU and under 40 GB memory during the simulation. The GPU was not used since MCsquare is based on multi-cores/threads CPU only. The number of parallel calculation threads was set as 0 (using all threads) in the config file. The default physics parameters, including nuclear interactions, secondary protons, secondary deuterons, and secondary alphas, were simulated for all cases without variance reduction methods. The average time includes pre-processing, second dose calculation, post-processing, and gamma analysis time. All 5 cases were used to determine the average calculation time for each site.

Discussion

This work commissioned the MCsquare beam model for Proteus®ONE proton therapy system at our institute, successfully integrated it into RayStation TPS to create an auto-fast independent dose verification platform for PBS proton therapy. A series of uniform target plans were designed to verify the beam model preliminarily. $3 \times 3 \times 3$ cm^3, $5 \times 5 \times 5$ cm^3, and $7 \times 7 \times 7$ cm^3 targets were used in this study. Depths of 5, 10, 15, and 20 cm cover most of the Proteus®ONE range. For all 33 tested beam energies, the in-air spot sigma difference between the MCsquare simulation and measurement was less than 1% at the isocenter position. For all 3 targets, the range (R80) difference was below 1%, and the distal 80%-20% distance was below 0.3 mm. The maximum FWHM and lateral penumbra difference were below 1 mm and 0.5 mm, respectively. Of the 36 planes, 29 reached a 100% gamma passing rate with a 2%/2mm criterion, and the minimum was 98.3%. All of which demonstrates the excellent agreement between MC2InRS simulation and the measurements. Among H&N, CSI, and prostate cases, H&N cases calculations were the fastest on the MC2InRS platform, which is not surprised since lower energies used in the H&N cases require fewer particle interactions and processes in the media. CSI cases have huge targets, which costs more time to perform the calculation. Above all, using the MC2InRS fast dose verification platform, with 1×10^8 protons on a 32 CPU-cores server, it took an average of 5.7 min, 3.5 min, and 4.4 min to finish one patient's QA plan in water for prostate, H&N, and CSI cases, respectively. For patient cases using CT, the corresponding time was 40.3 min, 26.6 min, and 54.9 min, respectively. The commission and validation results of this work proved that MC2InRS is accurate, fast, and has the potential to be used in clinical practice. As mentioned above, the highly integrated MC2InRS only took about 5 min to finish a water phantom-based PSQA. The dose comparisons with patient CTs between TPS and MCsquare are also meaningful and enrich the QA activities. The range shifter usually is a critical factor that has a positive influence on dose calculation for the pencil beam algorithm. We have not observed any significant dose or gamma passing rate discrepancies with and without range shifter since the RayStation MC algorithm was used at our institute. In this work, all patient cases except for prostate cases used a range shifter for each field. The patient results also indicate that the MC algorithm is accurate with or without a range shifter in PBS proton therapy.

This study is more focused on the clinical practice of integrating the MC algorithm within the TPS to create a dedicated platform for secondary dose calculation on both patient treatment plan and QA plan. Once the patient treatment plan and the QA plan are ready as we do in routine clinical practice, the user can choose either or both plans to perform a secondary dose calculation using MC2InRS. In our institute's proton practice, the pencil beam algorithm is used for prostate cases. The MC algorithm is used for all the other instances such as H&N, breast, CSI, etc. Since the implementation of MC2InRS, 3 different QAs are performed for each PBS patient: secondary calculation with patient geometry, secondary calculation in a water phantom, measurement-based QA with multiple depths for each beam in the water tank.

In secondary calculation with patient anatomy, we observed that for the majority of the cases, 3%/3mm gamma passing rate

Table 2. Gamma Analysis Results for PSQA in Water, H&N, and CSI Cases With a Range Shifter of 4.1 cm WET, Prostate Cases Without a Range Shifter.[a]

				2D (in water)						
			3D (in water)		MS-MC		MS-RS		RS-MC	
Case	ID	Beam	3%/3mm, 2%/2mm	MS depths	3%/3mm	2%/2mm	3%/3mm	2%/2mm	3%/3mm	2%/2mm
Prostate	1	1	99.8, 98.7	21,24	100,100	100,93	100,100	95.2,90.8	100,100	99.9,100
		2	99.9, 98.7	21,24	100,100	96.8,94.5	100,100	92.1,89.8	100,100	100,100
	2	1	99.8,98.2	18,22	100,100	98.6,99.3	100,100	100,99.3	100,100	100,100
		2	99.7,97.5	18,22	100,100	97.2,98.6	100,100	100,95.7	100,100	100,100
	3	1	99.6,97.3	19,23	100,100	98,100	100,100	100,100	100,100	100,100
		2	99.6,97.3	19,23	100,100	92.7,96.7	100,100	99.3,100	100,100	100,100
	4	1	99.6,97.4	16,23	94.5,100	92.8,100	96.7,100	93.4,100	99.9,100	99.5,100
		2	99.7,97.7	16,23	99.7,100	94.8,98.5	100,100	98.6,97.1	100,100	100,100
	5	1	99.5,97.5	17,23	100,100	96.5,99.2	100,100	94.5,100	100,100	99.7,100
		2	99.6,97.7	17,23	100,100	98.7,98.8	100,100	98.2,100	100,100	99.6,100
H&N	1	1	100, 99.9	6,9	100,100	98.8,100	100,100	100,100	100,100	99.8,99.6
		2	100, 100	6,9	100,100	100,100	100,100	100,100	100,100	99.9,99.9
		3	100, 100	6,9	99.3,100	91.3,100	98.6,100	94.3,100	100,100	99.4,99.2
	2	1	100, 99.9	6,8	99.4,96	89.3,85.6	99.4,96.6	86.4,87.9	100,100	99.8,99.8
		2	100, 100	6,8	98,97.5	96.6,83.8	97.3,97.5	93.2,88.8	100,100	99.9,99.5
		3	100, 100	6,8	99.1,100	94.2,99.2	98.2,100	93.4,99.2	100,100	99.8,99.9
	3	1	100,100	4,6	100, 100	96.9, 94.8	100, 98.7	97.5, 90.9	99.9, 100	99.5, 99
		2	100,100	4,6	100, 100	98.3, 99.3	100, 100	97.1, 99.3	100, 99.9	100, 98.6
		3	100,100	4,6	98.9, 98.9	92, 92.7	97.9,98.3	92, 89.9	100, 100	99.6, 99.8
	4	1	100,99.7	4,6	100,100	93.2,88.9	100,99.7	90.2,91	100,100	99.6,99.5
		2	100,99.6	4,6	99.2,96.1	91.7,82	99.7,98.4	94.4,87.2	100,99.9	99.6,99.5
		3	100,99.8	4,6	100,100	94.1,87.5	100,100	94.1,91.6	99.9,99.9	99.5,99.4
	5	1	100,99.9	4,7	99.7,100	99.2,99.6	100,100	99.2,99.6	100,99.9	99.5,99.1
		2	100,99.9	4,7	100,99.2	99.7,96.4	100,100	99.7,99.6	99.9,99.7	99.4,98.4
		3	100,99.9	4,7	99.7,100	99.1,99.7	99.7,100	98.8,100	99.9,99.9	99.6,99.1
CSI	1	1	99.8,98.9	7,9	100,98.1	96.3,94.6	100,100	98.1,90.4	100,100	100,99.6
		2	99.9,98.8	9,11	98.2,96	87.7,90	100,98	94.7,96	100,98.9	99.6,96.8
		3	99.7,98.7	7,9	100,98.2	92.9,75	100,100	96.4,83.9	100,99.9	100,99.5
	2	1	100,99.1	9,15	99.5,100	94.9,98.1	100,100	99,98.5	100,100	99.6,100
		2	100,99.8	5.5,7.5	99.3,97.6	94.8,83.5	100,100	98.3,92.9	100,99.9	99.8,97.4
		3	100,99.9	5.5,7.5	98.3,99.6	93.2,79.5	100,100	99.3,87.3	100,99.9	99.2,98.4
		4	100,99.6	7.5,9	100,93.8	97.8,91.9	100,99.2	99.7,94.6	100,99.7	98.8,96.3
	3	1	100,99.5	4,7	100,100	98.5,99.7	100,100	98.8,100	100,100	98.7,99.6
		2	100, 100	4,7	100,96.2	98.3,89.6	100,100	97,99.5	100,98.3	99.9,93.8
		3	100, 100	4,7	100,99.4	100,94.4	100,100	100,100	100,99.2	100,96.1
		4	100,99.9	4,7	100,100	97.7,96.4	100,100	96.9,100	100,99.3	99.9,96
	4	1	99.1,93.7	3,7	100,100	96.9,99.8	100,100	99.2,99.8	100,100	97.5,98.3
		2	100,99.1	3,7	100,100	99.3,99.6	100,100	100,99.6	100,100	100,100
		3	100,99.4	3,7	100,100	99.6,99.6	100,100	100,100	100,100	100,99
	5	1	98.1,91.5	5,7	100,100	92.3,97.8	99.8,100	96.3,97.4	99.7,99.8	96.3,97.4
		2	100,99.7	5,7	100,99.7	97.7,96.1	100,100	97.1,97.6	100,100	99.8,99.3
		3	99.8,97.7	5,7	100,100	99.7,99.3	100,100	99.7,98.8	99.8,99.6	99.3,98.6

Abbreviations: H&N, head and neck; CSI, craniospinal irradiation; ID, identification; MS, measurement; MC, MCsquare; RS: RayStation. RayStation algorithm: H&N and CSI cases: MC algorithm; Prostate cases: pencil beam algorithm.
[a]Local gamma criteria with a 10% low dose threshold were applied.

(local normalization, 10% dose threshold) between TPS calculation and MC2InRS is above 96%, 98%, for H&N, and all the other sites, respectively. The corresponding values for 2%/2mm are 92% and 93%. The acceptable agreement in Table 1 is set to meet both the 3%/3mm and 2%/2mm criteria above. The troubleshooting process will be triggered if proper criteria do not meet. The user then must compare the dose coverage for both targets and organs at risk from TPS calculation and MC2InRS calculation. DVH from each calculation will be exported to our in-house created golden sheet to ensure the dose constraints meet. Most of the time, the discrepancies from TPS and MC2InRS are from the dose by the in-air beam spots outside of the body because these plans are optimized by TPS using robust techniques. For secondary calculation in water, the

3%/3mm gamma passing rate between TPS calculation and MC2InRS is 100% for most cases, and 2%/2mm is above 96%. The acceptable agreement in Table 1 is set to meet the 2%/2mm criteria accordingly. Currently, we do not do any troubleshooting if the acceptance criteria do not meet but using the measurement-based QA to verify the results. Our measurement-based patient-specific QA is still serving as the gold standard, and 2 different depths are measured for each beam.

Table 3. MCsquare Calculation Versus RayStation Calculation 3D Gamma Analysis With Patient Geometry.[a]

	3D GPRs (3%/3mm, 2%/2mm)				
Case	1	2	3	4	5
Prostate	99.5,95.9	99.3,96.1	99.1,94.7	98.1,93.7	99.2,95.2
H&N	98,95.4	96,93.2	97.5,95.2	98.5,96.2	99.3,96.7
CSI	99.1,95.6	98.8,94.5	99,96.1	99.4,95.9	98.6,95.4

Abbreviations: H&N, head and neck; CSI, craniospinal irradiation; GPRs, gamma passing rates.
[a]Local gamma criteria with a 10% low dose threshold were applied.

There is a debate about how MC2InRS can be used in proton therapy. One opinion is only using MC2InRS as a standard clinical practice and keeping doing measurement-based PSQA. The other is to explore the potential of using MC2InRS to reduce measurements if the acceptable gamma passing rate mentioned above is achieved between MC2InRS and TPS with patient anatomy. Currently, MC2InRS is only used as a secondary dose calculation tool for PBS at our institute. We are still collecting secondary dose calculation data with both patient anatomy and water phantom to investigate further the possibility of reducing the number of measurements depending on the MC2InRS calculation.

This work introduces the entire workflow of commissioning, validating, and integrating MCsquare into RayStation for independent dose verification. Aside from the TPS's dose-calculation accuracy, the data transfer's integrity from the TPS to the accelerator control system and delivery of the treatment also must be checked during the PSQA process.[9] Machine log file-based QA was investigated by several studies.[31-33] This function is currently under development at our clinic and will be added to the MC2InRS platform in the future. Finally, in our opinion, the calculation-measurement-combined approach

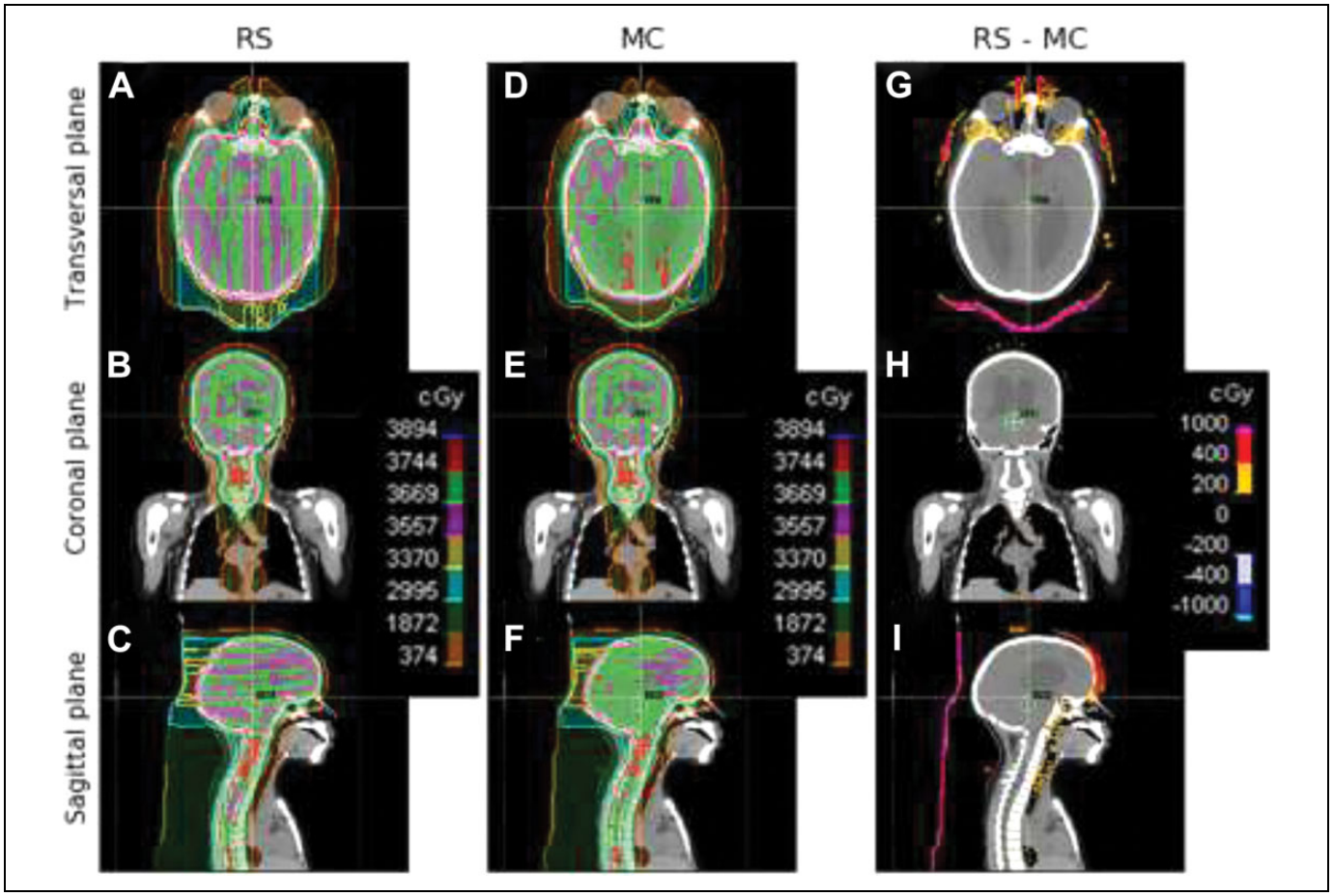

Figure 4. 2D dose distribution maps in 3 planes for CSI patient 3. A-C, RayStation calculation results. D-F, MC2InRS calculation results. G-I, 3D dose difference. RS indicates RayStation; MC, MCsquare.

Table 4. Time Analysis Table of the MC2InRS Platform.

Case	Size	Grid (mm)	Number of protons	Type	Average time (minutes)				
					Pre-processing	Auto-execute MCsquare	Post-processing	3D gamma analysis	Total
Dose in Water	X:150	X:2	1e8	Prostate	0.1	5.2	0.2	0.2	5.7
	Y:150	Y:2		H&N	0.1	3.0	0.3	0.1	3.5
	Z:152	Z:2		CSI	0.2	3.6	0.3	0.4	4.5
				Average	0.1	3.9	0.3	0.2	4.5
Dose in CT	X:512	X:1.17		Prostate	3.3	36.2	0.3	0.5	40.3
	Y:512	Y:1.17		H&N	5.8	19.5	0.5	0.8	26.6
	Z: [a]	Z:1		CSI	4.0	48.5	0.8	1.6	54.9
				Average	4.4	34.7	0.5	1.0	40.6

Abbreviations: H&N, head and neck; CSI, craniospinal irradiation.
[a]Z differs as the individual patient. Z is between 369-399, 387-415, and 343-463 for H&N, CSI and prostate cases, respectively.

would be more suitable for PBS secondary dose verification. Either adding or reducing the measurement can be determined by the users based on the second calculation results from the MC2InRS platform.

Conclusion

This study introduced an independent dose verification platform named MC2InRS based on the MCsquare dose calculation engine and RayStation TPS. Excellent agreement was observed between the measurement and the MC2InRS platform, which proves the platform's accuracy and reliability. In the future, more functions, including variable relative biology effectiveness (RBE)-based dose calculation and machine log file-based dose verification, will be integrated into this platform.

Acknowledgments

Chunbo Liu is supported by the China Scholarship Council (CSC) during his visit to the University of Florida Health Proton Therapy Institute (UFHPTI). The authors would like to thank MCsquare developers Dr. Kevin Souris and Ms. Marie Cohilis for their kindly help during MCsquare CT calibration. The authors also would like to thank Ms. Jessica Kirwan from the University of Florida Department of Radiation Oncology Research & Editorial Office for the editorial review of this manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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