Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Aurimas Krauleidis and Diana Adlienė 2024 *J. Phys.: Conf. Ser.* **2799** 012010

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Simultaneous comparison of two independent dosimetry verification systems for VMAT irradiation in assessing 4D dose distribution

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Abstract. Despite the rapid development of new technologies, 4D dose assessment related to the breathing movement of target organs during radiotherapy treatment is still a challenge. This study aimed to investigate the feasibility of polymer gel dosimeters to assess 4D dose distribution accuracy in VMAT radiotherapy treatment under dynamic conditions and to compare assessment results with the data obtained using a cylindrical water-equivalent phantom with a three-dimensional diode array (ArcCheck). For this purpose, several homemade polymer gels were filled in cylindrical containers and placed within the ArcCheck phantom. The entire system was mounted on rotating wheels and periodically moved by a connected robotic platform during irradiation. Generally, good agreement was found between measurement results of the 4D dose distribution obtained in the bulk of volume using homemade polymer gel dosimeters and diode detector system, indicating the potential to address the remaining small errors in further experiments. The latter implies the applicability of polymer gel dosimeters for the validation of high-dose stereotactic treatment plans under realistic 4D dose distribution conditions.

1. Introduction

Modern adaptive radiotherapy delivery techniques have become increasingly complex in recent years. The success of radiotherapy treatment of cancer patients depends on the proper planning and delivery of doses in each stage of the treatment. Even minor errors can compromise the effectiveness of the treatment. However, advanced delivery techniques are often associated with moving beams, small fields, steep dose gradients and the effect of tumour motion. The most challenging issue is the application of respiratory gating techniques related to the tumour movement due to the patient's breathing cycle [1]. The tumour can follow complex trajectories, and the breathing pattern may vary depending on the intensity, duration, regularity and starting position. Breathing related movements are contributing to the discrepancies between planned and delivered to the target dose distributions [2]. Application of respiratory gating technique aimed at reduction of dose delivery to the healthy tissues without compromising the established target coverage and shortening of treatment duration, its clinical implementation requires validation of the intended workflow using dynamic phantom experiments and 4D dose measurements [3].

Journal of Physics: Conference Series **2799** (2024) 012010 doi:10.1088/1742-6596/2799/1/012010

Polymer gel dosimeters can serve as independent 4D detectors having desired characteristics, like equivalency to biological tissues, accuracy and precision and providing ability to resolve three-dimensional (3D) dose distributions in dynamic dose verification [4, 5]. Polymer gel dosimeters can be used as an introduction to new benchmarking techniques in the clinic, adding an extra dimension to ongoing pursuit improved patient safety.

Moreover, in most studies a fixed setup measurements are investigated and data cannot show the dynamic dose distribution. In this study nMAG and nPAG polymer gel dosimeters were coupled to simulated dynamic organ displacement caused by motion phantom with a diode array detector.

2. Materials and methods

In this study, the ArcCheck verification system (model 1220) was used to simulate the patient's body and perform reference dose distribution measurements. Independent verification system is represented by a cylindrical water-equivalent phantom with a three-dimensional array containing of 1386 diode detectors, arranged on a phantom according to a helical geometry with

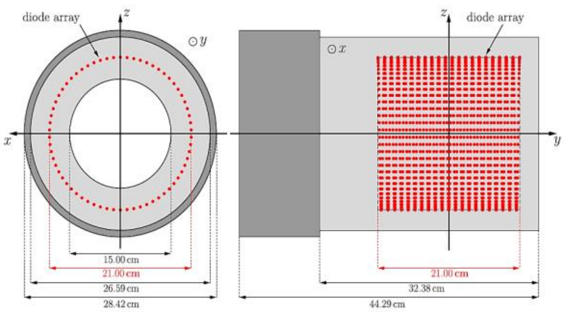

Figure 1. The geometry of the ArcCheck device.

Figure 2. Experimental setup of the system.

10 mm spacing in between (Figure 1). The diameter and size of the diode array is 21 cm. Each diode in the array has a sensitive volume of 0.019 mm^3 and provides updated dose measurement results within 50 ms intervals. The array itself is situated at a water equivalent depth of 3.3 g/cm^2. The central cavity of the device is cylindrical, having diameter of 15 cm. The experimental setup of the system (Figure 2) shows the ArcCheck, gel vial (inside the ArcCheck), wheels and motion phantom.

Normoxic methacrylic acid polymer gel dosimeter (nMAG) and normoxic polyacrylamide polymer gel dosimeter (nPAG) was used for 3D dose measurements. Polymer gel dosimeter 's recipes were taken and fabrication procedure was implemented following information provided in previous publications [6, 7]. Prepared polymer gels were poured into cylindrical PMMA containers (H=100mm, Ø 150 mm) and tightly closed to avoid oxygen contamination. To perform 4D dose measurements 4 containers were filled with two different polymer gels and placed in the centre of the ArcCheck phantom. Four wheels were attached to the phantom to enable its movement. At least one container filled with corresponding polymer gel dosimeters was not irradiated and left for reference.

The simulation of target 's movement was performed using respiratory gating robot (Anzai Medical) connected to an ArcCheck phantom that was set in sinusoidal motion along longitudinal direction. Movement rate of 15 rpm with an amplitude of 20 mm was chosen. During irradiation activated movement resulted in a simultaneous dynamic signal recording process by detector array and polymer gel dosimeter. 2 containers filled with different polymer gels were irradiated during movement and another 2 containers without movement.

A real lung stereotactic treatment plan with a single dose of 24 Gy was created by treatment planning system (Eclipse version 15.6) of RapidArc treatment modality using calculation algorithm AAA (Anisotropic Analytical Algorithm) with a calculation resolution of 1.25 mm. A linear accelerator (TrueBeam, Varian) was used to deliver the dose to a moving phantom with the polymer gel dosimeters inside. 6 MV FFF photon beam with a maximum monitor unit rate of 1400 MU/min was used for irradiation. The irradiation plan was realized using four partial arcs with total 9474 MU's. A calibration curve was obtained with doses ranging from 0 to 36 Gy.

Irradiated polymer gel dosimeters were evaluated in MRI facility analysing polymerization induced alteration of the relaxation rate R2 of the transverse magnetization depending on the absorbed radiation dose. Irradiated polymer gel dosimeters were scanned with a 1.5 T MRI unit Magnetom Aera (Siemens Healthineers) using the following imaging parameters: TR = 3000 ms, 32 equidistant echoes, TE = 22.5 – 720 ms, resolution = 1 × 1 × 1 mm^3. In parallel CT readouts of irradiated polymer gel dosimeters were performed using GE Discovery CT scanner. The CT scanning parameters were as follows: tube voltage - 140 kVp, tube current - 320 mAs, and slice thickness of 1 mm. Eclipse 15.6, IQ Works, ImageJ and Origin Pro software's were used for data processing and analysis. For CT and MRI data ROI was selected as a mean of area plot with the applied background subtraction. A dose profile was measured through the centre of the target. Image filtering was not applied. Additionally, special home-based algorithm developed using a MatLab R2021a programming platform and SNC patient software was applied to create dose distributions in the form of dose maps.

3. Results and discussion

The total effect of motion on the dose delivery to the target and surrounding tissues was evaluated, i.e. the 3D dose distribution difference between measurement results obtained using polymer gel dosimeters and ArcCheck detector during phantom motion. The blurring effect was identified when investigating dose distribution in polymer gel dosimeters irradiated under a moving system setup (Figure 3 and Figure 4).

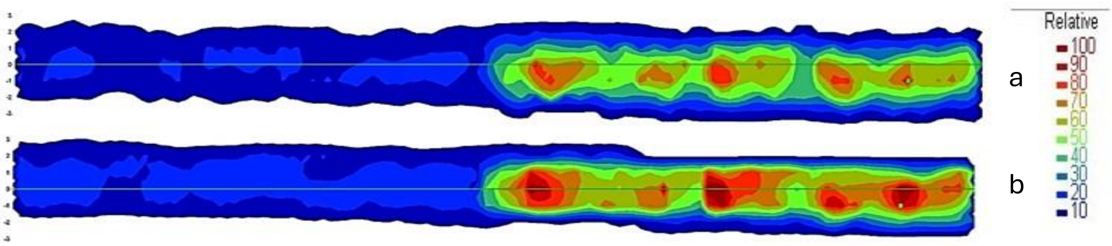

Figure 3. Comparison of the ArcCheck system dose maps: a) moving setup b) fixed setup**.**

It can be noticed that polymer gel dosimeters are less sensitive at lower dose gradients. However, dose values obtained using polymer gel dosimeters and ArcCheck were in good agreement within homogeneous areas. The average γ passing rates applying 3%/3 mm or 3%/2 mm criteria and the threshold of 10% were 99.9 % for ArcCheck system in the fixed setup compared to the target plan calculated by the treatment planning system, so we can consider the ArcCheck results as reference data.

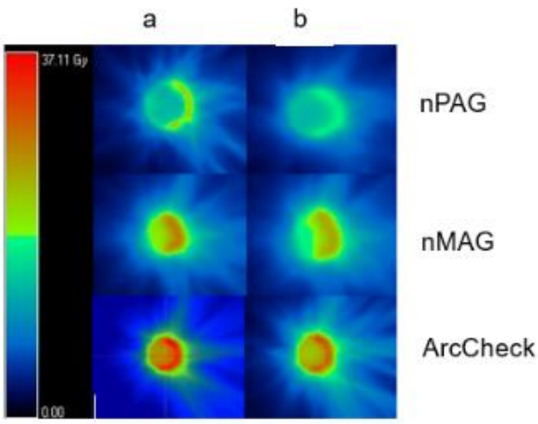

Figure 4. Dose distribution maps in the target a) fixed system setup and b) moving system setup.

For nMAG polymer gel dosimeter γ passing rates were greater than 90 % and for nPAG polymer gel dosimeter quite low, around 38 % respectively. For moving system setup γ passing rate applying 3%/3 mm was 51,3 %, 45,3 % and 27 % respectively (Figure 5 and Figure 6). The calculated percentage dose difference (DD, %) for the planning target volume (PTV) mean dose and maximum dose reached up to 32 %.

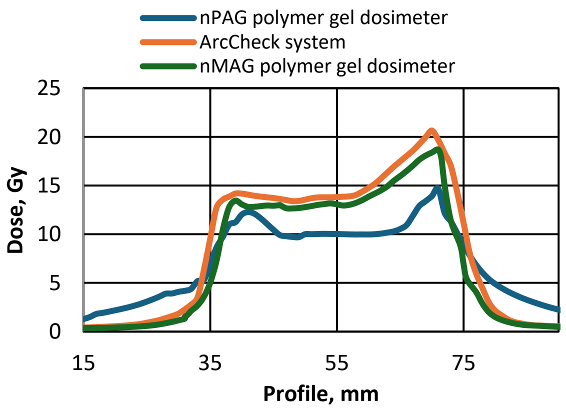

Figure 5. Comparison of the target dose profiles obtained using polymer gel dosimeters and the ArcCheck system in moving setup.

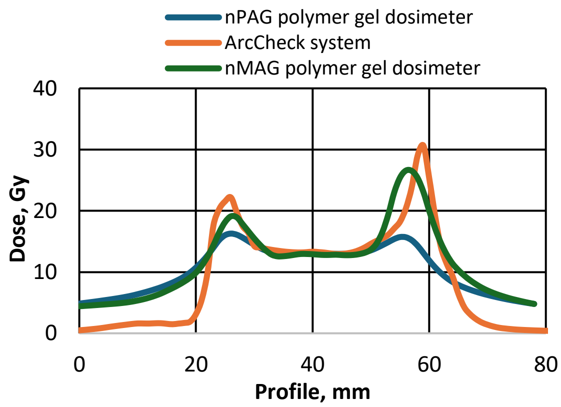

Figure 6. Comparison of the target dose profiles obtained using polymer gel dosimeters and the ArcCheck system in a fixed setup.

4. Conclusion

Investigated polymer gel dosimeters indicated their applicability for dose measurements during target movement and for dose verification of dynamic RT involving gated dose delivery. The combination of moving diode phantom with 3D polymer gel dosimeters might be a valuable tool for validating adaptive radiotherapy.

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