Applications of the RUBY phantom

in proton therapy

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Introduction

The availability of proton therapy is increasing with new centers starting operation throughout the world. The application of pencil beam scanning (PBS) is offering the largest potential for highly conformal dose distribution with enhanced sparing of organs at risk. New indications are being explored and the complexity of PBS treatments requires a thorough testing of all components of the proton therapy delivery chain.
The Westdeutsches Protonentherapiezentrum Essen is treating patients since 2013. Since then various upgrades have been installed, including the patient position verification system (PPVS).

The center is equipped with an IBA Proteus Plus multi-room proton therapy system and the majority of patients are treated with pencil beam scanning. A comprehensive quality assurance (QA) program is in place testing the single components on regular basis.
This document describes how RUBY was employed for detailed testing of the patient positioning workflow as well as for a systematic End2End test.

Patient positioning workflow QA

RUBY with Linac QA insert was positioned in a defined misalignment using the room laser system. The grey line enables translational displacement, the red line in combination with the tilted base enables translational and rotational displacement.

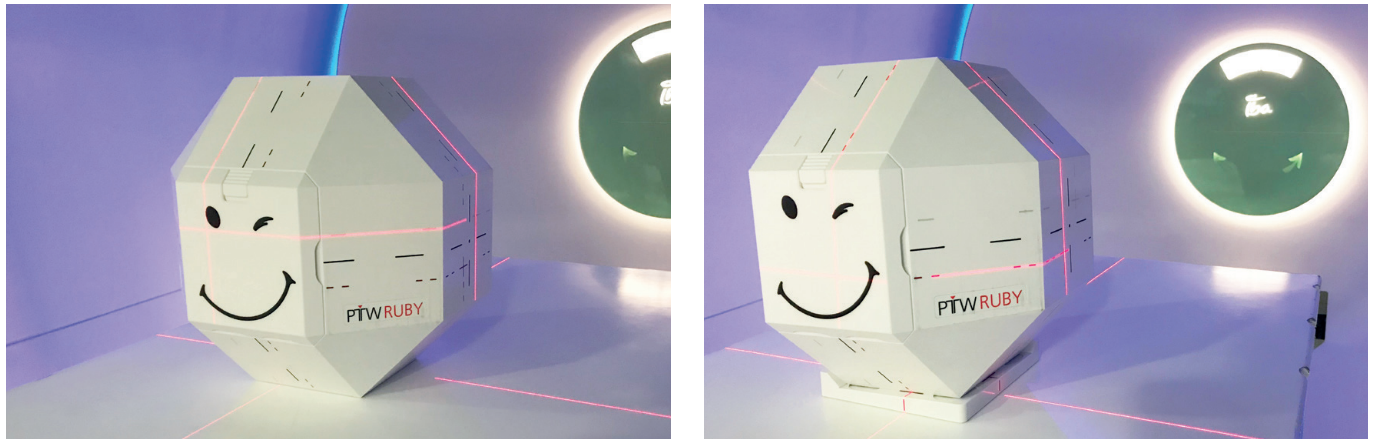


Figure 1: Left: RUBY positioned using the grey lines with translational shift. Right: RUBY positioned using tilting base and the red lines with translational and rotational shift.

VeriSuite

The patient positioning system VeriSuite (MedCom, Darmstadt) has been part of the initial system configuration. The system allows for a 3D/2D matching based on the initial planning CT and two orthogonal x-ray images. The determined correction vector is sent to the six-degree of freedom (6DOF) couch.

Orthogonal kV images were acquired using VeriSuite and pelvis preset. The image registration to the reference DRR images were performed by clinical staff manually. For both types of displacements, the defined misalignment was determined within 1 mm and 0.2° by the clinical staff.

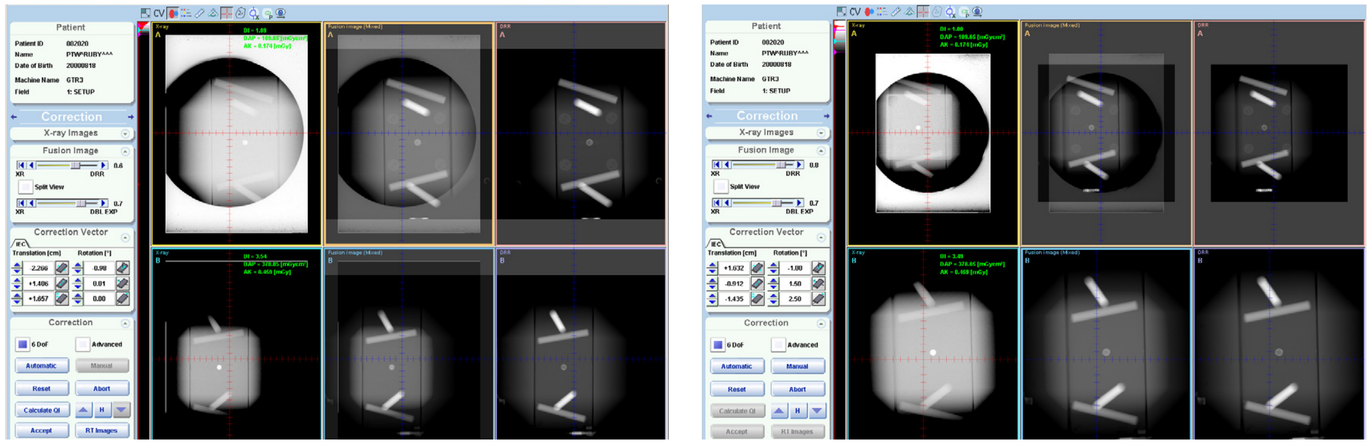


Figure 2: Left: Manual image registration for translational shift. Right: Manual image registration for translational and rotational shift.

AdaptInsight

AdaptInsight (IBA, Louvain La Neuve) works with a 3D/2D matching for the 6DOF couch of the delivery system. Orthogonal kV images were acquired using AdaptInsight and pelvis preset. The image registration to the reference DRR images were performed automatically. For both types of displacements, the defined misalignment was determined within 1 mm and 0.3° by automatic workflow.

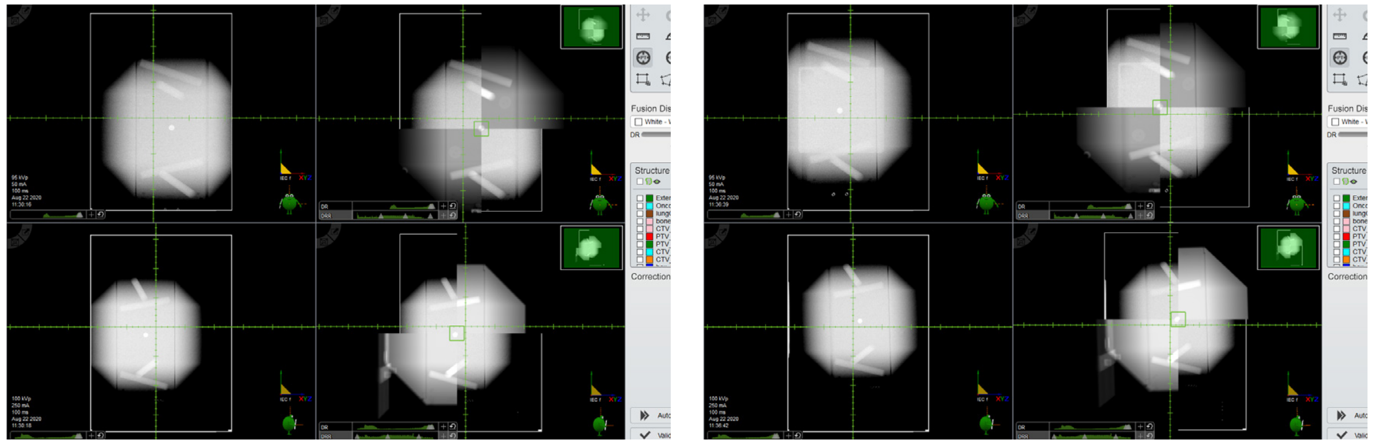


Figure 3: Left: Automatic image registration for translational shift. Right: Automatic image registration for translational and rotational shift.

End-to-end testing

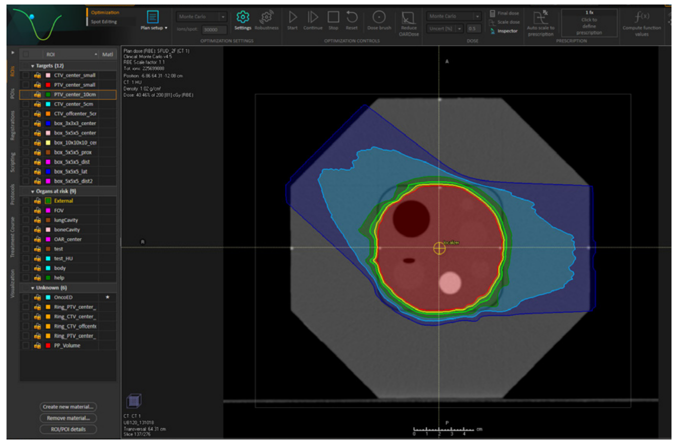
Planning CT

A planning CT with slice thickness of 1 mm from RUBY with RUBY insert System QA and homogeneous plug was acquired on a Philips Brilliance TM 16 BigBore. The CT dataset was imported into the RayStation TPS (Version 9B SP1)

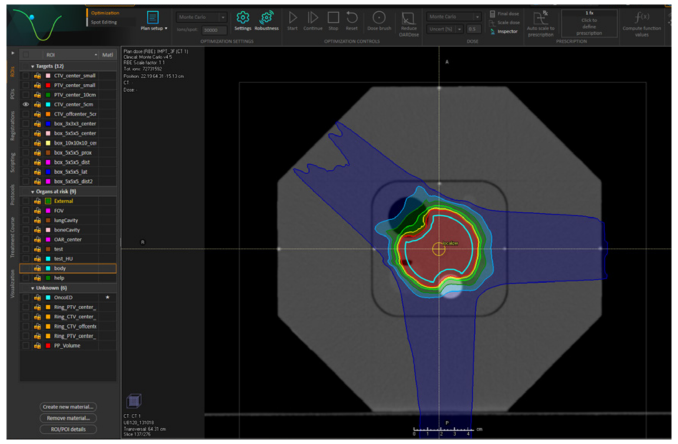
Plan optimization

Four treatment plans were optimized using RayStation with the Monte-Carlo based dose engine and the clinical HU-calibration curve for the selected scan-protocol. Dose was calculated on a 1 x 1 x 1 mm dose grid and averaged over a 3 mm diameter ROI representing the sensitive volume of the employed PinPoint 3D ionization chamber. The treatment plans had different complexities as described in the following:

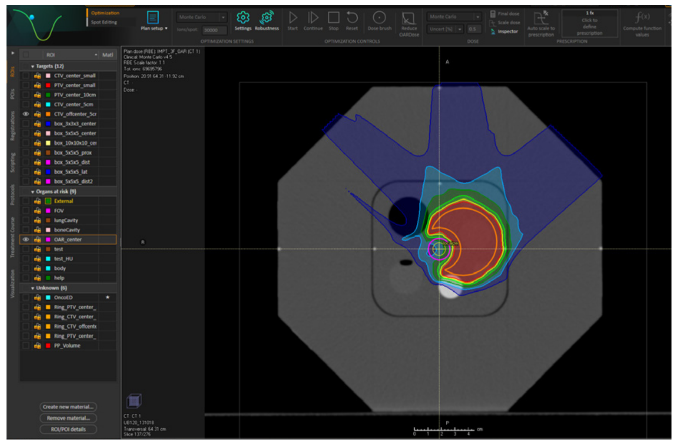
Plan 1:
Single field uniform dose (SFUD) plan for large target volume around the detector position with 2 gantry angles. The plan was optimized for a 10 cm diameter spherical target with its center at the ionization chamber location. The target dose was 2 GyRBE.



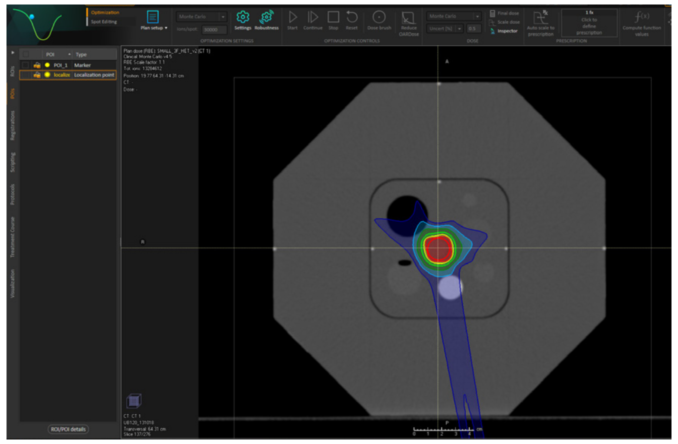
Plan 2:
Intensity modulated proton therapy (IMPT) plan with 3 gantry angles plan at which the cylinders of tissue equivalent materials are cropping the spherical 5 cm diameter target volume. The plan was robustly optimized on this target volume, i.e. taking a density uncertainty of 3.5 % and a setup uncertainty of 3 mm in all direction into account for the uniform dose objective (1.8 GyRBE).



Plan 3:
IMPT plan with 3 gantry angles at which the detector position is an OAR structure. The target structure was a 5 cm diameter sphere which was cropped by the spherical OAR and was robustly optimized for a uniform dose of 1.8 GyRBE. The objectives included a maximum dose of 75 % of the prescription in the OAR. One of the three beam angles included a range shifter.



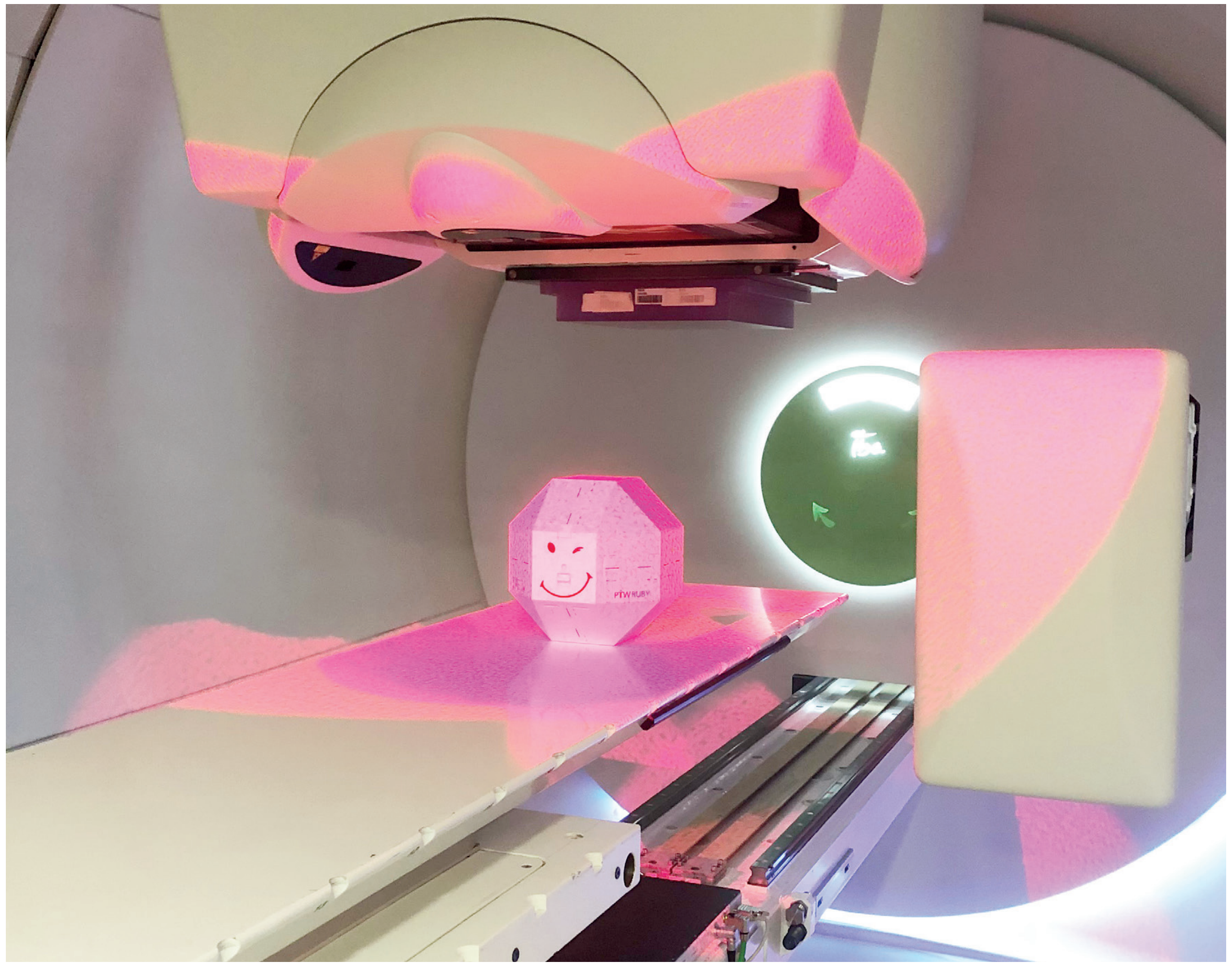
Plan 4:
Non-coplanar IMPT plan with 3 gantry angles and 3 couch angles optimized on a small target volume at the detector position. The target was 1 cm in diameter and robustly optimized. The beam angles were selected to directly pass through the bone, lung and brain inhomogeneities.



Patient positioning workflow

In order to integrate the patient positioning workflow in the End2End testing procedure, the SystemQA insert was filled with the homogenous plugs and aligned along the grey line (translational shift) using the laser systems. In addition, the AdaptRT surface scanner system was used to monitor the positioning. Using AdaptInsight, orthogonal kV images with pelvis preset were acquired and registered to the reference DRR using the automatic image registration function.

The structures of the SystemQA insert allow the automatic registration within 1 mm of the expected values. Also, the AlignRT surface guided system detected the incorrect positioning and after shifting, the positioning was within 1.5 mm with respect to the reference image.



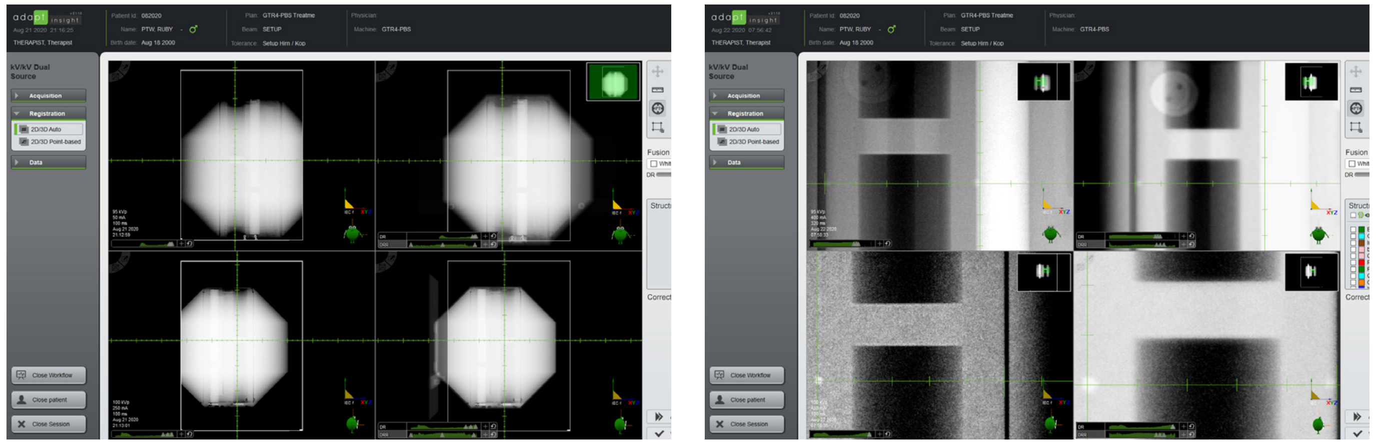


Figure 4: Automatic image registration using AdaptInsight of RUBY with System QA insert

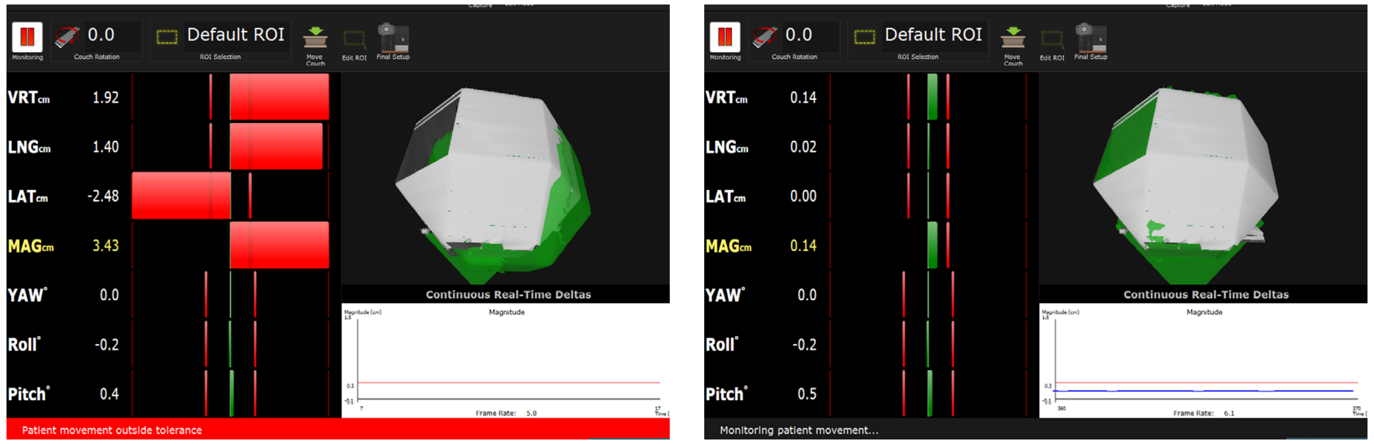


Figure 5: RUBY phantom monitored by surface guided system AlignRT. Left: With translational shift based on grey lines. Right: After couch correction based on AdaptInsight workflow

Dose measurement

After phantom positioning, the homogeneous plug was replaced by the detector holder for the PinPoint 3D and a PinPoint 3D ionization chamber was inserted and connected to a UNIDOS Tango electrometer system with high voltage at + 300V. In order to verify the positioning, kV images with high intensity (400 mA, 320 ms) were acquired. In this way, the chamber positioning can be checked, even with couch rotation.

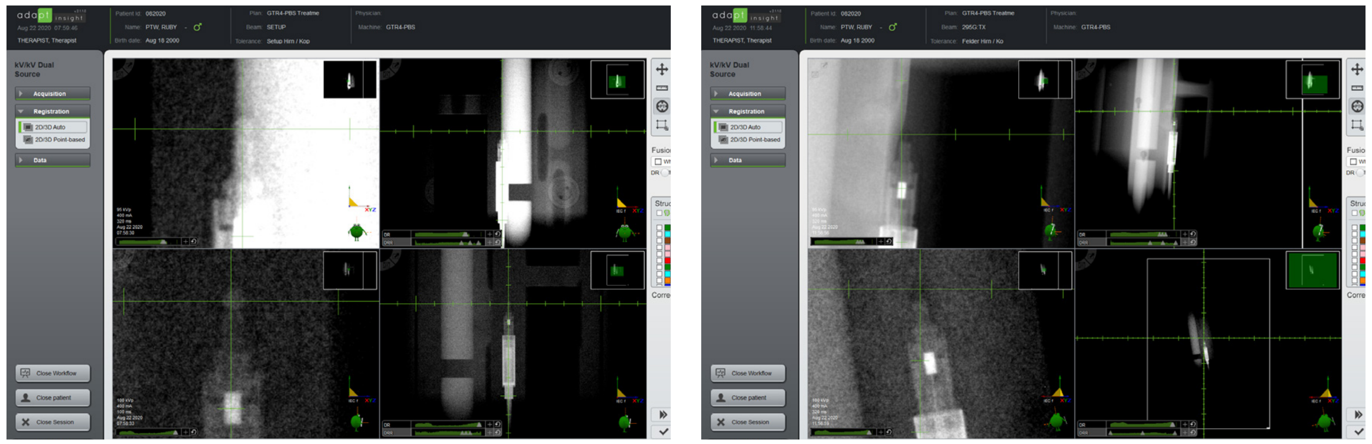


Figure 6: Check of chamber positioning using AdpatInsight kV planar imaging. Left: without couch rotation. Right: with couch rotation

All treatment plans were measured three times with the PinPoint 3D ionization chamber. A Monte-Carlo based kQ factor from Kretschmer et al. [1] was applied as average over the whole energy range as well as air density correction kTP. No further corrections were considered leading to an estimated standard uncertainty of 1.5%.
The agreement between chamber measurement and TPS calculation are shown in table I. The total deviations between measurement and TPS calculation were 0.4%, 0.5%, -4% and -1.7%. It must be noted that the dose gradient at the point of measurement in Plan 3 is leading to a strong positioning dependence. Taking the setup uncertainty of 1 mm based on the AdaptInsight positioning results into account can lead to calculated dose values well within 1% of the measurement.

	Plan 1	Plan 2	Plan 3	Plan 4
Field 1	- 0.1 %	0.7 %	- 3.7 %	- 2.2 %
Field 2	0.4 %	- 2.3 %	- 2.5 %	- 1.3 %
Field 3	-	- 0.4 %	- 6.0 %	- 1.5 %
Total	0.4 %	0.5 %	- 4.0 %	- 1.7 %

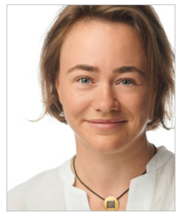
Table I: Results of measurement and TPS calculation for plan verification measurements with RUBY and Patient QA insert.

Conclusion

The RUBY system was shown to be suitable for workflow tests of patient positioning as well as the complete End2End testing chain on a proton IBA Proteus Plus facility. Treatment plans with different complexities were successfully verified and a compatibility of Linac QA insert and System QA insert with the imaging systems Verisuite and AdaptInsight was demonstrated.

References

[1] J Kretschmer, A Dulkys, L Brodbek, T S Stelljes, H K Looe, S Brandenburg, B Poppe: Monte Carlo simulated beam quality and perturbation correction factors for ionization chambers in monoenergetic proton beams, Medical Physics, 2020



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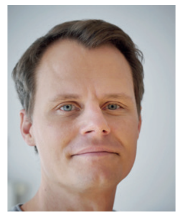

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