New developments in EPID-based 3D dosimetry in The Netherlands Cancer Institute

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Abstract. EPID-based offline 3D in vivo dosimetry is performed routinely in The Netherlands Cancer Institute for almost all RT treatments. The 3D dose distribution is reconstructed using the EPID primary dose in combination with a back-projection algorithm and compared with the planned dose distribution. Recently the method was adapted for real-time dose verification, performing 3D dose verification in less than 300 ms, which is faster than the current portal frame acquisition rate. In this way a possibility is created for halting the linac in case of large delivery errors. Furthermore, a new method for pre-treatment QA was developed in which the EPID primary dose behind a phantom or patient is predicted using the CT data of that phantom or patient in combination with in-air EPID measurements. This virtual EPID primary transit dose is then used to reconstruct the 3D dose distribution within the phantom or patient geometry using the same dose engine as applied offline. In order to assess the relevance of our clinically applied alert criteria, we investigated the sensitivity of our EPID-based 3D dose verification system to detect delivery errors in VMAT treatments. This was done through simulation by modifying patient treatment plans, as well as experimentally by performing EPID measurements during the irradiation of an Alderson phantom, both after deliberately introducing errors during VMAT delivery. In this presentation these new developments will be elucidated.

1. Introduction

The use of EPID-based 3D dosimetry in external beam radiotherapy has been addressed in several studies [e.g., 1-3]. The first two papers describe the use of the incident fluence, determined from a measured EPID transit image, followed by Monte Carlo techniques to assess the delivered 3D patient dose distribution. Van Uytven et al [3] have developed an algorithm that converts also a measured EPID transit image to incident fluence, and employs thereafter a collapsed-cone convolution calculation to determine the delivered 3D patient dose distribution.

In the Netherlands Cancer Institute (NKI) a back-projection algorithm has been implemented for the 3D dose verification of almost all IMRT/VMAT and 3DCRT treatments using in vivo EPID dosimetry [4]. Details of our method and its clinical implementation have been described elsewhere [5]. Briefly, our back-projection algorithm uses EPID measurements behind a patient or a phantom to determine the EPID primary dose, i.e. the dose component at the level of the EPID resulting from the primary radiation coming from the accelerator head. Using this EPID primary dose, a fast pencil beam-type of dose calculation algorithm reconstructs the 3D dose distribution in a patient or phantom in combination with the CT data of that patient or phantom. Reconstructed 3D dose distributions are then compared with planned dose distributions using 3D γ-evaluation within the 50% isodose surface using global 3%/3mm indicators. This rather high threshold was chosen to avoid artificial improvement of the
gamma evaluation results by including low dose volumes, and to avoid the build-up region. In this presentation we will elucidate the new developments in the field of EPID-based 3D dosimetry in our institution since our presentation at IC3DDose 2014 [5].

2. Real-time 3D dosimetry
The offline EPID-based 3D dosimetry system clinically employed at NKI is in principle suited for online treatment verification, provided the system is able to complete 3D dose reconstruction and verification within 420 ms, the present acquisition time of a single EPID frame. For this purpose the current 3D dose reconstruction algorithm was sped up via a new multithreaded implementation, and by performing all computations that are not dependent on portal image acquisition separately, thus removing the need for doing these calculations in real time. The real-time dosimetry system was tested by irradiating an anthropomorphic phantom with various VMAT plans. Two types of serious delivery errors were introduced: the number of monitor units per control point was doubled, and all moving MLC leaves and jaws were retracted 10 cm on both sides. Figure 1 shows the result of these real-time verifications of a VMAT prostate cancer treatment. The complete processing of a single portal frame, including dose verification, took 266 ±11 ms on a standard CPU. The introduced delivery errors were detected after 5–10 s irradiation time. The system is now tested clinically, particularly with respect to criteria to halt the linac.

3. Pre-treatment 3D dose reconstruction
EPID-based pre-treatment 3D dose verification is only performed at NKI for high dose single fraction treatments and for treatments where in vivo verification is not possible. In these situations, the clinical plans are verified with an EPID measurement behind a slab polystyrene phantom. These phantom measurements are also performed if in vivo dosimetry verification shows an alert for which no clear explanation can be given, for instance after inspecting the CBCT scan made prior to the in vivo dose measurement. In order to eliminate the need for phantom re-planning and the accurate positioning of a phantom for such a type of measurement, a new method for pre-treatment EPID-based 3D dose verification was developed. In this method our current algorithm was adapted to calculate the EPID primary dose behind the phantom using in-air EPID measurements of the treatment and CT data. Using this virtual EPID primary dose, the algorithm then reconstructs virtual phantom 3D dose distributions in combination with the CT data of the phantom.

Figure 1. Difference between reconstructed and planned mean dose in the PTV for three scenarios (no error, all leaves open error, double MU error), as a function of delivery time. The horizontal line indicates the detection threshold.
An even more interesting application of this novel method is the possibility to reconstruct virtual patient 3D dose distributions using the in-air EPID measurements in combination with patient CT data. Virtual patient dose distributions were determined and compared to the corresponding planned dose distributions using γ-evaluation (3% global dose/3mm), yielding γ-values that are very similar to the phantom verification data (see Table 1). In this way delivered dose distributions can also be analyzed in terms of dose-volume histogram (DVH) parameters, providing a useful indication to radiation therapy staff of the impact of detected deviations. By combining virtual patient dose distributions with in vivo data it is also possible to separate patient related errors from other types of uncertainties.

### 4. Sensitivity of EPID-based 3D dosimetry

The usefulness of different γ-evaluation indicators and DVH parameters in detecting errors, as well as the values for the alert criteria used in the clinic for these indicators, are continuously evaluated. We therefore investigated the sensitivity of our EPID-based 3D dose verification system to detect delivery errors in VMAT treatments. This was done in two ways; first the effect of delivery errors was simulated by modifying different VMAT plans (H&N, lung, prostate and rectum). These treatment plans were modified by adding a 3% and 6% offset to the given number of monitor units, and by systematic shifting leaf bank positions by various distances. The 3D in vivo dose distributions were then compared to the unmodified and modified treatment plans. To determine the detectability of the various delivery errors, we made use of a receiver operator characteristic (ROC) methodology. The results of the determination of the area under the ROC curve showed that the parameter γ\text{mean} is the best discriminator for the detection of leaf position and monitor unit errors. Compared to γ\text{mean} the DVH parameter ΔD_{50} for the PTV performed worse as a discriminator in all cases.

In a second study the sensitivity of our clinically used EPID-based 3D transit dosimetry approach in detecting deliberately introduced errors during VMAT delivery, was investigated experimentally. For this purpose EPID measurements were performed during the irradiation of an Alderson phantom in order to mimic the in vivo situation as close as possible. 3D dose distributions were then reconstructed using our back-projection model, and compared with planned dose distributions by means of 3D γ-evaluation (3% global dose/3mm). Quantification of individual and multiple leaf position errors (not shown) indicated that the lung plan was more sensitive to these errors than the prostate and head-and-neck plans (see Figure 2). A horizontal shift of the phantom of 2 cm showed that no alerts were raised for the prostate and lung case, but a very large difference was observed in the reconstructed 3D dose distribution.

### Table 1. Comparison of EPID-reconstructed virtual patient and real phantom dose distributions with the corresponding planned dose distributions using γ-evaluation data. A dose difference of 3% of the maximum planned dose and a distance-to-agreement of 3mm were used as criteria in the γ-evaluation. Results are presented as average value ± 1 standard deviation.

| #fields | γ\text{mean} | γ\text{99%} | %γ<1 |
|---------|--------------|-------------|-------|
| Virtual patient | IMRT | 0.38 ± 0.13 | 1.13 ± 0.43 | 95.6 ± 6.0 |
| | VMAT | 0.48 ± 0.09 | 1.34 ± 0.33 | 94.1 ± 4.7 |
| Real phantom | IMRT | 0.39 ± 0.13 | 1.08 ± 0.32 | 95.2 ± 7.6 |
| | VMAT | 0.45 ± 0.09 | 1.23 ± 0.33 | 95.2 ± 4.8 |

![Figure 2. Results of single leaf position error measurements during various VMAT irradiations of an Alderson phantom shown as dose difference at isocenter. The dashed and solid lines indicate the tolerance and action level, respectively, as currently applied in the clinic.](image)
for the head-and-neck cases. This can be expected because a shift of 2 cm moved the isocenter much closer to the outer contour of the head-and-neck cases compared to the lung and prostate plans, thus causing a large change in the transit dose.

Out of a total of 26 serious delivery errors in these plans, the number of errors detected using the Alderson phantom and our current alert criteria was 23 (88%) using $\gamma_{\text{mean}}$ and 15 (58%) with $\gamma_{1\%}$, thus confirming the results of the ROC study.

5. Conclusions
Our method of EPID-based 3D dosimetry was adapted for real-time dose verification, resulting in 3D dose verification in less than 300 ms. In this way a possibility is created for halting the linac in case of large delivery errors.

The results of the tests with the novel pre-treatment dose reconstruction algorithm showed that virtual patient dose reconstruction performs as accurate as real phantom dose reconstruction thus making pre-treatment QA faster and less cumbersome. This method, which uses planning CT data, allows also the use of DVH metrics for comparison with planned 3D dose distributions.

Determinations of the sensitivity of our EPID-based 3D dose verification method showed that the parameter $\gamma_{\text{mean}}$ might be the best discriminator for the detection of errors during VMAT delivery when using 3D $\gamma$-evaluation. The clinical use of DVH parameters still needs further investigation.

6. References
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