

# 4D dosimetry and its applications to pre-treatment quality control and real-time *in vivo* dosimetry of VMAT treatments

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**Abstract.** In this study, a 4D dosimetry concept was developed. This concept included a method for calculation of 3D reference absorbed dose matrices at every control point of the delivery using a clinical treatment planning system (TPS). Further, the gamma evaluation method was extended to incorporate the 4<sup>th</sup> dimension of the TPS calculated dose distributions. The applications of the 4D dosimetry concept on pre-treatment quality control and real-time *in vivo* dosimetry were investigated.

## 1. Introduction

The rapid development and introduction of new treatment modalities (e.g. intensity modulated radiotherapy, IMRT, and volumetric modulated arc therapy, VMAT) has made it possible to deliver highly conformal, individually-shaped dose distributions. However, because of the rapid implementation of new technologies, there is widespread concern that current quality assurance programs do not provide adequate safeguards against treatment delivery errors [1].

Pre-treatment measurements have been widely employed as a part of routine patient-specific quality control (QC) of intensity-modulated treatments [2]. Because VMAT plan delivery involves continuous gantry movement, there are usually no plan-specific control measurements of anything other than the entire composite dose distribution and it is therefore possible that potential delivery errors at certain gantry angles are blurred. By analyzing VMAT delivery at a control point level, both systematic and plan-specific errors that are not visible in the composite plan might be identified.

Fast 4D dosimetry systems could also be used for real-time *in vivo* dosimetry. By allowing the *in vivo* system to interrupt the treatment if the measurements are outside pre-defined tolerance levels, serious overexposures to patients can be avoided. It is therefore possible that a real-time *in vivo* system could provide such confidence that pre-treatment quality control measurements can be reduced.

The aim of this study was to develop tools for measurement and evaluation of VMAT treatments on a control point level. Applications for both pre-treatment quality control and to real-time *in vivo* dosimetry were investigated. The gamma evaluation method was extended to incorporate a 4<sup>th</sup> dimension (gantry angle interval) of the treatment planning system (TPS) calculated reference data.

## 2. Material and methods

The process of 4D dosimetry was divided into four different steps; extraction of 4D treatment planning system reference absorbed dose data, time resolved measurement, mapping of measured and calculated data, and comparison of measurements and calculations.



### 2.1. Extraction of 4D TPS reference dose data

In this study, a clinical version of the Eclipse TPS (Varian Medical Systems, Palo Alto, CA) was used for calculation of absorbed dose matrices in between each two consecutive control points (representing a small gantry angle interval) of VMAT treatment plans. Since the system only is able to calculate 3D dose matrices for each beam, the plan was exported to in-house developed MATLAB (MathWorks) software, where it was divided into a number of sub-arcs. The modified DICOM-RT plan files were imported back into Eclipse and 3D dose matrices were calculated using the Anisotropic Analytical Algorithm (version 10.0.0.28) for each imported beam (sub-arc).

### 2.2. Time resolved measurement

Two different detector systems were investigated in this study; the Delta<sup>4</sup> system (Scandidos AB, Sweden) and a prototype diode in-vivo dosimetry system integrated with the RayPilot real-time positioning system (Micropos Medical AB.). The Delta<sup>4</sup> system consists of a cylindrical polymethyl-methacrylate (PMMA) phantom with two orthogonal detector planes containing a total of 1069 p-Si diodes and has become a popular tool for pre-treatment QC of the total composite dose distribution of VMAT treatments. A research version of the Delta<sup>4</sup> software allowed for export of time stamped dosimetry readings. The RayPilot system is a clinical interstitial electromagnetic (EM) transponder system that can be used to monitor intrafractional prostate motion. A small p-i-n diode dosimeter was included in this device, which potentially could allow monitoring of target absorbed dose *in vivo* with little extra effort. The dosimetry readings from the two systems were analyzed using an application software developed in-house with support for 4D dose distributions.

### 2.3. Mapping of measured and calculated data

For VMAT plans, the gantry angle is directly related to the control point reached in the delivery. A gantry angle recording simultaneous with the cumulative detector reading can therefore be used to map the measured absorbed dose to the TPS calculated dose at the corresponding control point. Two different inclinometers (N62u, Nordic Transducer, Denmark and IK360, SIKO GmbH, Germany) were investigated for independent read-out of the gantry angle during delivery. Also, the use of gantry angle readings from DynaLog files, generated by the MLC computer, was investigated. The standard error of the mean in gantry angle readout was determined through the use of an alternating beam on/off pattern during continuous rotation for both a clockwise and a counterclockwise arc. The gantry angle was recorded simultaneous to read-outs of the beam's on/off status.

### 2.4. Comparison of measurement and calculation

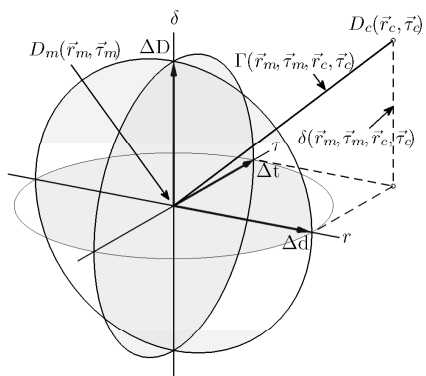
The gamma evaluation method [3] was extended in order to incorporate the 4<sup>th</sup> dimension (gantry angle interval or time) of the reference data. In addition to the dose difference criterion ( $\Delta D$ ) and the distance-to-agreement criterion ( $\Delta d$ ), a new time difference related criterion was introduced ( $\Delta t$ ). For rotational treatments (e.g. VMAT), the gantry angle difference can be used as the  $\Delta t$ -criterion. The extended method (hyper-gamma,  $\gamma_H$ ) simultaneously takes the dose difference, the distance in the Cartesian space and the time difference into account (figure 1) and is defined as:

$$\gamma_H(\mathbf{r}_m, t_m) = \min \left\{ \Gamma_H(\mathbf{r}_m, t_m, \mathbf{r}_c, t_c) \right\} \forall (\mathbf{r}_c, t_c) \quad (1)$$

where

$$\Gamma_H(\mathbf{r}_m, t_m, \mathbf{r}_c, t_c) = \sqrt{\frac{\tau^2(t_m, t_c)}{\Delta t^2} + \frac{r^2(\mathbf{r}_m, \mathbf{r}_c)}{\Delta d^2} + \frac{\delta^2(\mathbf{r}_m, t_m, \mathbf{r}_c, t_c)}{\Delta D^2}} \quad (2)$$

As in the original gamma evaluation method, the evaluated point passes the test if  $\gamma \leq 1$ .



**Figure 1:** A graphical representation of the extended gamma evaluation method.

### 2.5. Clinical applications

The Delta<sup>4</sup> system was used to evaluate 20 clinical VMAT arcs on a control point level delivered using a Clinac iX (Varian Medical Systems, Palo Alto, CA). Each control point was analyzed using the hyper-gamma evaluation method with [3%/3mm/0.5°] and [2%/2mm/0.5°] criterion. The plans had been previously verified using the Delta<sup>4</sup> system and the traditional gamma evaluation method as a part of the clinical pre-treatment verification process. Comparisons between 3D and 4D evaluations were undertaken.

Measurements with the prototype EM-positioning and dosimetry system in an anthropomorphic phantom with an open water container were undertaken to evaluate the feasibility of using an implantable radiation dosimeter and EM localization system for real-time verification of VMAT of the prostate. Internal intrafractional motion was simulated using a programmable motion stage. The measured cumulative absorbed doses were analyzed using the hyper-gamma method ( $[3\%/3\text{mm}/1^\circ]$ ), as well as by dose difference comparisons between the measurements and the corresponding TPS calculated dose corrected for the recorded localization of the detector. The following intentional errors were introduced to investigate the detectability of errors using the proposed concept:

- Monitor units increased by 3% and 5%
- Collimator rotation offset by  $\pm 3^\circ$  and  $\pm 5^\circ$
- Gantry angle offset by  $\pm 3^\circ$  and  $\pm 5^\circ$
- MLC banks shifted by  $\pm 3$  mm and  $\pm 5$  mm
- MLC opening increased by 1 mm and 3mm
- MLC opening decreased by 1 mm and 3 mm with a minimum opening of 0.6 mm
- MLC fully retracted

### 3. Results and discussion

### 3.1. Uncertainties in gantry angle determination

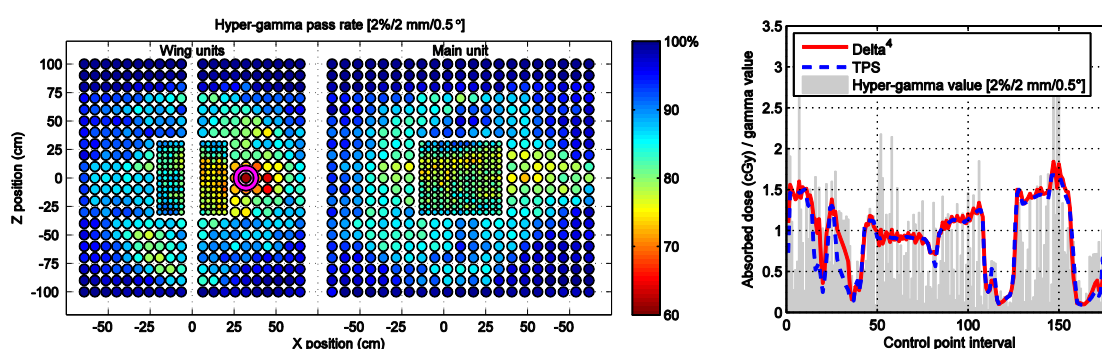
The uncertainties associated with the gantry angle determination for two full arcs of different rotation directions were 0.20°, 0.13° and 0.083° (1 s.d.) for N62u, IK360 and DynaLog, respectively. The DynaLog files were associated with the smallest uncertainty, and were therefore used to group the dosimetry data from the Delta<sup>4</sup> measurements. However, the DynaLog data are not independent of the accelerator. Therefore, simultaneous IK360 measurements were used to verify the actual gantry angle readings. The DynaLog data cannot be read-out until the whole arc has been delivered; hence the N62u inclinometer was used for *in vivo* dosimetry.

### 3.2. Pre-treatment QC

The mean hyper-gamma pass rates (over all control points) ranged from 84.7 to 97.1% and 93.4 to 99.6% for the [2%/2 mm/0.5°] and [3%/3 mm/0.5°] criteria, respectively. The conventional gamma pass rates ranged between 97.7 and 100.0% for the [3%/3 mm] criteria. A higher hyper-gamma pass rate was generally observed for gantry intervals around zero degrees (gantry in upright position).

However, a significant difference ( $\alpha=0.05$ ) in average pass rate was found only for the first and last angle intervals.

A difficult task with time resolved dose distribution comparisons is to display the results in an intuitive way. In this study, the data were collapsed into a 2D view, displaying the hyper-gamma pass rate for each detector element (figure 2, left). Spatial areas with potential issues were identified from this view. Generally, similar patterns were recognized between the hyper-gamma pass rates and conventional gamma values. The detector elements with the lowest hyper-gamma pass rates were evaluated using dose difference profiles along the detector arrays as well as in control point intervals (figure 2, right). The positions of these detector elements in the beams-eye-views (BEV) for each control point were used to determine the cause of differences between TPS calculations and measurements. The main cause of deviations found for specific detector elements and control point intervals was the presence of complex MLC motion over the detector element (as seen from BEV).



**Figure 2:** Hyper-gamma pass rate map [2%/2 mm/0.5°] (left) and a control point interval profile for the detector element (purple circle) with the lowest hyper gamma pass rate (right).

### 3.3. *In vivo* dosimetry

The maximum difference between all dosimeter readings and the corresponding TPS calculated cumulative absorbed doses for three consecutive deliveries with a static detector position ranged from -3.7% to -2.3% of the total TPS calculated absorbed dose and the hyper-gamma pass rate ranged from 94.9% to 100.0%. The introduction of intrafractional motion had a substantial impact on the measured absorbed dose for two of the trajectories investigated. The maximum dose differences for these two deliveries were -6.0% and 5.5%. However, using the position corrected TPS cumulative absorbed dose, the maximum dose differences were reduced to -3.2% and -2.8%, respectively. The absorbed dose difference exceeded the maximum absolute difference of the nonerroneous deliveries (3.7%) for three of the introduced errors and all trajectories. These errors were a 5% increase of MUs, MLC opening reduced by 3 mm, and a fully retracted MLC. The most severe treatment error (fully retracted MLC) was detected during an early stage of treatment. Serious radiation overexposure can be avoided in a clinical setting by allowing the *in vivo* system to interrupt treatment if the measurements are outside pre-defined tolerance levels. The hyper-gamma pass rate was reduced below 95% for 7 of the deliveries with introduced errors and a static detector position and it was also found to be sensitive to intrafractional motion (hyper-gamma pass rates for the two trajectories and for deliveries without errors introduced were reduced to 90% and 59%, respectively).

## 4. Conclusions

While the conventional gamma values provide an estimate of the accuracy of the entire delivery to a given point, the hyper-gamma and 4D analyzes can help identifying the actual cause of discrepancies between the calculated and measured absorbed dose. The beams-eye-view tool was valuable in order to investigate potential issues associated with specific control point intervals and detector elements.

It was found that if implantable EM-transponders are used for target localization, the addition of a dosimeter and an online dosimetric evaluation system provides a fast and resource-efficient *in vivo* dosimetry system.

## 5. References

- [1] Saw C *et al* 2008 *J. Biomed Imaging Interv.* **4** e48
- [2] Buonamici F B *et al* 2007 *Med. Phys.* **34** 1372-79
- [3] Low D A *et al* 1998 *Med. Phys.* **25** 656-61