Validation of 4D dose calculation using an independent motion monitoring by the calypso tracking system and 3D polymer gel dosimetry

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Abstract. This study aims to evaluate an in-house developed 4D dose calculation algorithm that uses Calypso motion tracking data and to compare the results against 3D polymer gel dosimetry measurements. For this, a cylindrical water phantom was constructed that allows to insert (i) the polymer gel, (ii) a PinPoint ® ionization chamber and (iii) Calypso beacons™ for motion tracking. A treatment plan covering a gel flask in the center of the static phantom plus a 1 mm margin homogeneously with dose was generated. During irradiation, however, the phantom was moved periodically by means of a robot with a peak-to-peak amplitude of 2.5 cm. The results of the 4D dose calculations show good agreement with the gel-dosimetric measurements in most of the volume. Remaining small deviations have to be evaluated in further experiments. The developed experimental setup allows for 3D-dosimetric validation of 4D dose calculations algorithms prior to application in patients.

1. Introduction

Modern adaptive radiotherapy techniques (e.g. gating or tracking) have the potential of significant normal tissue sparing. Clinical implementation of these techniques, however, requires validation of the intended workflow using both, phantom experiments and 4D dose calculations. Several experimental settings with dynamic phantoms have been proposed showing the feasibility of 3D dose measurements and 4D dose calculation algorithms [1, 2]. To further push 4D dose calculation towards clinical application, real-time target data from clinically accepted tracking devices need to be integrated into the 4D dose calculation. The aim of this study was to validate an in-house developed 4D dose accumulation algorithm, which uses motion tracking data from the Calypso system, by a comparison between the calculated dose distribution and a 3D polymer gel dosimetry [3] measurement in a moving phantom.
2. Material and Methods

2.1. Cylinder phantom
The phantom (figure 1) consists of a double-walled cylindrical polymethyl-methacrylate (PMMA) shell (diameter 16 and 18 cm, respectively, height 10 cm). In this experiment, both cavities were filled with water. To perform 3D dose measurements, a BAREX™ container filled with dosimetry gel (subsequently referred to as gel flask) was placed in the center of the phantom. An additional bore allows inserting a PinPoint® Ionization Chamber (31014, PTW, Freiburg, Germany) into the gel flask to perform absolute dose measurement (see figure 1). In this case, the dosimetry gel serves only as an absorber and is not evaluated.

2.2. Motion robot and tracking system
During irradiations, the phantom was moved periodically with a dedicated motion robot perpendicular to the incident beam in cranio-caudal direction with 2.5 cm peak-to-peak amplitude and a period of 7.5 seconds. A cos⁴ motion trajectory was applied as it has been demonstrated to provide a good fit to the population data for respiratory motion [4]. Both motion-tracking and beam-on/off monitoring during the irradiation was realized with the Calypso system (Varian Medical Systems Inc., Palo Alto, California, USA). The system uses three electro-magnetic markers, referred to as beacons™, emitting a stimulated response signal, which is then recorded by a sensor array and used for localization of the beacons within an accuracy < 1 mm at a repetition rate of 10 Hz [5]. The beacons were inserted into the gel flask adapter with a distance of approx. 4 cm to the center of the gel sample (see figure 1a).

2.3. 3D-polymer gel dosimetry
3D dose measurements were performed with the PAGAT dosimetry gel (PolyAcrylamide Gelatin gel fabricated at ATMospheric conditions). After irradiation, the gel polymerizes locally and alters the relaxation rate R₂ of the transverse magnetization depending on the absorbed radiation dose. This effect can be measured by magnetic resonance imaging (MRI). The PAGAT dosimetry gel consists of monomers (3% acrylamide and 3% N, N-methylene-bis-acrylamide) as active components embedded within a gelatin matrix (6% Gelatin Sigma Aldrich) and 10 mM THPC (bis[tetrakis(hydroxymethyl)-phosphonium] chloride) acting as an antioxidant. The production of the gel followed the protocol described elsewhere [6]. An absolute 3D-dose distribution can be determined after establishing a mono-exponential calibration curve [7]. Due to its chemically inert properties [8] a BAREX™ container (distributed by VELOX GmbH, Hamburg, Germany) was used as gel dosimetry storage container (length l = 45 mm, outer diameter d = 28 mm, wall thickness t = 0.6 mm and volume V = 25 ml). Prior
to the MRI evaluation, both calibration- and gel flask were stored for 2 h at room temperature inside a water-flow phantom keeping the temperature constant within ± 0.1 °C during the MR measurement. Calibration- and gel flask were then scanned simultaneously on a 3T Biograph mMR (Siemens Healthineers, Erlangen, Germany) using the following imaging parameters: \( TR = 3000 \text{ ms} \), 32 equidistant echoes, \( TE = 22.5 – 720 \text{ ms} \), resolution = \( 1 \times 1 \times 1 \text{ mm}^3 \), \( BW = 130 \text{ Hz/pixel} \) with a scan time of \( t = 6 \text{ min 24 s} \) for each of the 27 slices. To acquire sufficient information on the 3D dose distribution of the gel flask, 27 slices were measured and co-registered with the calculated treatment plan using dedicated MR-markers (Beekly Medical, Bristol, USA).

2.4. Phantom irradiation experiments

Treatment planning CTs for the static phantom were acquired on a SOMATOM Definition Flash (Siemens Healthineers, Erlangen, Germany). 3D conformal radiation therapy (3DCRT) treatment plan optimization was realized with the Raystation TPS (RaySearch Laboratories, Stockholm, Sweden) using a collapsed cone dose calculation algorithm with a dose grid resolution of \( 1.0 \times 1.0 \times 1.0 \text{ mm}^3 \). The gel flask plus a 1 mm margin was considered as planning target volume (PTV) and was covered homogeneously with a median dose of \( D_{50} = 4 \text{ Gy} \) delivered from 7 beam directions (0, 40, 80, 200, 240, 280, 320) using only one beam segment per gantry angle. Outside the PTV, the dose gradient was 2 Gy / cm. The treatment plan was delivered to the moving phantom using a 6 MV linear accelerator (Artiste, Siemens Healthineers, Erlangen, Germany) with photons and a dose rate of 300 MU/min. The calibration flasks were irradiated under reference conditions with doses between 0 and 7 Gy.

2.5. 4D Dose calculation

A 4D dose distribution has been calculated retrospectively using an in-house developed software by shifting the target point within the planning CT based on the motion information and beam status recorded with the Calypso system. For each target point position, a new sub-beam was assigned together with a weighting factor corresponding to the duration of the irradiation at the respective target point position. In total, 1227 sub-beams were used for the 4D dose calculation. As the 4D dose calculation uses the pencil beam algorithm of the in-house developed VIRTUOS treatment planning system (TPS) [9], the dose distribution for the static case was additionally recalculated with VIRTUOS using the same treatment parameters. To assess the accuracy of the dose calculation algorithms of both TPS, a PinPoint® chamber measurement was performed in the homogeneous region.

3. Results

3.1. Accuracy of dose calculation algorithms

Both dose calculation algorithms revealed very similar dose distributions (figure 2). With respect to the PinPoint® chamber measurement, only minor deviations of +0.7 % and -1.0 % were obtained for the Raysearch system and VIRTUOS, respectively.

3.2. 4D Dose calculation

A representative sagittal slice of the MR-based dose evaluation is displayed in figure 2a. Homogeneous target coverage was measured for approx. 80 % of the evaluated volume while an expected decrease of up to 62.5 % was seen towards the neck of the flask. Figure 2b compares measured and calculated dose profiles located at the central region of the gel flask. In all cases, measured and calculated dose agree well within the homogeneous area. The dose gradient region (position <15 mm), however, was better described by the retrospectively performed 4D than by the static dose calculation. Evaluation of the profile at the bottom-region (figure 2c) could not completely reproduce the measured dose distribution. The dose gradients were shifted by 3 mm against each other. Nevertheless, the measurement of this profile agreed better with the 4D than with the static dose calculation.
4. Discussion
The developed phantom setting allows (i) performing irradiations under dynamic conditions with arbitrary pre-defined motion patterns, (ii) measuring dose in 1D and 3D and (iii) recording motion trajectories with the Calypso system to retrospectively calculate a 4D dose distribution. In addition, absolute 3D gel dosimetry was performed. Due to the non-symmetrical \( \cos^4 \) motion-pattern and an amplitude of only 2.5 cm, a dose reduction was only visible at the neck of the gel flask. This decrease was also calculated with the in-house developed 4D calculation algorithm and the result showed a good agreement with measurements. At the bottom of the gel flask, however, the deviations were larger than at the center. Due to the applied workflow, positioning errors as well as dose differences resulting from temperature changes in the gel can be excluded. To further evaluate the source of this dose discrepancy, future measurements should also include a gel flask irradiation under static conditions to distinguish gel-dosimetric from motion-related error sources. In addition, a larger motion amplitude will be applied, which leads to a dose decrease on both sides of the flask and which would allow identifying potential artefacts at the neck of the flask. Finally, a dosimetric impact of the robot table in terms of beam attenuation and scattering has to be investigated.

Future experiments will also include patient-based motion-patterns in 3D as well as more complex irradiation techniques such as intensity modulated radiotherapy (IMRT) and gated beam delivery.

5. Conclusion
The combination of the moving phantom, the Calypso motion tracking system, 3D polymer gel dosimetry and the in-house developed 4D dose calculation algorithm are valuable tools for validating intrafractional adaptive radiotherapy by both, calculations as well as measurements. Especially, the Calypso system could also be used to reconstruct motion-related changes of the dose distribution in patients.

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7. References
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