RSC: Gel dosimetry as a tool for clinical implementation of image-guided radiotherapy

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Abstract. The implementation of new image-guided radiotherapy (IGRT) treatment techniques requires the development of new quality assurance (QA) methods including geometric and dosimetric validation of the applied dose in 3D. Polymer gels (PG) provide a promising tool to perform such tests. However, to be used in a large variety of clinical applications, the PG must be flexibly applicable. In this work, we present a variety of phantoms used in clinical routine to perform both hardware and workflow tests in IGRT. This includes the validation of isocenter accuracy in magnetic resonance (MR)-guided RT (MRgRT) and end-to-end tests of online adaptive treatment techniques for inter- and intra-fraction motion management in IGRT. The phantoms are equipped with one or more PG containers of different materials including 3D printed containers to allow for 3D dosimetry in arbitrarily shaped structures. The proposed measurement techniques and phantoms provide a flexible application and show a clear benefit of PG for 3D dosimetry in combination with end-to-end tests in many clinical QA applications.

1. Introduction
New radiotherapy (RT) treatment techniques, such as image-guided RT (IGRT), applied in clinical routine increase tumor-conformity while sparing surrounding organs at risk (OAR). However, the increasing complexity of such techniques requires the development of new quality assurance (QA) procedures ensuring correct dose delivery. Especially for new hybrid machines combining magnetic resonance imaging (MRI) and conventional RT (so-called MR-Linacs), the implementation of new QA protocols is of great interest. These protocols range from single component testing to the validation of new motion management and adaptive treatment strategies (such as gating and daily plan adaption). However, the complexity of such tests requires dedicated detectors allowing to test (i) geometric and (ii) dosimetric accuracy of the 3D dose distribution in (iii) phantoms, which are visible in MRI. One promising method meeting requirements (i)-(iii) are so-called polymer gels (PG) [1]. To be used in a larger variety of clinical QA procedures, the PG applications should be as flexible as possible including the use of arbitrarily shaped gel containers to simulate anthropomorphic structures. Furthermore, a geometrical evaluation of the gel directly after irradiation instead of after the long stabilization times of...
the gel’s polymerization processes of up to 48h [2] is of high importance for the evaluation of geometrical parameters. In this paper, we present a set of dedicated phantoms that can be equipped with arbitrary 3D printed gel containers [3] and that are used at the German Cancer Research Center (DKFZ) and University Hospital in Heidelberg, Germany, for a variety of clinical QA procedures of advanced treatment techniques. The experimental PG workflow as validated in [2] was applied in this work.

2. Polymer gel

2.1. Fabrication
As PG, the PAGAT (PolyAcrylamide Gelatin gel fabricated at ATmospheric conditions) was used and in-house produced following the protocol described elsewhere [2].

2.2. Gel containers
We used three different types of gel containers: (i) borosilicate glass flasks and (ii) BarexTM (VELOX GmbH, Hamburg, Germany) containers, which are two well established materials for the use with PG, but which are also limited in size and shape. Hence, we have developed a method to (iii) 3D print gel containers in arbitrary shapes using the VeroClearTM printing material of the Objet500 Connex 3 3D printer (Stratasys, Eden Prairie, USA) [3].

2.3. Evaluation
Gel evaluation was performed either (i) purely geometrically directly after irradiation on a 0.35T MR-Linac (ViewRay Inc., Ohio, USA) or (ii) dosimetrically 48h after irradiation on a diagnostic 3T Prisma® (Siemens Healthineers, Erlangen, Germany). For this, a turbospin- or multispin-echo sequence with 1/32 equidistant echoes acquired with an isotropic image resolution of 1 mm³ was used for (i)/(ii). For quantitative dose comparison, a 3D $\gamma$ evaluation with a passing criterion of 3%/3mm (dose difference/ distance-to-agreement) was employed, taking only dose levels larger than 10% of the maximum dose into account.

3. Clinical applications
A schematic overview of the phantoms presented in this paper is shown in Figure 1. Each phantom is equipped with one or more PG containers to either perform 3D geometric and/or dosimetric measurements in different scenarios.

3.1. 3D isocenter accuracy measurement in MRgRT
To test the alignment of imaging and irradiation isocenter in MRgRT, we used an in-house developed QA phantom [4]. The phantom is equipped with a spherical PG-filled glass flask of 8cm diameter (Fig. 1a). The phantom was aligned with the imaging isocenter of the MRI using dedicated fiducials (Fig. 1b, red marking) while the irradiation isocenter was measured by a star shot irradiation of the PG container. The PG was then geometrically evaluated in 3D using a $T_2$-weighted turbo spin echo sequence directly after irradiation without moving the phantom to determine the radius of the irradiation isocircle (ICr) and the distance between the imaging and irradiation isocenter (ICd). Results showed a mean ICr/ ICd of (0.4±0.1)mm/ (0.4±0.6)mm, which were well within the tolerance levels of 0.5mm and 1mm, respectively [4].

3.2. End-to-end tests of online adaptive IGRT procedures

3.2.1. Inter-fractional motion. With the introduction of new IGRT devices, the online adaption of treatment plans in case of inter-fractional anatomy changes became feasible. To validate these techniques, we used two deformable phantoms that can be equipped with 3D printed and PG-filled structures to validate the dose delivery.
3.1 Machine QA

3.2 End-to-end tests of online adaptive IGRT procedures

3.2.1 Inter-fractional motion

3.2.2 Intra-fractional motion

Figure 1. Schematic overview of the phantoms presented in this paper: a) a picture of the phantom for 3D isocenter accuracy measurements in MRgRT including the gel container (green) and b) the geometric PG evaluation including fiducials (red) for a correct positioning in the imaging isocenter. Pictures of the phantoms used for end-to-end tests of online adaptive IGRT procedures are given in c), e), g), and i) together with the respective treatment plan in d), f), h), and j).

i. AQUARIUM. To validate the online plan adaption process in MRgRT the AQUARIUM (Anthropomorphic QUality AssuRance phantom to study Interfractional Uncertainties in MRgRT) [5] was equipped with two PG-filled structures (OAR, tumor) as well as structures filled with anthropomorphic imaging contrast (Fig. 1c). PG containers were either 3D printed or made of Barex®. By a reproducible shift and rotation of the inner structures, a patient’s inter-fractional anatomy change was simulated and the applied dose to the tumor and OAR with and without an adaption of the treatment plan was evaluated in 3D. Results showed a very good agreement of PG evaluation with calculated treatment plans with passing rates >93% in 3D 𝛾-analyses. The online plan adaption successfully compensated under-/over-dosages (down to 45% / up to 180% of the prescribed dose) in the tumor/OAR that occurred without plan adaption.

ii. ADAM-PETer. Inter-fractional motion was simulated in a realistic setup using the ADAM-PETer phantom (Fig. 1e) [6]. To test a fractionated prostate irradiation scheme at a conventional linear accelerator (Artiste, Siemens Healthineers, Erlangen, Germany) with a microboost irradiation of an intraprostatic lesion (Fig. 1f), the phantom was equipped with a 3D printed and PG-filled prostate. The treatment fractions were irradiated directly after each other with the same PG container in the phantom. Between fractions, the position of the prostate was altered by changing the filling of an endorectal balloon. As expected, an under-dosage and a dose smearing within the microboost-volume were measured. Additionally, we could demonstrate significant inter-fractional shifts of the microboost volume of up to 5mm by the gel evaluation.

3.2.2 Intra-fractional motion. In case of intra-fractional patient motion (e.g. breathing), new IGRT treatment methods such as gating or tracking may be used for compensation. To test and validate an
existing gating procedure at the MR-Linac, two motion phantoms were equipped with a PG-filled Barex™ container simulating the tumor.

i. Geometric motion phantom. In a first experiment, the gating procedure at a clinical MR-Linac was simulated with a geometrical motion phantom consisting of a water-filled cylindrical case (d=22cm, l=50cm) holding a movable smaller water-filled cylinder (d=9cm, l=50cm) that can be loaded with the PG-filled Barex™ tumor (Fig. 1g). The phantom motion was based on a cos^4 trajectory with a peak-to-peak amplitude of 1.5cm. The gel was evaluated dosimetrically. Results for a gated treatment showed a homogenous target coverage similar to that of a static case with high 3D γ passing rates of >98.6%. Irradiation without motion compensation resulted in poor dose coverage with a γ_{3D} passing rate of 68.6%.

ii. Porcine lung phantom. To test the gated treatment at a clinical MR-Linac in a realistic setup, we used a porcine lung phantom (Fig. 1i) [2]. The PG tumor was sewed onto the mediastinum of the lung, which moved according to a real patient’s breathing pattern. The target structure could be tracked by MRI throughout the entire treatment session. Additionally, homogeneous dose coverage without significant under or over-dosage was found indicating a successful gated irradiation. Dosimetric evaluation yielded a high 3D γ passing rate of 95.9%.

4. Discussion and Conclusion
In this paper, we present a variety of phantoms equipped with PG, which were used in clinical routine to perform both hardware and workflow tests in IGRT. This includes 3D isocenter alignment measurements at a clinical MR-Linac and end-to-end tests of online adaptive treatment procedures for both inter- and intra-fractional motion management. One important step to achieve a realistic setting is the use of 3D printed PG containers. This allows for adapting and extending existing phantoms to applications that require 3D dose measurements in irregularly shaped structures, e.g. for the simulation of specific organ sites. Furthermore, experiments have also shown that a geometric evaluation of the PG is possible directly after the irradiation. If, however, a full dosimetric evaluation is required, it is a common procedure in PG dosimetry to await the stabilization time and to normalize the required calibration curve at a reference point with a known dose determined e.g. by an ionization chamber (IC). However, due to the lack of bores in our anthropomorphic phantoms, independent absolute dose measurements with an IC were not possible. Hence, we based the reference dose on the treatment plan. To overcome this limitation, a recently developed technique combining thermoluminescence detectors (TLD) with PG can be used. Due to their compact design, TLDs can be attached on the surface of various phantom structures (OARs and/or tumor) serving as a reference system for absolute dosimetry [7,8]. Overall, the presented techniques and phantoms provide a flexible application of PG for 3D dosimetry in complex radiotherapy treatment techniques.

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6. References
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