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Full-Angle PSQA Using a 4D Phantom: Advancing Toward Proton Arc Therapy QA

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ABSTRACT

Purpose: To introduce and evaluate a rotational integration phantom that enables full-angle patient-specific QA (PSQA) in proton therapy using a standard, ion chamber-based commercially available detector. The focus of this work is to develop an angle-dependent PSQA workflow suitable for advanced delivery techniques, including IMPT and emerging proton arc therapy approaches.

Methods: We inserted a clinically used ion-chamber array detector (PTW Octavius 1500XDR) into a rotational phantom (PTW Octavius 4D). The rotational phantom is controlled by an inclinometer attached to gantry, allowing it to rotate synchronously with gantry and maintain the detector array perpendicular to proton beam. Detector alignment to isocenter was verified using orthogonal kV imaging. Two clinical PSQA fields, consisting of brain and thorax plans, were delivered daily over three consecutive days at angles of 0°, 45°, and 90°. Gamma analysis was used to evaluate daily reproducibility and angular dependence of measured dose distributions.

Results: Dose measurements demonstrated high reproducibility across all days and gantry angles. At 3%/3 mm criterion, gamma passing rates for brain and thorax averaged 95.0% (SD = 0.96) and 98.5% (SD = 0.75), respectively, while at 2%/2 mm criteria averages were 89.1% (SD = 2.07) and 88.4% (SD = 3.31). These results were in very close agreement with corresponding clinical PSQA records. No systematic degradation was observed with gantry rotation, and all angles produced consistent results between measurement days.

Conclusion: This study demonstrates that full-angle PSQA can be achieved reliably using a single setup of a rotational phantom integrated with a standard ion-chamber array. The approach proved operationally practical and provided an efficient, clinically consistent framework, indicating that routine PSQA can be extended beyond fixed gantry orientations without added complexity. By incorporating custom depth capability, this framework enables smooth verification for wide range of angles and depths, laying the groundwork for QA methodologies required for emerging proton arc therapy techniques.

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INTRODUCTION

Our clinic utilizes the Mevion Synchrocyclotron Hyperscan S250i for proton therapy treatments. Treatments are delivered at a range of static angles from 0-180 degrees. Typically, patient-specific quality assurance (PSQA) is performed at 0 degrees for all treatment fields (**Fig. 1**), with occasional verification at 90 degrees. This setup is necessitated by the use of an ion chamber array detector that must remain perpendicular to the beam during measurement. While this workflow is effective, small variations in machine performance can be seen for the same field when delivered at multiple angles. This project incorporates a rotating 4D phantom to allow PSQA to be evaluated at multiple gantry angles, with the ultimate goal of evaluating beams at the treatment angle. The development of this workflow would also pave the way for assessing emerging proton are therapy treatment plans.

METHODS AND MATERIALS

Regular PSQA workflow utilizes the PTW Octavius 1500XDR, an ion chamber array detector. This detector is compatible with the PTW Octavius 4D, a rotational phantom controlled by an inclinometer attached to the gantry. The inclinometer and rotational feature ensure the ion chamber array remains perpendicular to the beam at all times. For initial setup, the ion chamber array and phantom were aligned to isocenter at 0 degrees, with the array facing upward (**Fig. 2**). Isocenter alignment was verified using orthogonal kV imaging in both the lateral and anterior/ posterior directions. Once alignment was verified, the inclinometer was activated, allowing the phantom to rotate with the gantry to the specified angles. Calibration of the detector was performed each day, followed by verification of the beam at 0 degrees.

Two clinical fields (one brain, one thorax) were delivered at angles 0, 45, and 90 degrees. Fields were evaluated via gamma analysis for reproducibility and angular dependence. The results of the gamma analysis of rotational workflow measurements were compared to those of conventional PSQA measurements.

Figure 1. Conventional PSQA setup at 0 degrees, with added solid water build up.

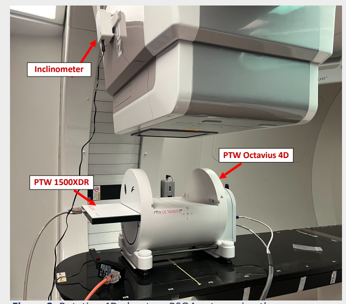

Figure 2. Rotating 4D phantom PSQA setup using the same array detector.

Table 1. Gantry angle-dependent gamma results of average passing rate over all measurements for the Thorax clinical plan.

Thorax – Rotating Phantom		
Gantry Angle	Average Passing Rate (2%/2mm)	(3%/3mm)
0	85.8	97.9
45	88.2	98.3
90	91.1	99.3

Table 2. Gantry angle-dependent gamma results of average passing rate over all measurements for the Brain clinical plan.

Brain – Rotating Phantom		
Gantry Angle	Average Passing Rate (2%/2mm)	(3%/3mm)
0	88.3	95.0
45	90.7	95.0
90	88.3	95.0

Table 3. Gamma analysis results of the Thorax and Brain plans using the conventional PSQA method (Gantry = 0 degrees).

Thorax & Brain – Conventional PSQA		
Treatment Plan	Passing Rate (2%/2mm)	(3%/3mm)
Thorax	88.7	100.0
Brain	90.2	96.1

RESULTS

Table 1 and **Table 2** display the average passing rate for each measurement taken at the specified gantry angle for the Thorax plan and Brain plan, respectively.

The total average passing rate for the Thorax plan was 89.1% (SD=2.07) using 2%/2mm criterion and 98.5% (SD=0.75) using 3%/3mm criterion. The passing rates of this plan using the conventional PSQA workflow were 88.7% (2%/2mm) and 100% (3%/3mm).

The total average passing rate for the Brain plan was 88.4% (SD=3.31) using 2%/2mm criterion and 95.0% (SD=0.96) using 3%/3mm criterion. The passing rates of this plan using the conventional PSQA workflow were 90.2% (22%/2mm) and 96.1% (3%/3mm).

DISCUSSION

The test angles of 0, 45, and 90 degrees were chosen as representative angles to evaluate a rotational PSQA workflow. Measurements taken at these angles demonstrated consistent gamma analysis passing rates and were consistent with passing rates of the conventional PSQA workflow. Future development of the rotational workflow will include consideration for attenuation of the treatment couch, allowing for verification of angles 90-180 degrees.

A current limitation of rotational PSQA is the inability to adjust measurement depth using solid water build up, as is common in conventional proton PSQA. This limits the selection of beams for testing to those with shallow depths to ensure the detector array is measuring within the ≥90% isodose region. This limitation could be mitigated by the use of modular phantom tops to allow testing of deeper fields.

CONCLUSIONS

The integration of the PTW Octavius 4D phantom with the Octavius 1500XDR enabled reliable proton PSQA measurements at multiple gantry angles using a single detector setup. Measured dose distributions showed reproducible gamma passing rates and close agreement with our clinic's conventional PSQA workflow, supporting the feasibility of treatment angle-specific verification. This methodology extends PSQA beyond fixed gantry orientations and provides a practical framework for the development of QA strategies for advanced proton delivery techniques, including proton arc therapy.