Evaluation of a clinical dose accumulation algorithm using deformable gel dosimetry

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Abstract. Deformable 3D dosimetry represents a robust method of verifying the accuracy of clinical deformable dose accumulation algorithms used to monitor interfraction anatomical changes during radiotherapy treatments. For this study, a deformable abdominal phantom was developed incorporating a deformable nPAG gel dosimeter for the dose verification of Adaptivo™, a commercial software program with a deformable dose accumulation algorithm. A comparison was made for three single fraction irradiations of gel dosimeters, each with a different deformation state. Additionally, a comparison was made for the cumulative dose over a three-fraction treatment of a single gel dosimeter with individual fraction deformations matching those of the single fraction measurements. The single fraction irradiations resulted in target contour dose volume histograms (DVH) created by Adaptivo™ that were in close agreement with those determined by gel dosimeter measurements for doses similar to and higher than the planned target dose, with two of the three cases matching to within 5%. Discrepancies are attributed to a deformed contour compression during analysis in the cases where the phantom was deformed. The three-fraction treatment resulted in very close agreement between the DVHs determined through the gel dosimeter measurements and Adaptivo™ calculations across the full range of doses, with an average absolute discrepancy of 2.0% and a maximum absolute discrepancy of 6.3%.

1. Introduction
Deformable dose accumulation algorithms have been developed to manage patient anatomy changes and other forms of interfractional patient motion during the course of radiotherapy treatments. These algorithms make use of patient imaging data during treatment to deform the delivered patient dose distribution back to the original planning images, providing clinicians with information of how closely the delivered patient treatment matches the planned treatment and allowing for subsequent treatment fractions to be adapted accordingly. To implement these systems clinically, AAPM Task Group 132 recommends the use of physical phantoms and measurements to verify the accuracy of calculations [1]. Although these measurements can be done on a point-by-point basis, a deformable 3D dosimeter allows for the most robust testing of systems.

Deformable 3D dosimetry has been investigated by several groups to address this need for robust deformable dose accumulation algorithm evaluation. Studies have shown that when a gel dosimeter is incorporated into a deformable mold or a radiochromic 3D dosimeter itself is deformable, it can be used as a physical deformable phantom to test these algorithms [2-5]. These dosimeters can be placed in different deformation states during irradiation and imaging, allowing for a measurement of the dose.
related back to the undeformed state. Although some studies have been performed with these dosimeters placed in large, rigid motion phantoms, none have been performed within fully deformable anthropomorphic phantoms. The goal of this study was to use a deformable, anthropomorphic abdominal phantom which incorporates deformable polymer gel dosimetry for the purpose of testing a deformable dose accumulation program.

2. Methods

2.1. Deformable Abdominal Phantom
A deformable abdominal phantom (Figure 1) was developed to evaluate Adaptivo™, which is a commercially available deformable dose accumulation program. The phantom was fabricated using polyvinyl chloride plastisol (PVCP) (M-F Manufacturing, Fort Worth, TX), a liquid plastic phantom material which can be mixed with a hardener or softener during fabrication to change the density and radiological properties of the material [6]. The phantom featured a higher density bulk phantom material. Lower density sections of the phantom were developed to represent abdominal organs at risk, including the colon, kidneys, and spleen. Additionally, a spine surrogate was created from a high-density casting material. Finally, a cavity was created in the phantom for the placement of a deformable gel dosimeter representing the treatment target. Phantom motion and deformation was driven by the s-axis 1D stage of the Washington University 4D Phantom [7].

![Figure 1. Model of the deformable phantom apparatus. The phantom features a deformable abdominal phantom made of high density PVCP bulk material and low density PVCP organ sections. It also features a deformable gel dosimeter cavity and a programmable 1D motion stage.](image)

2.2. Gel Dosimeter Fabrication
Five deformable gel dosimeters were created in-house at the University of Wisconsin Medical Radiation Research Center (UWMRRRC) using a 6%T normoxic polyacrylamide gel (nPAG) formula. The nPAG formula was fabricated using the mixing methods described by Yeo et al. [5]. Deformable molds were made using PVCP to house the gel dosimeters (Figure 2). The exterior of the deformable mold conformed to the cylindrical cavity in the deformable abdominal phantom, while the inner cavity of the mold was shaped using an asymmetric 3D printed insert (Figure 2). Molds were capped and sealed using additional PVCP and injected with nPAG during dosimeter fabrication. The final dosimeter mold design allowed for a more accurate representation of an asymmetric tumor volume made up of nPAG. Fiducial markers were drilled into the top and the bottom of the outer shell of each dosimeter mold after fabrication to assist with image co-registration.
2.3. Deformable Dose Accumulation Program

The deformable dose accumulation program evaluated in this study was Adaptivo™ (Standard Imaging, Middleton, WI), a commercial software product developed to monitor dose to patient structures on a fraction-by-fraction basis using deformable image registration (DIR) to deform the structure doses back to the original planning CT. Dose calculations are performed using a reference dose perturbation algorithm [8]. To perform these calculations the software uses cone-beam CT (CBCT) images gathered before each fraction to calculate the differences between the treatment setup and the planning CT, which is then used to estimate the dose distribution during that fraction. The software outputs dose-volume histograms (DVH) of the delivered treatment for each organ or target contour deformed from the CBCT to the planning CT. These DVHs can be viewed for each fraction along with a cumulative DVH of all fractions up to a specified fraction.

2.4. Phantom Irradiation

The same liver VMAT treatment plan was delivered to four of the gel dosimeters while a separate dosimeter used for calibration was irradiated with a simple four-field plan. The liver VMAT treatment plan was created using Eclipse™ (Varian Medical Systems, Palo Alto, CA) with 3 Gy per fraction dose to the target volume, which was a 1.5 cm subtraction of the nPAG contour. This subtraction of the gel contour was used to avoid oxygen and other PVCP plasticizer related contaminants in the target region to ensure accurate gel measurements. Organ dose limits were based on established clinical protocols scaled to the target dose per fraction. Of the four gels irradiated with the VMAT treatment plan, three received only a single fraction, while the remaining dosimeter received all three fractions of the treatment.

All dosimeters were irradiated using a Clinac 21EX medical linear accelerator at the UWMRRC using the phantom setup shown in Figure 3. The three gels irradiated with single fractions were placed under different deformation states using the motion stage: no deformation, 1 cm of deformation, and 2 cm of deformation. Deformation was estimated by the amount of deflection by the side of the phantom opposite of the motion stage plunger. The gel dosimeter that received three fractions underwent one fraction without deformation, one fraction with 1 cm of deformation, and one fraction with 2 cm of deformation to show the effect of dose integration over all three fractions. A CBCT was performed before the delivery of each treatment fraction to allow for the deformable dose accumulation algorithm to estimate the delivered dose for each irradiation.
2.5. Data Analysis

All dosimeter dose data were gathered using a multiple spin-echo (MSE) R₂ mapping sequence on a 3T MRI scanner (SIGNA PET/MR, GE Healthcare, Waukesha, WI) using an 8-channel receive-only head coil. The sequence scanning parameters are shown in Table 1. The echoes from each scan were fit to exponential decay curves on a voxel-by-voxel basis to create R₂ maps. R₂ maps and target contours were co-registered to respective planning CTs using fiducial markers with Amira™ (Thermo Fisher Scientific, Waltham, MA).

| Parameter                  | Value                       |
|---------------------------|-----------------------------|
| Repetition Time (TR)      | 5000 ms                     |
| Echo Spacing (ESP)        | 40 ms                       |
| Echoes (NE)               | 16                          |
| Averages (NEX)            | 1                           |
| Acquisition Matrix        | 128 x 128                   |
| Field of View (FOV)       | 128 x 128 mm²               |
| Spatial Resolution        | 1 mm²                       |
| Number of Slices (NS)     | 28 - Coronal                |
| Slice Thickness           | 3 mm                        |

Gel dose-response calibrations were created separately for the lower dose single fraction dosimeters and the high dose three fraction dosimeter. The single fraction dosimeters were calibrated using the R₂ map and planned dose distribution of the dosimeter that did not undergo a deformation to allow for accurate calibration over the small dose range. Due to the much larger dose range, the three-fraction dosimeter was calibrated using the separate gel dosimeter that underwent a four-field irradiation to allow for a larger range of dose values to be calibrated accurately. Each of the dosimeter dose maps were used to calculate a dose volume histogram (DVH) of the target region of the dosimeter.

The CBCT data gathered before each fraction delivery was imported into Adaptivo™ and used to calculate the cumulative doses for each of the irradiated dosimeters. The cumulative DVH for each dosimeter treatment course was exported to be compared to the DVH calculated by the corresponding dosimeter.
3. Results and Discussion
The resulting DVHs from the single fraction experiments are shown in Figure 4. In each case both DVHs matched very well at the prescribed dose of 3 Gy per fraction. For the undeformed dosimeter and the dosimeter that was deformed 2 cm, the two DVHs matched within 5% for all doses above 2.5 Gy. In the low dose region, the gel dosimeters showed lower DVH values than Adaptivo™ did, especially for the two deformed cases. This was attributed primarily to the deformation of the target contour by the DIR algorithm slightly compressing the contour to be a smaller volume than contoured during treatment planning. The main cause of this compression was that the DIR algorithm was presented an extremely difficult case to deform – a contour based on a subtraction of another contour and not physical image intensity boundaries. This compression of the target contour caused the deformable dose accumulation algorithm to lose some lower dose components, raising its estimated low dose DVH values.

![Figure 4](image.jpg)

**Figure 4.** The target contour DVHs determined by both the nPAG gel dosimeter and the Adaptivo™ deformable dose accumulation algorithm over a single fraction with no deformation (Top), 1 cm of deformation (Bottom Left), and 2 cm of deformation (Bottom Right).

The resulting DVHs from the multiple fraction experiment along with point-by-point DVH differences are shown in Figure 5. Over the entire dose range, the DVHs agreed within 6.3%. The average absolute deviation between the two DVHs was 2%. In this experiment, the DIR algorithm showed very little target contour compression, causing the low dose DVH values to match well.

It is important to note that uncertainties arise in the DVHs calculated in both experiments from gel dosimetry and from deformable dose accumulation. It can be conservatively estimated that the nPAG gel dosimeter has a voxel-to-voxel combined uncertainty (k=1) of approximately 5.2%. This combined uncertainty is based on the 3.7% average Type A uncertainty of the nPAG dose measurements used for calibration, the maximum 3.6% of Type B MRI polymer gel dosimetry related uncertainties [9], and the 0.9% of linac related Type B uncertainties [10]. This combined uncertainty can be propagated to assume a 5.2% maximum uncertainty on each measured nPAG DVH value. Additionally, based on a previous study, the reference dose perturbation method used to calculate dose in the deformable dose accumulation algorithm can be estimated to have an uncertainty of approximately 3% [8]. There is also significant additional uncertainty in the deformation of the target contour by the DIR algorithm due to the challenging case presented, as previously discussed. Considering the combination of these uncertainties...
uncertainties, the observed agreement between the nPAG gel measurements and the deformable dose accumulation algorithm calculations was considered reasonable for this study.

![Figure 5](image)

**Figure 5.** (Left) The cumulative target contour DVHs determined by both the nPAG gel dosimeter and the Adaptivo™ deformable dose accumulation algorithm over three fractions which underwent static deformation states of no deformation, 1 cm of deformation, and 2 cm of deformation. (Right) A point-by-point DVH difference of the two DVHs calculated by subtracting the gel DVH value from the Adaptivo™ DVH value.

4. Conclusions
In this study, a deformable abdominal phantom was paired with a deformable gel dosimeter to compare phantom measurements to the output of Adaptivo™. The first comparison made was over single fraction irradiations in which each gel was irradiated in a different deformation state. The target DVHs created by the two methods matched closely at doses at or above the 3 Gy target dose, but deviated some at low dose values due to the compression of the target contour during DIR. The second comparison was made for the cumulative dose following the delivery of three treatment fractions with different deformation states. The resultant DVHs for the two methods matched very closely, with a maximum deviation of 6.3% and an average deviation of 2.0%. In conclusion, this study provided a methodology to test and compare deformable dose accumulation algorithm calculations to physical measurements and found good agreement between the Adaptivo™ deformable dose accumulation algorithm and measurements made with a gel phantom.

5. Acknowledgements
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6. References
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