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Published in:
Biomedical Physics and Engineering Express

DOI:
[10.1088/2057-1976/ac3e37](https://doi.org/10.1088/2057-1976/ac3e37)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2022

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Brodbek, L., Kretschmer, J., Büsing, K., Looe, H. K., Poppe, B., & Poppinga, D. (2022). Systematic end-to-end testing of multiple target treatments using the modular RUBY phantom. *Biomedical Physics and Engineering Express*, 8(1), [015018]. <https://doi.org/10.1088/2057-1976/ac3e37>

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To cite this article: Leonie Brodbek *et al* 2022 *Biomed. Phys. Eng. Express* **8** 015018

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OPEN ACCESS

RECEIVED

5 November 2021

REVISED

18 November 2021

ACCEPTED FOR PUBLICATION

29 November 2021

PUBLISHED

9 December 2021

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Systematic end-to-end testing of multiple target treatments using the modular RUBY phantom

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Keywords: SRS QA, system QA, end-to-end testing, single-isocenter multiple target VMAT, QA phantom

Abstract

The RUBY head phantom in combination with the System QA insert MultiMet can be used for simultaneous point dose measurements at an isocentric and two off-axis positions. This study investigates the suitability of the system for systematic integral end-to-end testing of single-isocenter multiple target stereotactic treatments. Several volumetric modulated arc therapy plans were optimized on a planning CT of the phantom positioned in a stereotactic mask on the stereotactic treatment board. The plans were created for three artificial spherical target volumes centred around the measurement positions in the MultiMet insert. Target diameters between 5 and 40 mm were investigated. Coplanar and non-coplanar plans were optimized using the collapsed cone algorithm of the Oncentra Masterplan treatment planning system and recalculated with the Monte Carlo algorithm of the Monaco treatment planning system. Measurements were performed at an Elekta Synergy linear accelerator. The head phantom was positioned according to clinical workflow comprising immobilization and CBCT imaging. Simultaneous point dose measurements at all target positions were performed with three PinPoint 3D chambers (type 31022) as well as three microDiamond detectors (type 60019) and compared to the treatment planning system calculations. Furthermore, the angular dependence of the detector response was investigated to estimate the associated impact on the measured point dose values. Considering all investigated plans, PTV diameters and positions, the point doses calculated with the Monaco treatment planning system and the microDiamond measurements differed within 3.5%, whereas the PinPoint 3D showed differences of up to 6.9%. Point dose differences determined in comparison to the Oncentra Masterplan dose calculations were larger. The RUBY system was shown to be suitable for end-to-end testing of complex treatment scenarios such as single-isocenter multiple target plans.

1. Introduction

For intracranial lesion irradiations, several publications [1–3] indicate that the stereotactic treatment of multiple lesions is associated with better neurological outcomes and less toxicity compared to whole brain radiation therapy. Stereotactic volumetric modulated arc therapy (VMAT) of multiple targets with a single-isocenter has increased rapidly in recent years due to the improved efficiency of treating several lesions simultaneously and the growing confidence in high-precision radiation equipment [4–7].

From the quality assurance (QA) perspective, treatments using small non-isocentric fields are challenging. In addition to the challenges associated with small field dosimetry, such as the possible uncertainties in dosimetry or dose calculations, off-axis fields are especially sensitive to rotational errors or mechanical inaccuracies in the radiation treatment system [5, 8] consisting of the gantry, treatment couch and image guidance system. Additionally, the penumbra of small off-axis fields may not be symmetric. In the past years, dedicated protocols have been published providing recommendations for QA of geometric and

dosimetric accuracy required for stereotactic treatments [9–11]. These QA measurements include an integral system specific end-to-end (E2E) test of the complete treatment chain generally performed with a dedicated phantom. The E2E test comprises the acquisition of planning CT and magnetic resonance imaging (MRI) of the phantom to localize the target volume, treatment planning with dose optimization, positioning and localization of the target prior to the treatment, motion management and treatment delivery system. During irradiation, dose measurements are performed in the phantom [9]. While there are several approaches to perform an E2E test for the case of isocentric single lesion irradiations [12], an E2E test for the irradiation of multiple and/or off-axis targets requires a specialized phantom suitable for such complex scenarios.

For E2E tests or other systematic tests of the special case of single-isocenter multiple target treatments, radiochromic films [5, 13–16] or gel dosimetry [7, 17] have been used, where the gamma passing rates were determined as a measure of plan quality. Although these dosimetry methods offer 2D or 3D measurements, they are also time-consuming [14]. In other studies, single point dose comparisons using ionization chamber measurements were carried out [5, 15]. Recently, Ahmed *et al* [14] tested a diode detector array in combination with a phantom to measure the dose in off-axis targets. While this method showed good agreement to radiochromic film measurements, it is limited to off-axis target positions in the detector plane.

In this study, the RUBY head phantom in combination with the System QA MultiMet insert for E2E testing of multiple target treatments was investigated. The workflow of the E2E test comprises all relevant recommended steps [9] including localization and imaging, target volume definition, treatment planning and dose calculation, patient positioning and IGRT-based virtual simulation, as well as treatment delivery. In addition to an isocentric target, two off-axis target

positions located up to 60 mm from the isocenter can be defined and measured simultaneously during the E2E test with the RUBY insert. The phantom and insert were tested systematically using coplanar and non-coplanar single-isocenter multiple target VMAT treatment plans for target volumes of diameters between 5 and 40 mm.

2. Materials and methods

2.1. Phantom

In this study, the RUBY head phantom (PTW Freiburg, Freiburg, Germany, type T40072.1.800) was used in combination with the RUBY System QA MultiMet insert (PTW Freiburg, Freiburg, Germany, type T40072.1.500). The head phantom is a homogeneous phantom made of white polystyrene simulating the human head and hence compatible with stereotactic patient fixation systems. The MultiMet insert is also made of white polystyrene and contains three cylinders made of bone-equivalent material as well as three openings to position point detectors inside the phantom for dose measurements at three different target positions. For the planning CT each detector opening can be filled with a homogeneous plug instead of a detector. The three detector positions are indicated by CT markers made of bone equivalent material on the outer sides of the insert. Figure 1 shows a drawing of the MultiMet insert with the detector positions.

2.2. End-to-end test workflow

The E2E test comprises all relevant recommended steps [9] including localization and imaging, target volume definition, treatment planning and dose calculation, patient positioning and IGRT-based virtual simulation, as well as treatment delivery. The setup used for the test chain is shown in figure 2. A dedicated stand was used with the head phantom to ensure consistent rotational alignment of the phantom during the workflow.

Figure 2. The RUBY Head Phantom with the MultiMet insert was placed under an immobilization mask and fixed in the HeadStep patient immobilization system. Three detectors of the same type (PinPoint 3D or microDiamond) were used to measure the dose at the dedicated positions in the MultiMet insert simultaneously.

2.2.1. Immobilization and planning CT

In a first step an immobilization mask was prepared for the head phantom and the phantom was positioned using the HeadStep (Elekta, Stockholm, Sweden) patient immobilization system. A three-dimensional CT scan of the phantom, in combination with the RUBY System QA MultiMet insert and homogenous plugs filling the detector openings was performed for target volume localization and definition. The CT was performed according to the clinical protocol for intracranial stereotactic treatments using a Siemens Sensation 64 CT (Siemens Healthineers, Erlangen, Germany) equipped with an Elekta treatment table iBEAM evo (Elekta, Stockholm, Sweden). The CT was reconstructed with 1 mm slice thickness.

2.2.2. Target volume definition and treatment planning

The planning CT was imported to the treatment planning system (TPS) Oncentra Masterplan (version 4.5.3, Elekta, Stockholm, Sweden). Using the markers embedded in the phantom insert, spherical target volumes with diameters of 5, 10, 20, 30 and 40 mm (corresponding to a volume of 0.02, 0.4, 3.7, 13.4 and 32.8 ccm, respectively) were defined at each of the three detector positions. Coplanar and non-coplanar

single-isocenter VMAT treatment plans with 6 MV flattened beam were optimized for each target volume diameter using a dose prescription of 6 Gy (80% isodose) to all three targets. For all plans the isocenter was defined at the center of the insert that corresponds to the position of the central target volume. The coplanar plans were optimized for a single full arc. For the non-coplanar plans, one full arc at 0° couch angle and three half arcs at 45°, 315° and 270° couch angle were selected for optimization. The dose calculation was performed with a grid size of $2 \times 2 \times 1 \text{ mm}^3$ [3] using a collapsed cone algorithm. In addition, the treatment plans were exported to a Monaco TPS (version 5.51.10, Elekta, Stockholm, Sweden) and recalculated using a Monte Carlo dose engine with the same dose grid and 0.5% uncertainty. For comparison with the detector dose measurements, the dose values at the center of the target volumes were extracted from both TPS. Figure 3 shows the dose distribution at the three target positions (columns) exemplarily for the coplanar plan and 10 mm target diameter.

The percentage difference Diff(%) between the measured dose values and those calculated by the TPS were calculated according to equation 1 such that a positive percentage difference indicates a higher mea-

Figure 3. Planning CT and isodose distributions in transversal, coronal and sagittal plane (rows) for the coplanar single-isocenter treatment plan and 10 mm target diameter at the three target positions (left: caudal target; center: isocentric target; right: cranial target).

sured dose value.

$$\text{Diff}(\%) = \left(1 - \frac{\text{Dose}_{\text{TPS}}}{\text{Dose}_{\text{Detector}}} \right) \cdot 100 \quad (1)$$

2.2.3. Phantom positioning and treatment delivery

Measurements were performed at an Elekta Synergy accelerator with Agility MLC (Elekta, Stockholm, Sweden). The machine is equipped with both MV (iViewGT, Elekta, Stockholm, Sweden) and kV (XVI, Elekta, Stockholm, Sweden) onboard imaging systems and operated with the R&V system MOSAIQ (version 2.6, Elekta, Stockholm, Sweden). The RUBY phantom with the MultiMet insert and the mask was positioned in the HeadStep patient immobilization system. A CBCT using the ‘fast head and neck’ preset was performed with automatic image registration in ‘Bone (T & R)’ mode for final positioning. The homogenous plugs were used to fill the detector openings during the CBCT acquisition.

2.2.4. Point dose measurements

After the CBCT-based positioning, the homogenous plugs were replaced by detectors. Dose measurements were performed simultaneously using three PinPoint 3D ionization chambers (PTW Freiburg, Freiburg, Germany, type 31022) and three microDiamond detectors (PTW Freiburg, Freiburg, Germany, type 60019) placed at the target centers. The ionization chambers were operated at + 300 V and the microDiamonds were operated at 0 V and read out with UNIDOS electrometers (PTW Freiburg, Freiburg, Germany). For the PinPoint 3D chambers, the

measured dose values were obtained by applying the detector specific calibration factors determined at a secondary standard laboratory, and corrections for air density and beam quality. The microDiamond detectors were cross calibrated at 6 MV and $4 \times 4 \text{ cm}^2$ field size. No further corrections were applied.

Since the measurements were performed with three detectors simultaneously, the detector-cable-electrometer combinations were compared beforehand showing a maximum inter-chamber deviation of 0.6%.

2.3. Angular response of the PinPoint 3D chamber and the microDiamond detector

Because of their rotational symmetry around the detector axis, the orientation of the detectors with respect to the beam direction is the same for all gantry angles in case of 0° couch angle. In other words, the detector axis is always perpendicular to the beam axis. In contrast, for other couch angles, the angle between detector axis and beam axis varies with gantry rotation. To estimate the uncertainty caused by a possible directional dependence, the angular response of the PinPoint 3D chamber and the microDiamond detector has been investigated using the RUBY base phantom (PTW Freiburg, Freiburg, type T40072.1.001) and the PatientQA insert (PTW Freiburg, Freiburg, type T40072.1.100). The RUBY base phantom and Patient QA insert consist of a homogeneous body made of white polystyrene. The insert allows the positioning of a detector at its center. Figure 4 shows the setup used to measure the response of the detectors in dependence of the irradiation angle.

Figure 4. Setup to determine the angular response of the PinPoint 3D ionization chamber and microDiamond detector placed in the RUBY base phantom in combination with the PatientQA detector insert.

Figure 5. Percentage difference between the relative dose calculated by Monaco (left) and Oncentra Masterplan (right) and the PinPoint 3D measured dose (red) and the microDiamond measured dose (blue) in dependence of the gantry angle.

The RUBY phantom with the detector at its center was positioned in the isocenter but turned by 90° . Measurements were performed using a 6 MV $20 \times 20 \text{ cm}^2$ field and 50 monitor units irradiated at gantry angles between -90° and 90° in 15° increments. Three repetitions were performed per measurement point. For comparison the dose was calculated using the Oncentra Masterplan and Monaco TPS according to the methods described in section 2.2. The measured values as well as the TPS calculated values were normalized to 0° gantry angle and the difference was calculated according to equation (1).

3. Results

3.1. Directional dependence of PinPoint 3D chamber and microDiamond detector

Figure 5 shows the directional dependence of the dose response of the PinPoint 3D chamber and the

microDiamond detector as the percentage difference to the TPS calculated dose. The results are normalized to 0° gantry angle, which corresponds to a 90° angle between beam and detector axis. With increasing angle in both directions, the difference between the detector measurement and the TPS calculation increases. Considering angles between -75° and 90° , a maximum difference of -5% was observed for both detectors and calculation approaches for -75° , where the beam directed from the stem side of the detector. Since only positive angles relative to the detector orientation have been used in the non-coplanar VMAT treatment plans delivered within this study, the uncertainty associated with the angular response in the dose measurements is smaller.

3.2. Phantom positioning and CBCT

Figure 6 shows the registration of the CBCT to the planning CT of the RUBY head phantom and Multi-Met insert. The image registration was carried out

Figure 6. Transversal (left), coronal (center) and sagittal (right) plane of the CBCT registration used for phantom positioning prior to plan delivery.

Figure 7. Differences between the dose values calculated with the TPS and the PinPoint 3D ionization chamber measurements. Left: Coplanar treatment plans, Right: Non-coplanar treatment plans. Top: Difference between Monaco TPS and dose measurement, Bottom: Difference between Oncentra Masterplan TPS and dose measurement. The bars show the difference between measurement and TPS calculation for both detectors and three target positions. The green area shows a $\pm 3\%$ limit.

automatically and revealed maximum translations of 1.8 mm and rotation errors smaller than 0.5° using the automatic image registration in 'Bone T & R' mode. The clipbox in which the registration was performed is indicated by the dashed lines that enclose the Multi-Met insert with the embedded bone structures. The calculated translational couch corrections were executed.

3.3. Dose measurements

The percentage differences between the point dose measurements and the TPS calculations for the three targets with diameters between 5 mm and 40 mm are shown in figure 7 for the PinPoint 3D ionization

chamber measurements and in figure 8 for the microDiamond detector measurements.

The results of the coplanar treatment plans calculated in Monaco show deviations less than $\pm 3\%$ except for the caudal PTV position at the smallest PTV diameter (5 mm). In case of the non-coplanar treatments, the deviations are less than $\pm 3\%$ for all PTV diameters at the isocenter position. For 5 and 10 mm PTV diameter, the PinPoint 3D measurements show larger deviations at off-axis positions, whereas the difference between Monaco and microDiamond measurement is less than $\pm 3\%$ for all conditions.

Generally, the differences between measurements and calculations are larger with the Oncentra Masterplan TPS than the Monaco TPS. For small PTV

diameters, the observed differences are comparable between the two TPS, but at the larger PTV diameters of 30 mm and 40 mm, the differences at off-axis positions are larger than $\pm 3\%$ for Oncentra Masterplan TPS. The results indicate possible discrepancies between the calculations at the off-axis positions between the TPS for these target volumes.

The PinPoint 3D and microDiamond measurements show good agreement for PTV diameters larger or equal to 20 mm. For smaller PTV diameters of 10 mm and 5 mm, the measured values using the PinPoint 3D chambers are always lower than that obtained using the microDiamond detectors and from TPS calculations.

4. Discussion

In this study, a systematic, integral E2E test for the treatment of multiple lesions was performed. As recommended by Schmitt *et al* [9] for integral tests, localization, CT, dose calculation and optimization, positioning workflow with CBCT and the final dose measurement were integrated into the test procedure using a single phantom setup. Dose measurements were realized at the isocenter as well as at two off-axis positions covering a ± 50 mm range around the isocenter. The PTV size was systematically varied down to 5 mm PTV diameter.

This integral E2E test is considered essential for safe application of multiple lesion treatments. In contrast to conventional plan verification applications,

the patient positioning workflow can be integrated into the test. Thus, the positioning of the phantom can be performed according to clinical IGRT workflow using the CBCT scans, whereas conventional plan verification systems are generally aligned to external laser systems. Furthermore, couch corrections are limited to translational movements in this study, although a maximum rotation error of 0.5° was detected. This discrepancy may influence the dose coverage of off-axis targets for non-coplanar plans that could partially explain the lower agreement between TPS calculations and measurements in these cases. Therefore, extra measures should be implemented to minimize these geometrical uncertainties in clinical practice. It is noteworthy that for 6DoF couch systems, the corrections for rotational errors could be included during the E2E test.

With the demonstrated integral E2E test it could be shown that the treatment of multiple targets with PTV diameters between 5 mm and 40 mm with and without couch rotation can be realized within an accuracy of $\pm 3\%$ at the treatment machine used in this study. However, this applies only for calculations using the Monte Carlo algorithm of the Monaco TPS and dose measurements using microDiamond detectors. Larger deviations were observed for PTV diameters of 10 mm and 5 mm when measurements were performed using PinPoint 3D chambers. This behaviour is expected as the treatment plans used in this study were highly modulated and contain segments smaller than $10\text{ mm} \times 10\text{ mm}$ or $5\text{ mm} \times 5\text{ mm}$. Therefore, the PinPoint 3D chamber measurements are

subject to volume effect and the chamber is not recommended for these small PTV diameters.

Furthermore, the localization of the effective point of measurement in the phantom is an important aspect for E2E testing phantoms. In the case of RUBY, the reference point of the detector is indicated by the CT markers. In the TPS, the reference point of the detector can be localized for each of the three detectors based on the three CT markers. In the case of the microDiamond detector, this localization is very precise as it determines the position of the diamond chip. For the ionization chamber, the CT markers define the reference point of the chamber, which is the center of the chamber on the inner electrode, leading to an additional uncertainty. The actual measurement point of the chamber is defined by the effective point of measurement, which is shifted towards the beam source. Due to the irradiation from different directions, this position changes with the irradiation angle. The Pin-Point 3D ionization chamber has an inner radius of 1.45 mm, so the effective point of measurement is approximately 0.75 mm from the reference point. By comparison to depth dose curves, we estimate the uncertainty in this study to 0.5%.

Our results show discrepancies between the TPS calculations at off-axis positions, whereas better agreement was obtained between measurements and Monaco calculations. The same observation has been reported in a previous study by Poppinga *et al* [18] with point dose measurements. Kim *et al* [19] also compared ArcCheck measurements to both calculation algorithms by gamma index analysis, where higher gamma passing rates were achieved with Monaco calculations. Therefore, clinical calculations for treatment plans with off-axis targets using the collapse cone algorithm of Oncentra Masterplan should be evaluated with care.

For the measurement of non-coplanar plans, the directional dependence of the detectors used should be taken into consideration during the evaluation. Figure 5 shows a maximum difference of 2.4% for the microDiamond chamber and 4.7% for the PinPoint 3D chamber in the range of positive angles when compared to Monaco TPS. This fits with the results of Shaw *et al* [20], who observed a maximum deviation of about 2.5% for 6 MV for the microDiamond. During irradiation, these differences will smear out over the irradiation arcs, and therefore we consider the associated uncertainty to be significantly smaller than limits of clinical accuracy of $\pm 3\%$. Furthermore, it must be noted that this angular dependency only impacts measurements of non-coplanar arcs.

The RUBY Phantom is limited to point measurements with single detectors. The doses are measured at the centers of the target volumes. No information can be given about the conformity of the dose distribution. This detailed verification of entire target volumes must be carried out with 2D detectors like ionization chamber arrays or film.

5. Conclusion

The RUBY head phantom in combination with the MultiMet insert was evaluated for the systematic integral E2E testing of single-isocenter VMAT irradiations of multiple targets. The phantom combination was found to be suitable for point dose verifications using the microDiamond detector at the isocenter as well as at off-axis positions during coplanar and non-coplanar deliveries. Because of the shape of the RUBY phantom mimicking the human head, all steps in the radiotherapy workflow could be performed in a realistic manner as in patient treatments.

Acknowledgments

The authors would like to thank Marco Biehler for providing figure 1 for this publication and PTW Freiburg for providing the RUBY head phantom for this study.

Leonie Brodbek was funded by the Joint Research Training Group of the University of Oldenburg and the University of Groningen.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

Daniela Poppinga is an employee of PTW Freiburg, Germany. All other authors have no conflicts of interest to declare.

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