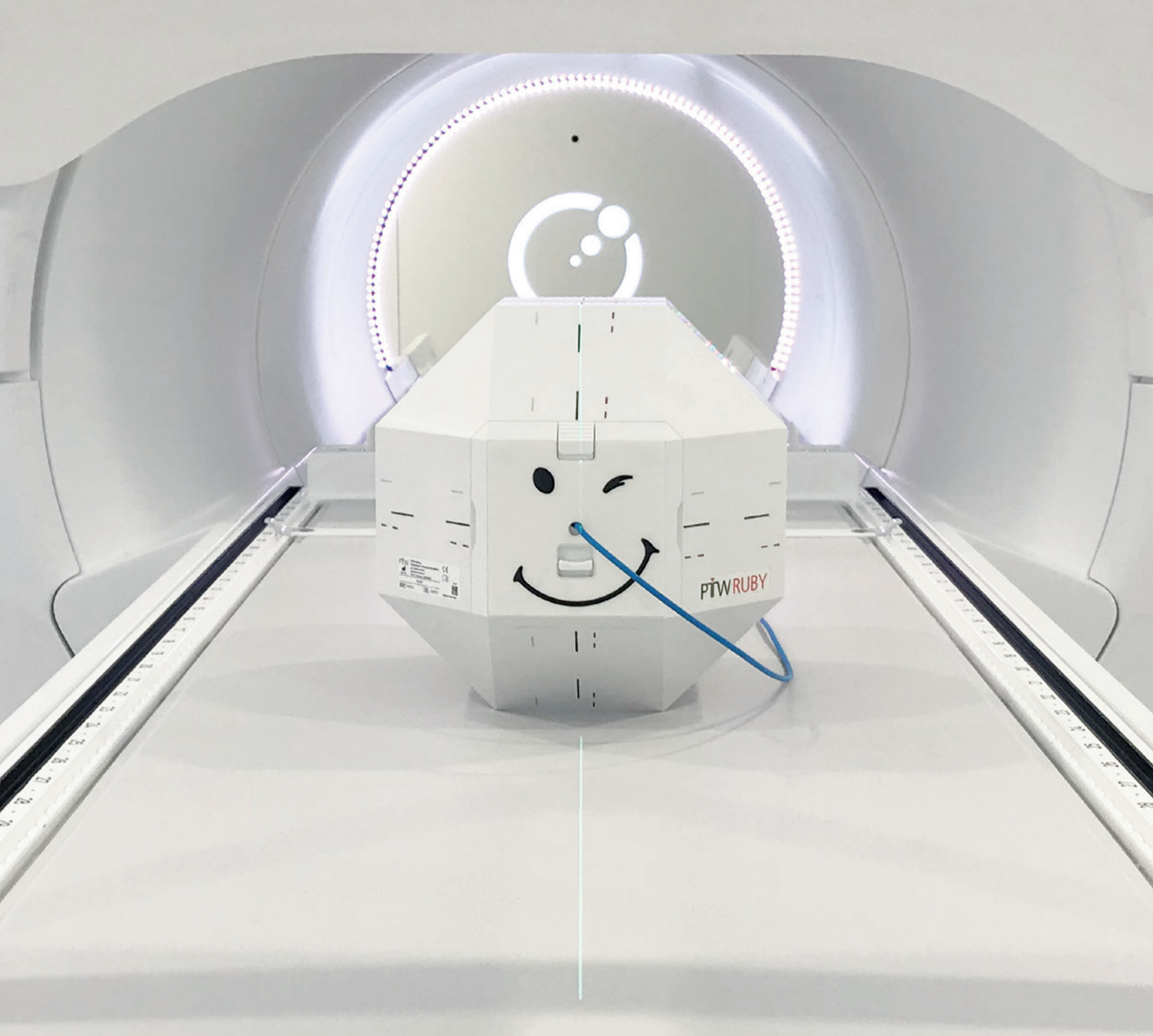

Applications of the RUBY phantom

at the high field MRI-linac Elekta Unity

Abstract

The aim of this white paper is the application of the RUBY phantom at the MRgRT system Elekta Unity, a 1.5 T high field MRI-linac. A possible workflow for point-based plan verification in a homogenous phantom based on RUBY and Patient QA insert is presented. Furthermore, a complete End-to-End test workflow based on RUBY and SystemQA insert is described. With RUBY, both clinical workflows – adapt-to-shape and adapt-to-position - have been completely run through and tested.

Introduction

Magnetic resonance guided radiotherapy (MRgRT) is the latest achievement in radiation therapy. The combination of MR imaging and linear accelerator enables a new quality of imaging during the performance of radiation therapy using linear accelerators. However, MRgRT also brings new challenges for quality assurance. Products not only have to be usable in a magnetic field, i.e. classified as MR conditional, they also should be MRI visible. The goal of this white paper is the application of the RUBY phantom in MRgRT using an Elekta Unity accelerator. First, the article describes the use of RUBY combined with the Patient QA insert for plan verification in combination with the Elekta Unity imaging system MVIC and second, the application of RUBY as an End-to-End phantom for MRgRT. Considering the complexity of MRgRT, especially adaptive MRgRT, the implementation of an end-to-end test is essential for the QA workflow. The RUBY SystemQA insert includes MRI visible elements, CT visible inhomogeneities as well as the possibility to insert a detector for dose measurements. The article describes step-by-step the use of the SystemQA insert for an end-to-end test of the workflows adapt-to-position and adapt-to-shape at an Elekta Unity.

Plan verification

Point measurement

Preparation

Planning CT

A planning CT with slice thickness of 3 mm from RUBY with RUBY insert Patient QA - detector and homogeneous plug was performed and imported into the Monaco TPS. During the CT, the RUBY phantom was positioned with an indexing bar and the room laser system. The indexing bar was positioned on position 20, so that the center of RUBY was placed at position 22.

TPS

Three treatment plans with target volumes of 17.6 cm³ and 5.9 cm³ were calculated in the treatment planning system (Monaco 5.40, Elekta AB, Sweden) on the RUBY CT data set. All plans consisted of a 9 beam step and shoot technique with a dose prescription of 1.8 Gy per fraction to the PTV. Plans were optimized for conformality and steep dose gradients outside the PTV. Calculation uncertainty was 1 % over the calculation. The isocenter position corresponds in longitudinal and lateral orientation to the phantom center, which is indicated by the CT marker positions. The phantom center corresponds to the reference point of the inserted detector. In vertical orientation, the isocenter position does not correspond to the phantom center. Since the treatment couch of the Unity System is not movable in vertical direction, the isocenter is located above the phantom center (see Figure 1). The dose was calculated in a volume whose position corresponds to the reference point of the chamber. The CT markers were used to localize this position. The size of the calculation volume corresponds to the active volume of the ionization chamber used (Semiflex 3D).

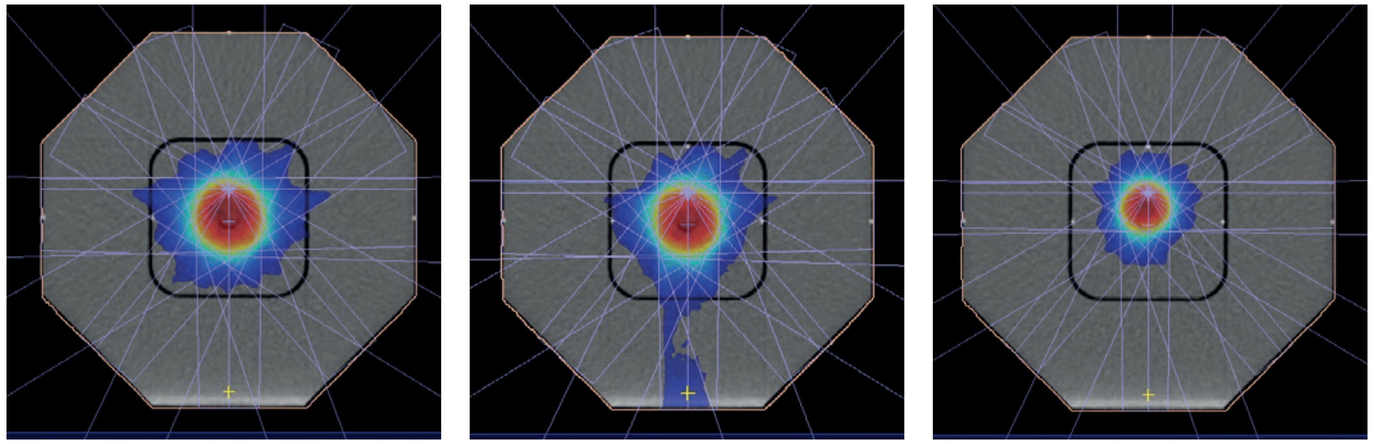

Figure 1: Slice of the CT dataset where the center of RUBY is visible according to the six visble CT marker. The isocenter is visible as well as the dose calculation point in the center of the phantom according to the detector positioning during measurement. Color shades show doses between 0.6 Gy (blue) and 1.9 Gy (red).

Measurement

Phantom positioning

The RUBY phantom with RUBY insert Patient QA – detector, detector holder for Semiflex 3D and Semiflex 3D ionization chamber were positioned on the treatment table according to the planning CT using indexing bar and room laser system as shown in Figure 2. The Semiflex 3D was connected with an UNIDOS webline electrometer (+400 V) positioned outside the treatment room. The table position was exported from the TPS and RUBY was positioned in the bore.

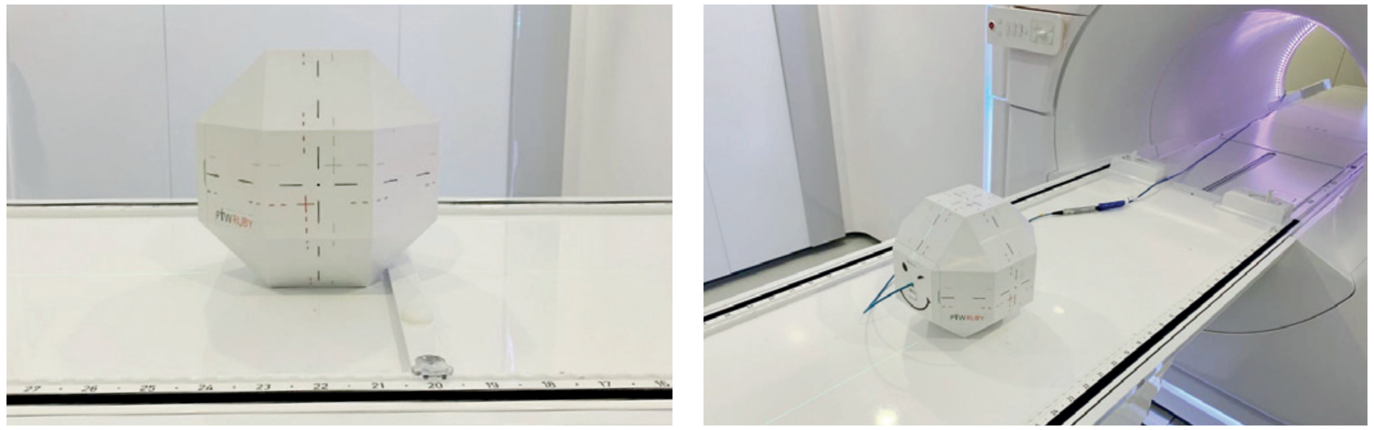

Figure 2: RUBY positioning according to the planning CT. Longitudinal positioning with adapter plate, lateral positioning with laser.

The positioning was checked using the MV imaging controller system (MVIC) as shown in Figure 3. Reference geometries of the ionization chamber can be identified in the MV image and the positioning of RUBY can be checked.

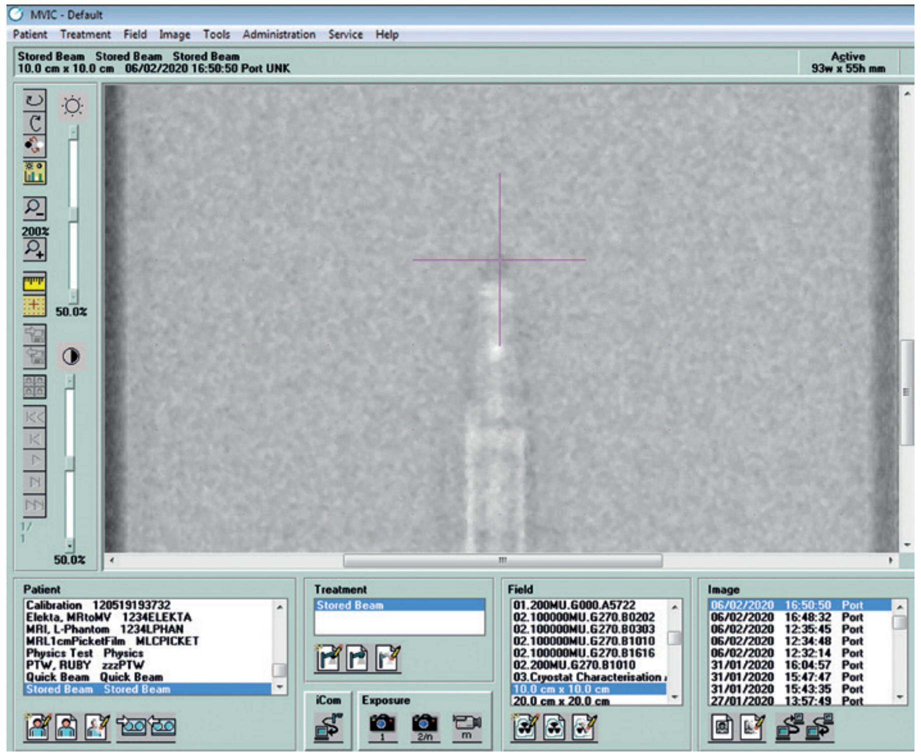

Figure 3: MVIC image of the Semiflex 3D positioning in the RUBY phantom

Dose measurement

After pre-irradiation of the chamber, the plan dose was assessed by measuring the ionization chamber signal M. The final plan dose to water was calculated according to the following equation:

$$\mathbf{D = M \cdot N \cdot k_Q \cdot k_B \cdot k_{TP}}$$

where N represents the calibration factor for Co60, k_Q is the beam quality correction, k_B represents the correction for the presence of a magnetic field and k_{TP} the correction for pressure and temperature. k_Q and k_B depend on detector type and detector orientation. For this report k_Q = 0.9924 and k_B = 0.984 were applied. k_B was derived by an chamber individual crosscalibration with alanin. Temperature in air and pressure were T=24.43° and p=978.3 hPa which leads to a correction factor of k_{TP} = 1.051. Saturation effect as well as polarity effect were neglected.

Results

The results are shown in Table I. The differences between measurement and TPS are within 2 %.

	Measurement [Gy]	TPS [Gy]	Difference [%]
Plan 1	1.886	1.858	1.5
Plan 2	1.878	1.863	0.8
Plan 3	1.707	1.680	1.6

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

End-to-End testing

Preparation

Planning CT

A planning CT from RUBY with RUBY insert System QA was performed and imported into the Monaco TPS. During the CT, the RUBY phantom was positioned with an indexing bar and the room laser system. The indexing bar was positioned on position 20, so that the center of RUBY was placed at position 22.

TPS

The CT dataset was imported into the Monaco TPS and a "RUBY patient" was created. The MRI and tissue equivalent inserts were contoured as well as the external contour (Figure 5). The relative electron density values were defined for the external structure as well as for the brain, lung and bone structure according to the RUBY specification and summarized in table II.
A PTV structure was added in the center of the phantom and an IMRT plan with 9 gantry angles [180°/140°/90°/60°/25°/340°/300°/270°/220°] was optimized. The plan was optimized with a prescription dose of 50.4 Gy in 28 fractions (1.8 Gy/Fx) based on a rectum plan template with one target objective and conformality as additional optimization parameter (Figure 4). The optimized reference plan before the online adaptation consisted of 24 segments and 249.5 MU. All optimized plans were calculated with a monte-carlo uncertainty of 1 % over the calculation.

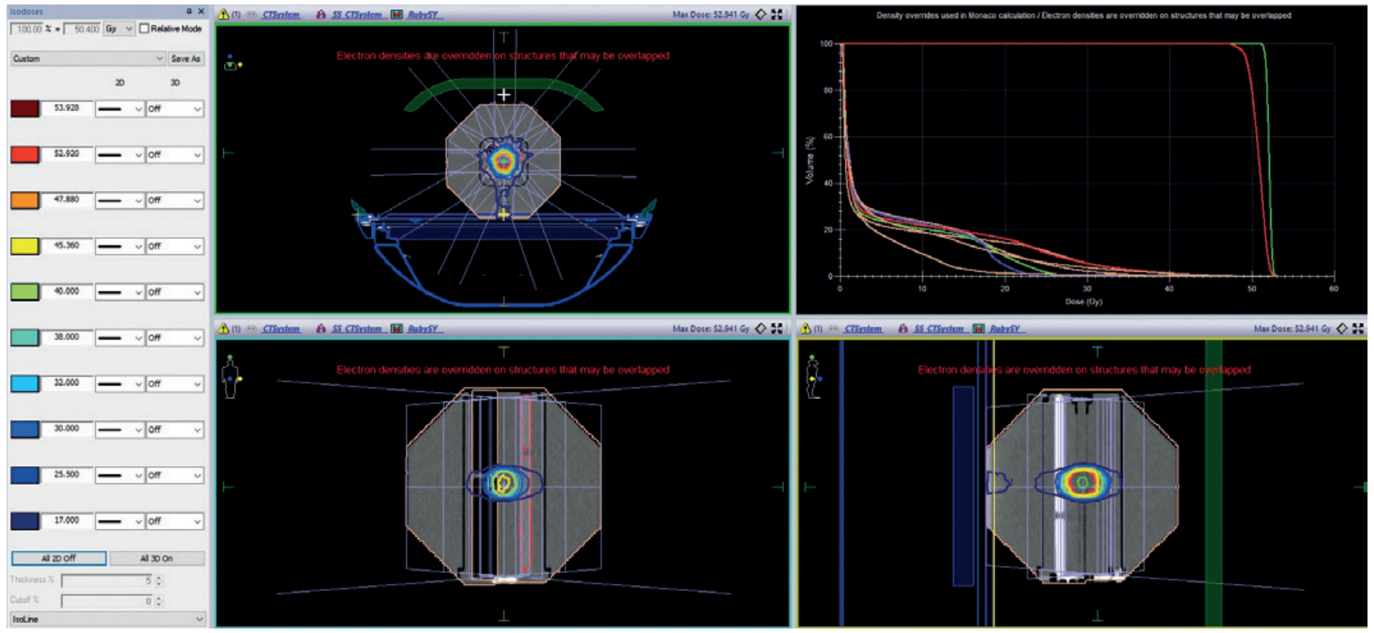

Figure 4: Screenshot from TPS (Monaco) before the adaptation

Material	Relative electron density (RED)
Bone	1.567
Brain	1.038
Lung	0.235
RUBY material	1.012

Table II: Relative electron density values

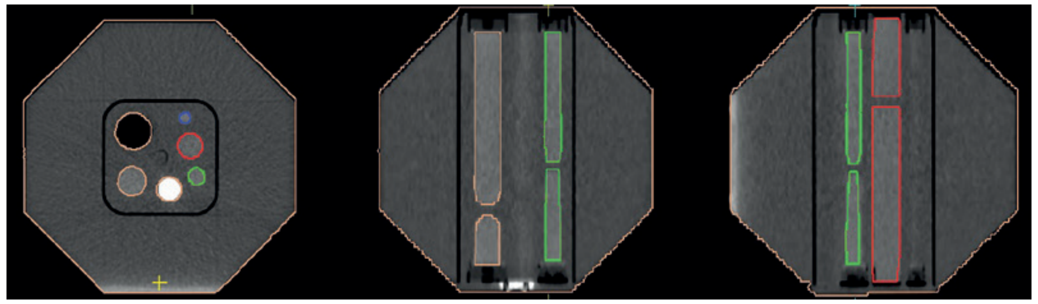

Figure 5: Contoured RUBY insert System QA and defined electron density values

Adapt to position workflow

The RUBY phantom with RUBY insert System QA, detector holder for Semiflex 3D and Semiflex 3D ionization chamber was positioned on the treatment table in the same way as for the planning CT. In contrast to the previous test, no misalignment was applied. The body coil was positioned above the phantom and RUBY was positioned in the bore according to the treatment planning table position (see Figure 6).

Figure 6: RUBY with lateral misalignment and inserted Semiflex 3D ionization chamber.

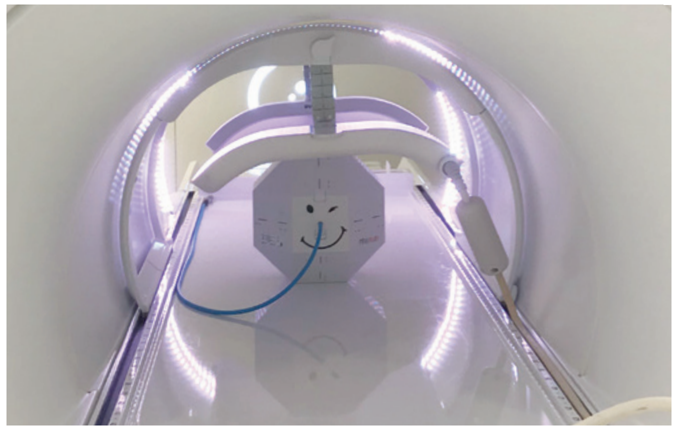

Figure 7: RUBY phantom in the bore with body coil.

The patient workflow within MOSAIQ was started and an MR image sequence (T2 3D, 2 min) was generated. Using Online Monaco the MR image was fused to the reference CT dataset. Based on the isocenter shift between the reference image and the online MRI a geometric shift of the MLC positions was applied and the new dose distribution on the reference CT was calculated. The online plan therefore consisted of the same segments (24) and MU (249.5 MU). The dose to the chamber was calculated based on spherical volume at the center of the phantom with diameter of 2.5 mm according the chamber dimensions. A dose value of 1.884 Gy was calculated. Then, the plan was irradiated and the chamber signal was recorded. A dose of 1.891 Gy was measured.

The comparison between calculated value of 1.884 Gy and measured value of 1.891 is 0.4 %.

	Measurement [Gy]	TPS [Gy]	Difference [%]
Plan 1	1.891	1.884	0.4

Table III: Result of measurement and TPS calculation for End-to-End test of adapt-to-position workflow with RUBY phantom and System QA insert.

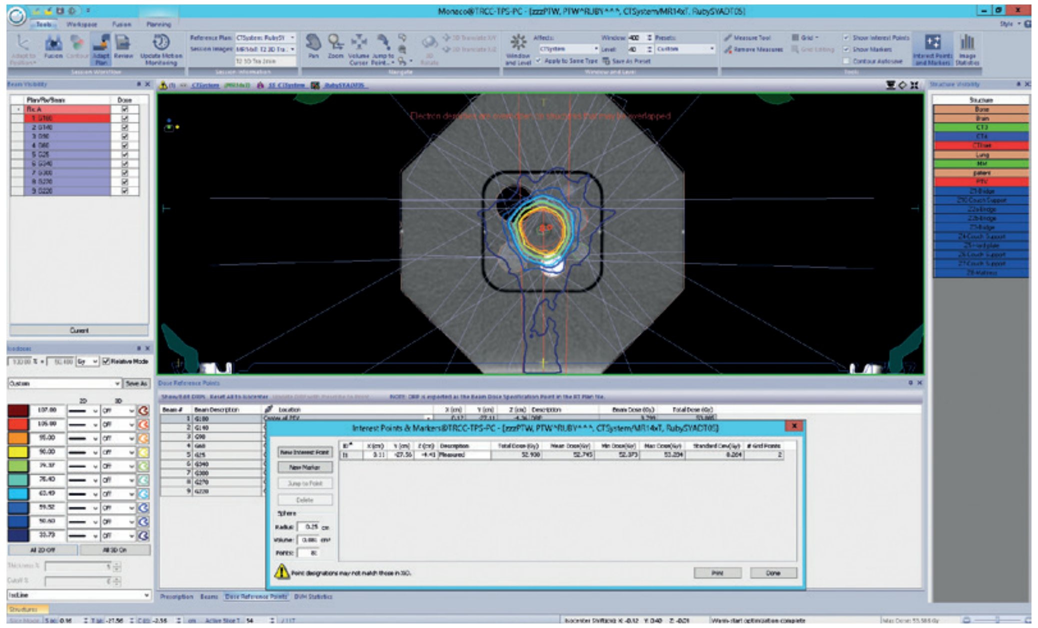

Figure 8: Re-optimized treatment plan on the reference CT dataset based on the adapt to position workflow

Adapt to shape workflow

The RUBY phantom with RUBY insert System QA, detector holder for Semiflex 3D and Semiflex 3D ionization chamber was positioned on the treatment table in the same way as for the planning CT. Then a lateral misalignment was applied by positioning RUBY laterally (2.5 cm) on the grey line. The body coil was positioned above the phantom and RUBY was positioned in the bore according to the treatment planning table position (see Figures 6 and 7).

The patient workflow within MOSAIQ was started and an MRI image sequence (T2 3D, 2 min) was generated. Using Online Monaco the MRI image was fused to the reference CT dataset and the lateral misalignment was detected with 2.47 cm (see Figure 9). The Semiflex 3D ionization chamber produced small artifacts on the MR image data, which however did not impact the registration (see Figure 10).

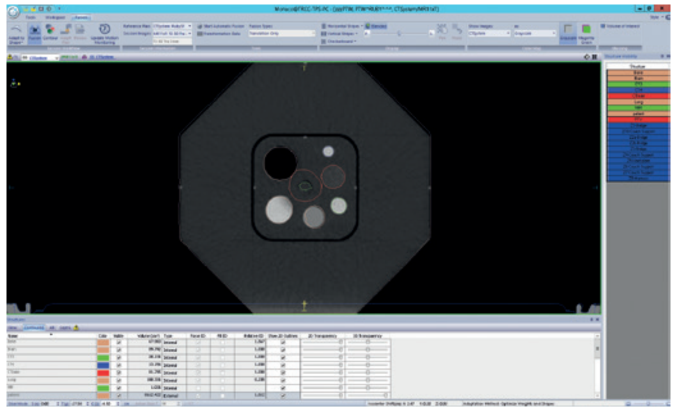

Figure 9: CT/MR fusion: Misalignment was detected correctly.

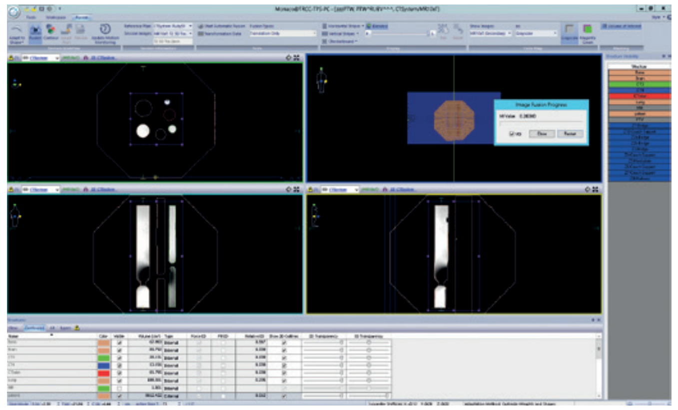

Figure 10: Artifacts caused by the Semiflex 3D chamber. Artifcats did not impact the image registration.

After the CT/MR fusion a synthetic CT based on the MRI image was created (see Figure 11) and the treatment plan was re-optimized and adapted to the new PTV position (see Figure 12). The online optimized plan consisted of 31 segments and 308.9 MU. The dose point was positioned according to the CT marker at the center of the phantom. The dose to the chamber was evaluated in a spherical volume according to the active volume of the Semiflex 3D with a diameter of 2.5 mm. A dose value of 1.820 Gy was calculated.

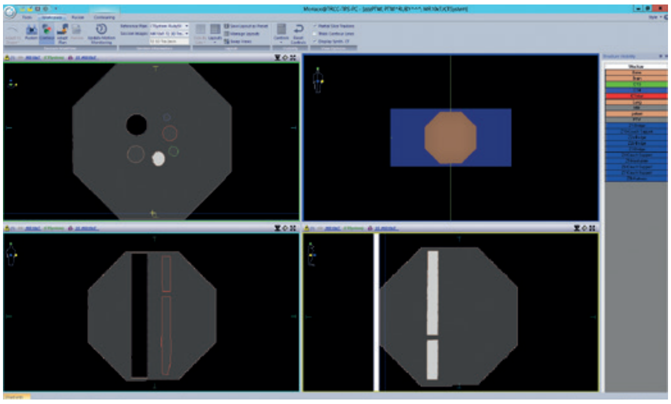

Figure 11: Synthetic CT.

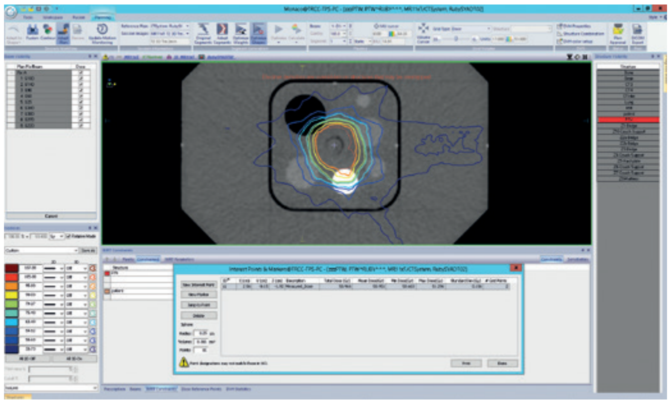

Figure 12: Re-optimized treatment plan based on adapt to shape workflow

The re-optimized treatment plan was applied to the phantom and the chamber signal was recorded. A dose of 1.811 Gy measured, yielding a relative difference of 0.5 % with respect to the calculated dose value.

	Measurement [Gy]	TPS [Gy]	Difference [%]
Plan 1	1.811	1.820	0.5

Table IV: Result of measurement and TPS calculation for End-to-End test of adapt-to-shape workflow with RUBY phantom and System QA insert.

Summary

The RUBY phantom is an appropriate QA tool for QA at the high field MRI-linac Unity. The RUBY phantom is suitable for plan verification based on a single detector measurement combined with MVIC imaging. Moreover, RUBY combined with System QA insert enables a complete End-to-End testing of the system. It was shown that both possible workflows – adapt-to-shape and adapt-to-position - could be fully tested with RUBY.

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