Tumor-tracking radiotherapy of moving targets; verification using 3D polymer gel, 2D ion-chamber array and biplanar diode array

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Abstract. The aim of this study was to carry out a dosimetric verification of a dynamic multileaf collimator (DMLC)-based tumor-tracking delivery during respiratory-like motion. The advantage of tumor-tracking radiation delivery is the ability to allow a tighter margin around the target by continuously following and adapting the dose delivery to its motion. However, there are geometric and dosimetric uncertainties associated with beam delivery system constraints and output variations, and several investigations have to be accomplished before a clinical integration of this tracking technique. Two types of delivery were investigated in this study I) a single beam perpendicular to a target with a one dimensional motion parallel to the MLC moving direction, and II) an intensity modulated arc delivery (RapidArc®) with a target motion diagonal to the MLC moving direction. The feasibility study (I) was made using a 2D ionisation chamber array and a true 3D polymer gel. The arc delivery (II) was verified using polymer gel and a biplanar diode array. Good agreement in absorbed dose was found between delivery to a static target and to a moving target with DMLC tracking using all three detector systems. However, due to the limited spatial resolution of the 2D array a detailed comparison was not possible. The RapidArc® plan delivery was successfully verified using the biplanar diode array and true 3D polymer gel, and both detector systems could verify that the DMLC-based tumor-tracking delivery system has a very good ability to account for respiratory target motion.

1. Introduction
The desire to increase the conformity of the dose distribution in external radiotherapy has resulted in advanced treatment procedures, for instance techniques using intensity modulated beams and arcs [1-3]. The advantages of these techniques are the increased possibility to deliver a high absorbed dose to
the target volume while minimizing the dose to normal tissues. However, intra-fractional tumor motion, mostly due to respiration, can be a major challenge to the ambition to deliver the desired dose distributions. An illustration of how the high dose volumes shrink due to motion is presented in figure 1, where polymer gel measurements are compared to the treatment planning system (TPS) for moving targets treated using arc therapy. Large respiratory motion is generally accounted for by increased margins, which implies an increased risk of morbidity from late toxicity. It is therefore important to find better ways to take respiratory motion into account when treating targets in the thorax region.

A novel promising motion-compensation strategy uses the dynamic multileaf collimator (DMLC) to continuously align and reshape the treatment machine apertures so as to following the target motion in real time [4, 5]. The advantage of this so called real-time DMLC tumor-tracking radiation delivery is the ability to allow a tighter margin around the target by continuously following, and adapting the dose delivery to its motion. This kind of treatment delivery represents a new level of complexity, and a thorough dosimetric verification is therefore highly desirable. Recently published data find that DMLC tracking together with the intensity modulated radiotherapy technique RapidArc®, is capable of improving the dose distribution delivered to a moving target [6] and improves the accuracy of RapidArc® delivery [4]. In both studies the biplanar diode array Delta4® (ScandiDos, Inc., Sweden) was used for dose verification, and further studies using a true 3D detector would be of great interest. Using high resolution gel dosimetry [7], the absorbed dose can be obtained in the entire irradiated volume and the response is independent of the direction of the incident radiation. Previous work demonstrate the use of polymer gel dosimetry to verify dynamic radiotherapy, both under respiratory-like motion [8], as well as in intensity modulated arc therapy delivery [9]. This makes polymer gels potentially useful for tracking measurements during both conventional and arc delivery.

The aim of this study was to carry out a dosimetric verification of a DMLC-based tracking delivery using true 3D polymer gel dosimetry, a 2D ionization chamber array, and a biplanar diode array. Results are presented from a feasibility study using a single beam perpendicular to a target with a one dimensional motion parallel to MLC motion direction, and from a verification of a target with a diagonal motion to the leaf trajectory during an intensity modulated arc delivery.

2. Material and methods

2.1. The detector systems
The 2D ionization chamber array seven29® (PTW, Freiburg, Germany), with 729 measurement points consists of 27 x 27 cubic chambers with a center-to-center distance of 10 mm. The chamber size is 0.125 cm³ and the detector housing material is PMMA. The seven29® was used for measurements during the feasibility study. The biplanar diode array Delta4® (ScandiDos, Inc., Sweden) is a cylindrical PMMA phantom with two orthogonal detector boards. The dedicated software can interpolate measured data from the two planes to obtain a 3D matrix. The center-to-center distance is 5 mm in a central 6x6 cm² region of the detector and 10 mm in the rest of the 20 x 20 cm² measurement area in each of the planes. The Delta4® was used for measurements during the tumor-tracking arc delivery. The 3D normoxic polyacrylamide gel (nPAG) detector system was based on 3% w/w
acrylamide and 3% w/w \(N,N'\)-methylenebisacrylamide. Gelatine was used as the matrix substance and tetrakis(hydroxymethyl)-phosphonium chloride as an oxygen scavenger. The remaining constituent was ultra pure deionized water. The chemical information and the mixing procedure is published elsewhere [8]. For each batch, an identical un-irradiated gel phantom was used to acquire a background value and gel vials irradiated to known doses were used to assure the linearity of the gel dose response.

2.2. The tumor-tracking radiotherapy delivery

2.2.1. The feasibility study.

The real-time DMLC motion-tracking system was used together with an optical real-time positioning system (RPM™, Varian medical systems). A respiratory-like target motion was simulated mechanically. The movement was perpendicular to the beam direction and parallel to the leaf motion, with a 2 cm peak-to-peak motion extent and a 5 second period. A small circular, \(r = 15\) mm, 6 MV beam with a target dose of 2 Gy and a constant dose rate of 300 MU/min was delivered to three identical 250 ml nPAG flat-sided phantoms and the seven29®. A 20 mm thick PMMA build up was placed on top of the seven29® and 5 mm thick PMMA back scatter was placed below. The delivery was carried out in the following modes: 1) detector in motion and the tracking system disconnected (i.e. motion mode) 2) detector at rest and the tracking system disconnected and (i.e. static mode) and 3) detector in motion and the tracking system connected (i.e. tracked mode).

2.2.2. The arc delivery with diagonal target motion.

The DMLC real-time motion-tracking system was used together with the optical part of the ExacTrac system (BrainLab, Germany). The respiratory-like target motion was simulated mechanically as in 2.2.1, with 4 s period. A RapidArc® 6 MV lung plan, with a 45 degree collimator rotation and a 358-degree arc rotation was delivered using 790 MU. The plan was delivered with a varied dose rate of up to 600 MU/min to three identical 500 ml circular nPAG phantoms and to the Delta4® system. The prescribed dose to the 4.86 cm³ target volume was 4 Gy and the delivery was carried out in the same 3 modes as presented in 2.2.1 and in a additionally static mode with the tracking system connected. To avoid any possible contributions from discrepancy between measurements and TPS when evaluating the DMLC tracking performance, the measurements during motion were evaluated to the static measurement for the respective detector system. Further, a more strict gamma criterion of 2%/1mm was used within the volumes enclosed by the 50% and 90% iso-dose surface.

2.3. Gel-readout and analysis

Magnetic resonance imaging (MRI) of the gel was used to evaluate the absorbed dose response. The images were acquired using a 1.5 T MRI unit (Siemens Symphony, Siemens Medical Systems) and a 32-echo multi spin echo sequence with an inter-echo spacing of 25 ms. In-house developed software was used for T2 calculations [10], and MATLAB 7.4.0 was used for image processing and 3D rendering. The R2 data of the irradiated gel phantoms was converted to relative absorbed dose using background subtraction and normalization in a region of homogenous dose. An in-house developed 3D gamma evaluation program was used to compare all the gel measurement. Both the seven29® and Delta4® detector system uses its own analysis software. However the 3D gamma evaluation method in Delta4® is based on the same theory as the one developed in-house [11].

In the feasibility study the raw unfiltered gel data are presented and for the arc delivery study, the raw data was smoothed with a 3x3x3 box-filter and resampled from 1x1x3 mm³ to 1x1x1 mm³ voxel size to enable 3D gamma evaluation.
3. Result and discussion

3.1. The feasibility study
As expected, the motion introduced a significant dose-blurring when the tracking system was disconnected (figure 2a). The sharp MLC defined field edge was clearly visible in the static measurement (figure 2b). When tracking was applied, the dose-blurring due to motion was well compensated for (figure 2c). The distance between the 50% absorbed dose contour of the static and tracked gel-measurements was less than 1 mm for 96% of the points along the contour (max 1.4 mm). The absorbed dose in planes through the depth of dose maximum in the static and tracked gels was also compared. A 91% pass rate was reached for a gamma criterion of 3%/3mm for a region where the absorbed dose was greater than 80%. For doses >20% the pass rate was 82% where most of the dose points failing the gamma criterion occurred in the penumbra region, possibly due to motion induced dose-smearing effects, which were not adequately compensated. Overall, the seven29® measurements agreed well with the gel measurements (figure 3). However, due to the limited spatial resolution of the 2D array a detailed comparison was not possible. The feasibility study showed that high resolution 3D polymer gel dosimetry has a potential to perform a dosimetric verification of a tumor-tracking delivery.

3.2. The arc delivery with diagonal target motion
Good agreement was found when comparing TPS and the static gel measurements, as well as TPS and the static Delta® measurements. The 3D gamma analysis was carried out using the criteria 3%/3mm and pass rates above 97% were obtained for both detector systems when comparing to TPS. The 2%/1mm gamma evaluation between measured volumes in motion without MLC tracking vs. static measurements, within volumes enclosed by the 50% and 90% isodose surface, resulted in pass rates between 25%-37% (table 1) which suggests a significant motion induced dose-blurring when the tracking system was disconnected. The gamma

| Table 1. 3D gamma evaluation results using criterion 2%/1mm |
|------------------------------------------------------------|
| Detector system   | Delta® | Gel |
| Measurement vs. reference | pass rate [%] for γ<1 |
|                   |        |     |
| Within the 90% iso-dose surface |        |     |
| Tracked vs. static target | 70.6   | 96.8 |
| Moving vs. static target  | 35.3   | 37.1 |
| Within the 50% iso-dose surface |        |     |
| Tracked vs. static target | 87.2   | 82.1 |
| Moving vs. static target  | 36.2   | 25.2 |
evaluation comparing tracked and static measurements resulted in pass rates between 70%-97%. The highest pass rate were obtained with the gel measurements in the volume enclosed by the 90% isodose level. A relatively low pass rate, 70%, was obtained with Delta® in the same volume, and further studies will be carried out to investigate the reason to this result. Nevertheless, overall the motion was well compensated for when the tracking system was connected (Figure 4 and 5).

4. Conclusion
The ability of a DMLC-tracking system to account for target motion during radiotherapy was investigated by carrying out measurements using polymer gel, seven29® and Delta®. Both a feasibility experiment and an intensity modulated volumetric arc delivery were investigated. Good agreement in absorbed dose was found between the static and tracked measurements.

![Polymer gel](image)

**Figure 4.** The 90% isodose surface overlay of the three gel measurements. The wire framed volume represents the static gel and the transparent blue represents the tracked gel. The red non-tracked volume visualizes the reduction of the 90% isodose volume.

![Delta®](image)

**Figure 5.** Profiles measured with Delta® during four conditions; the detector at rest and the tracking system disconnected, the detector at rest and the tracking system connected, the detector in motion and the tracking system connected and the detector in motion and the tracking system disconnected.

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