2D AND 3D dose verification at The Netherlands Cancer Institute-Antoni van Leeuwenhoek Hospital using EPIDs

Ben Mijnheer, Anton Mans, Igor Olaciregui-Ruiz, Jan-Jakob Sonke, Rene Tielenburg, Marcel van Herk, Ron Vijlbrief, Joep Stroom

Department of Radiation Oncology, The Netherlands Cancer Institute - Antoni van Leeuwenhoek Hospital, Plesmanlaan 121, 1066 CX Amsterdam, The Netherlands

b.mijnheer@nki.nl

Abstract. A review is given of the clinical use of EPID dosimetry in the Department of Radiation Oncology of The Netherlands Cancer Institute-Antoni van Leeuwenhoek Hospital. All curative plans (almost all IMRT or VMAT) are verified with EPID dosimetry, mostly in vivo. The 2D approach for IMRT verification and the 3D method for VMAT verification are elucidated and their clinical implementation described. It has been shown that EPID dosimetry plays an important role in the total chain of verification procedures that are implemented in our department. It provides a safety net for advanced treatments such as IMRT and VMAT, as well as a full account of the dose delivered.

1. Introduction
In January 2005, the demand for an efficient and accurate dose verification increased in our department with the use of a new treatment planning system (Pinnacle V8.0h, Philips Medical Systems, Eindhoven, The Netherlands), the large-scale introduction of IMRT on our 9 Elekta SL20i linear accelerators (Elekta, Crawley, UK), higher dose prescriptions (e.g., 78 Gy for IMRT prostate treatments) and the gradual transfer of data management systems from paper to digital format. Since January 2008, we verify all curative treatment plans (almost all IMRT) with EPID dosimetry, mostly in vivo; i.e., the dose distribution is reconstructed within the patient from images acquired for each field during treatment. In August 2009 volumetric-modulated arc therapy (VMAT) has been introduced in our department for prostate treatments and later that year for lung stereotactic body radiotherapy. Also all VMAT treatments are verified by means of EPID dosimetry.

Measurements made with aSi EPIDs (PerkinElmer RID 1680 AL5/Elekta iView GT) are converted to dose by a back-projection algorithm. For IMRT verification, dose distributions are verified in 2D per field [1], while for VMAT verification, or if further analysis of an IMRT check is necessary, 3D verification is performed by summing back-projected images to a volume [2, 3].

Our philosophy of patient-specific QA is to use fast or automatic pre-treatment checks to prevent large errors, and in addition to have an independent end-to-end check of planned versus delivered dose distribution in the patient. Such an end-to-end test should not be limited to testing individual steps in the treatment process, but rather evaluate the complete process from image-based treatment design through the dose calculation to measured dose delivery, and should preferably be performed by the same persons who treat patients. This philosophy is translated into three-fold patient-specific QA. First, an
independent monitor unit check is performed. Second, a consistency check of the basic plan properties is done by the therapists at the treatment machine of the data in the treatment planning system and the record-and-verify system. Third, a 2D verification of individual IMRT beams, or a 3D verification of the total dose distribution of a VMAT plan, is executed by EPID dosimetry, if possible in vivo, and otherwise pre-treatment. In our opinion, such a three-stage verification process is adequate and efficient for safe IMRT and VMAT delivery.

2. 2D IMRT verification
All our static beam IMRT treatments are verified with EPID dosimetry using a back-projection model [1]. The algorithm accounts for the inverse-square law, attenuation of the beam between the exit plane and the reconstruction plane (estimated from CT data), and three types of scattered radiation (within the EPID, from the patient to the EPID, and within the patient). The algorithm also takes couch attenuation and changes in EPID sensitivity with time into account. The planned and reconstructed dose distributions are compared for each beam in a plane through the isocentre perpendicular to the beam direction. The dose at the isocentre is checked for each beam, as well as the total dose per fraction. In addition a 2D gamma analysis is performed for each beam. The results of this analysis are given as a "dosimetry report" for each patient (see figures 1-3). Phantom measurements showed that for prostate, rectum, and head-and-neck cases, the percentage of points within $\gamma$-agreement are 99.9%, 98.1%, and 96.6%, respectively. At the dose prescription point, the dose values based on EPID measurements and the TPS agree generally within 1% [1, 3].

2.1. Clinical implementation
Within a few weeks of clinical use, EPID dosimetry replaced film measurements in a phantom and within 8 months in vivo EPID dosimetry replaced pre-treatment verification for all prostate IMRT checks. Currently EPID dosimetry is the only routine IMRT plan verification performed in our hospital. In vivo EPID dosimetry was performed for the following sites and number of patients in 2009: breast (779), lung (279), head-and-neck (241), prostate (233), rectum (206), and others, e.g., skull and liver, (285). Pre-treatment EPID dosimetry is performed for single fraction brain treatments (20) and plans with fields larger than the detector area (160). Several patients had multiple plans (e.g., a boost plan) that were checked. The total number of plans verified in 2009 was 2835.

One of the therapists (actually 2 part-time people) analyses these IMRT plans. Physicists are responsible for the initial calibration of each EPID for the various photon beams on all our accelerators, and are available to resolve problems that arise. For each field, a treatment image and an "open image" (no patient in the beam, acquired outside treatment time) is required to determine the dose inside the patient. These “open images” are measured by the therapists, which takes about 5 to 10 minutes per plan. When images have been acquired, the total analysis time per plan is about 10 min required for 3 fractions in vivo compared to about one hour for pre-treatment verification. In the near future we will replace the measured transmission data by calculated values, thus saving about 400 hours/year spent on measurement of “open images”.

An alert is raised to potential clinical errors when criteria based on the $\gamma$-index (3.0% of the maximum dose per field and 3.0 mm distance) are surpassed. The mean $\gamma$-value ($\gamma_{\text{mean}}$), the maximum 1% $\gamma$ value ($\gamma_{\text{max}1\%}$) and the percentage of points with $\gamma>1$ ($P_{\gamma>1}$) are calculated within the 20% isodose line of each field. The alert criteria depend on the tumour site and are for prostate cancer verification:

- $\gamma_{\text{mean}} > 0.5$, i.e. when average differences exceed $\pm 1.5\%$ or 1.5 mm
- $\gamma_{\text{max}1\%} > 2.0$, i.e. when maximum differences exceed $\pm 6.0\%$ or 6.0 mm
- $P_{\gamma>1} > 15\%$, i.e. when more than 15% of points exceed 3.0% or 3.0 mm
- $\Delta D_{\text{iso}} > 3.0\%$, i.e. when the total dose at the isocentre deviates by more than 3.0% from the prescribed dose
2.2. Errors prevented
Since the clinical introduction of EPID dosimetry in January 2005 to July 2009 treatment plans of 4337 patients were verified. In 17 cases, major deviations detected gave rise to an intervention. In seven cases patient anatomy changes resulted in substantial dosimetric deviations due to weight loss (2), (recovery from) atelectasis (2), patient contour change (2), and emptying of a post-operative cavity that was filled during the planning CT (see figure 1). In four cases, the plan was flawed during transfer from the TPS to the treatment machine (one human error and three system communication errors). In two instances the fine-tuning of parameters in the TPS were found to be sub-optimal. Two plans were accidentally modified in the R&V system just prior to delivery of the first fraction. In one case, planning protocols were not obeyed, resulting in an undeliverable plan. Finally, the linear accelerator failed to deliver one of the segments of a step-and-shoot IMRT beam. A detailed analysis of the errors detected by means of our EPID dosimetry programme has been published recently [4]. In addition to these major deviations, a number of minor deviations resulted in re-planning of the patient.

3. 3D VMAT verification
For VMAT verification it was necessary to modify our software to incorporate gantry-angle resolved image acquisition. Furthermore, the 3D back-projection model applied for IMRT verification [3] was adapted to include a calculated transmission from CT data instead of measured transmission data, e.g., no “open arc images” are needed for VMAT verification. The total 3D dose distribution is reconstructed and compared with the planned dose distribution using a 3D gamma evaluation, with 3% of the maximum planned dose and 3 mm as dose difference and distance-to-agreement criteria, respectively. Details of the adaptation of our back-projection portal dosimetry method for accurate 3D dose verification of VMAT can be found elsewhere [5].

3.1. Clinical implementation
The results of the 3D verification of each arc of a clinical VMAT plan are also presented as an EPID dosimetry report, in the same way as for 2D IMRT verification. Figures 2 and 3 show, as an example, dosimetry reports for a pre-treatment and an in vivo verification of the delivery of a single arc prostate cancer VMAT treatment. The pictures illustrate the results of the gamma evaluation in a sagittal, axial and coronal plane through the isocentre, while the data for the various gamma evaluation parameters within the 50% isodose surface, as well as the total dose at the isocentre, are also given. If the total
dose is deviating more than 3.0% a warning is given (tolerance level exceeded), while for a deviation larger than 5% an error report is sent to a physicist (action level exceeded). Gamma evaluation statistics are reported with tolerance/action levels: 0.50/1.00 for the mean gamma value, 2.0/4.0 for the maximum gamma value, and 85%/70% for the percentage of gamma values below one, respectively. The average difference of the dose at the isocentre was for the first 10 prostate cancer VMAT plan verifications (-0.2±1.6)% and (+0.4±1.6)% for the pre-treatment and in vivo results, respectively. A preliminary analysis of the parameters applied for the 3D gamma evaluation showed almost the same results for pre-treatment and in vivo verification of the 3D dose distribution for prostate cancer VMAT (see figures 2 and 3). For instance, the average of the mean gamma values of these 10 patients is 0.42±0.12 and 0.48±0.06 for the pre-treatment and in vivo results, respectively.

Figure-2. EPID dosimetry report of a 3D pre-treatment verification of a VMAT treatment of a prostate cancer patient.

Figure-3. EPID dosimetry report of a 3D in vivo verification of a VMAT treatment of the same prostate cancer patient.
3.2. 2D versus 3D comparison

Our current γ-evaluation for IMRT applies a 2D comparison of measured and planned dose distributions in a plane through the isocentre perpendicular to each IMRT beam. The criteria for IMRT verification are based on the γ-index as well as the dose at the isocentre and differ for the various treatment sites. At present we are using the same criteria for the 3D dose comparison of VMAT checks. Because the 3D dose distribution in the target volume is generally intended to be uniform, the dose difference criterion will be dominant. However, dose deviations in a single beam or segment will be diluted in the total dose distribution and serious errors in the dose calculation or in the position of the leaves may no longer be detected. The distance-to-agreement criterion will mainly contribute to the γ-value in the dose gradient region at the border of target volumes. With the implementation of IMRT and VMAT combined with position verification techniques, increased dose conformality is achieved and the distance-to-agreement criterion will gain importance. Therefore, we are currently considering stricter γ-criteria for 3D dose verification in the clinic, such as 2%, 2 mm or 2%, 1.5 mm, also since identical criteria always yield smaller γ-values in 3D dose verification than in 2D [6].

More clinical data are needed to assess the values applied for our gamma evaluation criteria for 3D VMAT verification. Currently, our clinic does not have strict criteria for plan adaptation when EPID dosimetry data (or IGRT procedures) show deviations exceeding action levels. In such cases, the physicist informs the responsible physician, who decide together if plan adaptation is necessary.

4. Discussion and conclusions

The use of EPIDs for dosimetry purposes has matured and is now a reliable and accurate dose verification method that can be used in a large number of situations [7]. From our clinical results it can be concluded that EPID dosimetry is a valuable tool for 2D verification of IMRT and 3D verification of VMAT delivery, both pre-treatment and in vivo.

The drawback of applying in vivo verification only is that a small part of the treatment has already been given before an error is detected. The advantages, on the other hand, are verification of the actual patient treatment and (for our method) workload reduction. Certain types of errors can also easily be detected by pre-treatment methods. However, these methods are not capable of detecting a number of other errors due to, for instance, considerable variation in patient anatomy or patient position, and obstructions from table arms or immobilization devices. Furthermore, treatment parameters can be (accidentally) modified between pre-treatment verification and the first treatment, as we have detected several times. For these reasons, the choice was made in our department to use in vivo EPID dosimetry for all treatments with curative intent. When making this decision, verification of the entire radiotherapy chain, including the actual patient treatment was a strong argument.

The additional workload involved with EPID dosimetry is limited and little or no extra time is needed at the accelerator. Analysis of the results of EPID dosimetry during IMRT made it possible to identify small systematic errors related to the dose calculation in the TPS. Methods to integrate 3D in vivo dosimetry and IGRT procedures, such as the use of kV cone-beam CT, are under development [2, 7]. The acquisition and analysis of EPID dosimetry data can be performed by therapists if simple measurement and pass/fail tools are available. Compared to pre-treatment verification, in vivo EPID dosimetry is not only capable to detect errors but can also assess quantitatively the dosimetric impact of these errors and the need for plan adaptation (see figure 1). In combination with delineated structures from the plan, dose-area or dose-volume information can be obtained for the target volume as well as for organs at risk, based on 3D EPID-based reconstructed dose distributions (see figure 4).
In this way clinical judgment of deviations between planned and actual dose distributions is possible. Furthermore, in a growing number of countries in vivo dosimetry is required by law or strongly recommended by (inter)national organizations to avoid serious errors.

It can be concluded that EPID dosimetry plays an important role in the total chain of verification procedures that are implemented in our radiotherapy department. It provides a safety net for advanced treatments such as IMRT and VMAT, as well as a full account of the dose delivered.

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