Quality assurance

3D dose reconstruction for clinical evaluation of IMRT pretreatment verification with an EPID

Mathilda van Zijtveld*, Maarten L.P. Dirkx, Hans C.J. de Boer, Ben J.M. Heijmen

Department of Radiation Oncology, Division of Medical physics, Erasmus MC-Daniel den Hoed Cancer Center, Rotterdam, The Netherlands

Abstract

Background and purpose: Pretreatment verification with an electronic portal imaging device is an important part of our patient-specific quality assurance program for advanced treatment techniques. Up to now, this verification has been performed for over 400 IMRT patient plans. For every treatment field, a 2D portal dose image (PDI) is measured and compared with a predicted PDI. Often it is not straightforward to interpret dose deviations found in these 2D comparisons in terms of clinical implications for the patient. Therefore, a method to derive the 3D patient dose based on the measured PDIs was implemented.

Methods and materials: For reconstruction of the 3D patient dose, the actual fluences delivered by the accelerator are derived from measured portal dose images using an iterative method. The derived fluence map for each beam direction is then used as input for the treatment planning system to generate an adapted 3D patient dose distribution. The accuracy of this method was assessed by measurements in a water phantom. Clinical evaluation of the 3D dose reconstruction was performed for 17 IMRT patients with different tumor sites. Dose differences with respect to the original treatment plan were evaluated in individual CT slices using dose difference maps and a 3D γ analysis and by comparing dose-volume histograms (DVHs).

Results: The measurements indicated that the accuracy of the 3D dose reconstruction was within 2%/2 mm. For the patients observed dose differences with respect to the original plan were generally within 2%, except at the field edges and in the sharp dose gradients around the planning target volume (PTV). Gamma analysis showed that the dose differences were within 2%/2 mm for more than 95% of the points in all cases. Differences in DVH parameters for the PTV and organs at risk were also within 2% in nearly all cases.

Conclusion: A method to derive actual delivered fluence maps from measured PDIs and to use them to reconstruct the 3D patient dose was implemented. The reconstruction eases the estimation of the clinical relevance of observed dose differences in the pretreatment measurements.

Keywords: Quality assurance; Intensity modulated radiotherapy; EPID; Portal dosimetry

The increased use of advanced techniques like intensity modulated radiotherapy (IMRT) for treatment of cancer patients puts higher demands on the quality assurance (QA) program for verification of dose delivery. In our clinic, a patient-specific IMRT QA protocol is under development that consists of several components. First, to verify that the calculated 3D dose distribution is highly accurate, the treatment plan of each patient is recalculated with a fully independent dose engine. Second, to check the proper transfer of treatment parameters and the correct execution of the plan at the treatment unit, measurements with an electronic portal imaging device (EPID) are performed prior to the start of the actual treatment. By comparing realized portal dose images with predictions, errors in the delivered fluence maps can be intercepted before any dose is delivered to the patient, thereby avoiding any possibly harmful clinical impact. During each treatment fraction, in vivo measurements are performed with the EPID to verify the delivered IMRT fields. Using the so-called Split IMRT Field Technique (SIFT) [10], errors in the delivered fluence maps of 1–2% can be detected, even if large changes of the patient anatomy with respect to the planning CT scan exist. At the same time, information about patient set-up and geometrical changes within the patient may be obtained, allowing reconstruction of the actually delivered 3D dose to the patient during treatment.

Until recently, IMRT pretreatment verification with EPIDs was performed in our clinic by verification of the fluence delivery of each individual treatment field of a patient plan [7,11]. For those measurements, a fluoroscopic, cooled CCD-camera based EPID was used [1,2]. In a recent publication [11] the results of the measurements were quantified in...
more detail using the average $\gamma$ value inside the treatment field and the percentage of points with a $\gamma$ value larger than 1. It was demonstrated that the analysis of joined areas with $\gamma$ values larger than 1 aided the assessment of possible clinical implications of observed deviations. However, it remains difficult to derive the impact of observed deviations between measured and predicted portal doses in a single field on the overall 3D patient dose distribution. This impact depends on the total number of treatment fields in the IMRT plan, the relative dose contributions of the different beams and on the deviations in each of the fields. To ease interpretation of the clinical relevance of observed pretreatment portal dose deviations in individual treatment fields, a 3D reconstruction of the patient dose distribution based on the measured fluences in all treatment fields and the planning CT scan may be applied. This allows the use of standard tools such as dose-volume histograms (DVHs) for the comparison of the originally planned and reconstructed delivered dose distribution.

The use of 3D dose reconstruction for the evaluation of pretreatment measurements has been previously described [8,9]. Renner et al. [8] used film measurements to derive the delivered fluence maps for each beam direction. Based on those fluences a dose reconstruction was performed using a pencil beam superposition algorithm that was independent of that of the planning system. For comparison with the original treatment plan they suggest using the standard deviation of the dose differences and an analysis of the isocenter dose and hot spots. Stciw et al. [9] described a similar approach for measurements with an amorphous silicon flat panel EPID. To account for signal spread in the EPID due to radiation and optical scatter, measured 2D EPID images were deconvolved with kernels derived by Monte Carlo simulations. The resulting fluence maps were used as input to the treatment planning system (TPS) to perform a 3D dose reconstruction. Compared to the original patient plan, large differences were observed in high gradient regions, leading to clinically significant dose differences in some organs at risk. From the good agreement of the reconstructed dose with TLD measurements, they concluded that those differences were to a large extent due to an inaccurate modeling of the fluence in the TPS, prior to the dose convolution.

In this study, an iterative method using CCD-camera based EPID measurements is described to derive delivered fluence maps from measured PDIs and to use these maps to reconstruct the 3D patient dose. The concept of this approach is described in detail. The method is validated experimentally to assess its accuracy. Clinical evaluation of the dose reconstruction is reported for 17 patients treated with IMRT.

Methods and materials
Measurement and prediction of portal dose images
For the measurements of 2D PDIs a fluoroscopic Theraview NT (TNT) EPID (Cablon Medical — Theraview Technology, Leusden, The Netherlands) with a cooled CCD camera is used. This system has shown to be well suited for dosimetric measurements for IMRT fields produced with dynamic multi-leaf collimation, because of its stable response, a short deadtime of only 0.2 ms between acquisition of frames and its simultaneous integration of signal in $1024 \times 1024$ pixels [1]. Due to the cooling, image degradation related with radiation damage to the CCD chips is low. Therefore the life time of these cameras is high (up to 5 years), avoiding frequent dosimetric re-calibration. For the measurements the focus to fluorescent screen distance is set to 150 cm, allowing for a maximum field of view of $22 \times 22$ cm$^2$ defined at isocenter height.

The dosimetric calibration of the EPID is entirely based on the EPID images of square fields [3]. To derive position dependent crosstalk kernels $2 \times 2$ cm$^2$ off-axis fields are used [2]. In addition, EPID images are acquired for symmetric square fields ranging from $6 \times 6$ cm$^2$ up to $40 \times 40$ cm$^2$ to derive the screen kernel that describes the conversion of fluence into visible light from the fluorescent screen, the open beam profile, the local epid sensitivity and the impact of head scatter on the measured on-axis EPID signal. All images are normalized to the on-axis grey value measured for a $10 \times 10$ cm$^2$ field.

For pretreatment verification of IMRT profiles delivered with dynamic multileaf collimation at a Clinac 2100C (Varian Associates, Palo Alto, CA) equipped with an 80-leaf MLC (leaf width 1 cm), EPID images are acquired without a phantom in the beam for every treatment field of an IMRT patient, before the start of the first treatment fraction. The acquired images are then converted into measured PDIs, by correcting for dark current and a small non-linearity of the CCD-camera response [1], removal of the crosstalk contribution and normalization [3]. For PDI prediction, the calculated fluence maps are exported from the Cadplan TPS (Varian Associates, Palo Alto, CA). These fluences are corrected for head scatter, multiplied with the open beam profile and convolved with the screen kernel to obtain the predicted PDI [3].

Dose reconstruction algorithm
To reconstruct the 3D patient dose, delivered pretreatment fluence maps for each treatment field are derived from the PDIs measured without a phantom in the beam using an iterative method that is similar to the method described by McNutt et al. [5]. In contrast to our PDI measurements, McNutt et al. measured the fluence behind a phantom. In the first iteration, the measured and predicted PDIs are compared, and the original fluence map is multiplied with the relative dose differences between these PDIs to derive the first estimate of the delivered fluence. With this modified fluence, a new portal dose image is predicted, which is again compared to the measured PDI to yield an adapted fluence map. This process continues until the root mean square of the relative differences between the measured and the predicted PDIs is minimized. The iteration stops when the root mean square difference is less than 0.5% or if the change between successive iterations is less than 0.05%. This convergence is always reached within 10 iterations; while usually less than 5 iterations are needed. The fluence map that is obtained at that point is imported into the TPS replacing the original fluence file. With the
modified fluences and the planning CT data, the dose distribution in the patient is then calculated using the TPS.

Experimental validation of the 3D dose reconstruction method

For the validation of the 3D dose reconstruction method, errors were simulated in the fluence delivery of a flat 10 × 10 cm² field delivered with DMLC. Errors of −5%, −10%, −25% and +10% were deliberately introduced in the central part of the fluence profile. Also gradients of −10% and 10% were introduced in the fluence profiles, simulating a situation in which one of the leaves is travelling too slow or too fast. In addition, errors of −10% were simulated in the fluence maps of some IMRT patients.

PDI measurements were performed (without a phantom in the beam) for the fluence maps with simulated errors. Based on these results and the PDI prediction using the unmodified fluence map, the actually delivered fluence was reconstructed as described before. This reconstructed fluence was imported into the TPS to calculate the dose distribution in water at a depth of 5 cm.

For the modified fluence maps, dose profiles were measured at 5 cm depth in a water phantom using a linear diode array (Scanditronix, Welhöfer, Uppsala, Sweden), consisting of 11 shielded p-type diodes. The diode readings were converted to absolute dose using calibration factors obtained from measurements in the center of a static 10 × 10 cm² field for 100 MU. The measured dose profiles were compared to those calculated using the 3D dose reconstruction method.

Clinical evaluation of the 3D dose reconstruction method

The procedure is clinically evaluated for 10 recently treated head and neck cancer patients and 5 rectum cancer patients. In addition, for 2 patients in which errors were intercepted during our previous 2D pretreatment verification procedure [11] a 3D dose reconstruction was performed.

DVHs of the original and reconstructed plan were compared for both the PTV and critical organs. DVH parameters that are considered relevant for the examined structures and that are often applied as dose constraints in the optimization process of the IMRT plan are used for quantitative comparison. For the PTV the Equivalent Uniform Dose (EUD) [6] (i.e. the uniform dose that is considered to result in the same biological effect as a given non-uniform dose distribution), the minimum dose in 99% of the volume ($D_{\text{min}}$) and the volume percentage that receives at least 95% of the prescribed dose ($V_{95\%}$) are used. For the parameter $a$ in the EUD model [6] a value of −10 was considered. For head-and-neck cancer patients the mean dose in the parotid glands and oral cavity and the maximum dose in the cord are evaluated. For the rectum cancer patients, the maximum dose in the bladder, the colon volume receiving at least 100% of the prescribed dose, and the small bowel volumes receiving at least 85% or 100% of the prescribed dose are compared. Differences in the dose parameters were quantified relative to the prescribed dose. Volume differences were calculated relative to the total volume of the particular structures. Besides DVH analyses, the reconstructed dose distributions (i.e. based on the fluence maps derived from the PDI measurements) and the original 3D dose distributions were compared slice-by-slice, using dose difference maps and a 3D $\gamma$ analysis [4]. For this $\gamma$ evaluation, 2% of the prescribed dose and 2 mm distance to agreement were used as reference criteria.

Results

Experimental validation of the 3D dose reconstruction method

In Fig. 1 two examples of the experimental validation are shown. In Fig. 1a, the measured and reconstructed dose profiles are compared for fluence maps in which errors of −25%, −10%, −5% and +10%, respectively, were introduced in the center of the 10 × 10 cm² field. Fig. 1b shows the results for a clinical IMRT profile. For all cases the measured and reconstructed dose profiles agreed within 2%/1 mm, showing the good accuracy of this method.

Clinical evaluation of the 3D dose reconstruction method

Results for head and neck cancer patients

For one typical head-and-neck cancer patient, dose-volume histograms for the original and reconstructed treatment plans are depicted in Fig. 2; for each of the organs, only small differences are observed. Fig. 3 shows a comparison of the dose distributions in three axial slices using dose difference maps (top row) and 3D $\gamma$ images (bottom row). The PTV is visible in the middle and the right slice, while the left slice is taken in a high dose gradient region 0.5 cm superior to the PTV. Most dose differences are less than 2% of the prescribed dose, except in the dose gradient regions around the PTV and along the beam edges. The 3D $\gamma$ analysis shows that these differences fulfill a 2%/2 mm criterion, in 95.8% of the pixels (i.e. these pixels have a $\gamma$ value smaller than 1).

A summary of the DVH parameters for all head and neck cancer patients is shown in Table 1. For both the PTV and organs at risk only minor differences in those parameters were observed (generally within 2%). For these patients, no clinically relevant dose differences were observed in the slice-by-slice comparisons either, indicating the good agreement between the original and the reconstructed plan. For some organs at risk a slightly larger dose than in the original treatment plan was found, but in none of these cases were the dose constraints, which were used in the inverse planning process, exceeded. The largest differences (up to 3.7%) were observed in the maximum cord dose for 2 patients, for which the cord was situated in a high dose gradient region near the PTV.

Rectum patients

An overview of the results for the five rectum cancer patients is shown in Table 2. Again, all DVH parameters were generally within 2% of the original plan. Slice by slice
comparison of the 3D dose distributions showed similar results as for the head and neck cancer patients. In all patients at least 95% of the points fulfilled a 2%/2 mm criterion in the 3D analysis.

3D dose reconstruction for intercepted errors

In 400 patients, our pretreatment procedure based on multiple 2D analyses intercepted 4 clinically relevant errors [11]. In one case, a wrong treatment plan was sent to the accelerator. For this patient, DVHs for the reconstructed treatment plan indicate that in both the PTV and the cord a 20% higher dose than was intended would have been delivered (see Fig. 4). Especially for the cord this could have resulted in severe complications.

In the other three cases, malfunctioning of one of the leaves was detected. For one of these patients, differences between measured and predicted PDIs of about 10% were

Fig. 1. Comparison of the calculated dose profile at 5 cm depth in water based on the planned (unmodified) fluence map (black line), the reconstructed dose profile based on the measured PDI for the modified fluence map (grey line) and the measured dose profile in water for the modified fluence map. In (a) errors of −5%, −10%, −25% and +10% were introduced in the center of a flat 10 × 10 cm² field; in (b) errors of −10% were introduced in a clinical IMRT field for a prostate cancer patient.

Fig. 2. Comparison of the original and reconstructed dose distributions based on the DVHs of the PTV for both parotid glands and the spinal cord for one typical head-and-neck cancer patient.

Fig. 3. Comparison of the original and reconstructed dose distribution in three slices for one of the head-and-neck cancer patients using dose difference maps (top row) and 3D γ images (bottom row). For the γ analysis a 2%/2 mm criterion was used. The white contour indicates the PTV volume. The left slice was taken in a high gradient region just above the PTV, the middle and right image show slices through the PTV.
seen for one leaf pair over a distance of 7 cm. Due to the combination of the different treatment fields, the dose differences reduced to 5% in the reconstructed 3D-dose distribution (see Fig. 5a). At the projection of the malfunctioning leaf, most pixels inside the PTV failed the $\gamma$ evaluation. For slices projected 1 cm above and 1 cm below the malfunctioning leaf, the differences were within 2%/2 mm again. Comparison of the DVH of the PTV (Fig. 5b) showed hardly any difference between the original and reconstructed plan. The local underdosage in part of the PTV could not be detected due to the large size of the tumor. This indicates that for clinical evaluation of the dose distributions one cannot rely on the comparison of DVH and DVH parameters only, but that a proper local dose evaluation is important as well, for example by using an automated slice-by-slice comparison.

### Discussion

Pretreatment verification with an EPID is part of our patient-specific QA program for advanced treatment techniques. On its own, it only verifies parts of the patient-independent factors involved in an adequate dose delivery to the patient: (a) the transfer of a treatment plan from the planning system to the treatment unit and (b) the mechanical and dosimetrical functioning of the treatment unit. This means that both deviations in the delivered fluence maps and in the output (cGy/MU) of the accelerator can be detected. However, the pretreatment measurements do not allow verification of the monitor unit calculation of the TPS, because this number is used as input for the PDI prediction, but also delivered at the treatment unit when performing the PDI measurement. Errors in the beam model of the TPS are not detected either, because the same model is used for calculating the originally planned and reconstructed 3D patient dose distributions. For verification of both the monitor unit calculation and the dose modeling, we are currently implementing a 3D dose calculation with a fully, independent dose engine in addition to the described pretreatment verification. For reconstruction of the 3D patient dose from pretreatment measurements, Renner et al. [8] used a dose engine that was different from the one that was used to calculate the original treatment plan. In this way they were also able to verify the accuracy of their dose calculation. A disadvantage of this approach might be that it is not straightforward to distinguish whether observed deviations in the reconstructed patient dose are related to errors in one of the dose engines, or to errors in the fluence delivery at the treatment machine. In our approach this is possible.

The dose reconstruction of the pretreatment results does not provide a means for the verification of the dose that is actually delivered during patient treatment. For that purpose, the use of the dose reconstruction method described in this article in conjunction with cone-beam CT-scans acquired immediately prior to treatment and PDI measurements during treatment is currently being investigated.

Pretreatment verification allows detection of errors in fluence delivery, prior to the start of the patient treatment, such that they will not have any effect on the dose delivery. In the assessment of the clinical relevance of differences between measured and predicted portal dose, 3D reconstruction of the patient dose using fluences derived from...
2D portal dose images and the planning CT-scan proved to be a powerful tool. Commonly accepted tools for evaluation of patient dose distributions, such as dose-volume histograms, can be used to make the clinical interpretation of the results more straightforward. For the majority of pretreatment measurements, only small deviations in the 3D patient dose and in DVH analyses were observed even if larger differences were observed in the multiple 2D analysis. This is due to the averaging effect of multiple beam directions. For only 2 patients in the present study did the deviations in the multiple 2D analysis result in deviations in the reconstructed dose larger than 2–3%. Because DVHs and DVH parameters summarize the dose distribution in an entire volume and lack geometric information, larger dose differences in a relatively small volume may be obscured, while they possibly have some clinical impact. Therefore, the analyses of the DVHs and DVH parameters should always be combined with an evaluation that is sensitive to local differences in the dose distributions, for example by using an (automated) slice-by-slice comparison or a comparison based on biological parameters.

The procedure described in this paper is currently being incorporated into our clinical routine. For comparison of 2D portal dose images, we apply a 3% local dose difference and 3 mm distance to agreement in the $\gamma$ evaluation [11]. This implies that, when differences in 2D portal dose images are small, a 3D dose reconstruction will hardly provide any additional information, because the differences between the original and reconstructed dose distribution will remain within 3%, both in the PTV and the organs at risk. Therefore, dose reconstruction will only be performed for patients for whom larger dose differences are observed in one or more beams, i.e., in cases where at least one beam is not approved automatically in our current 2D analysis [11]. The automatic evaluation scheme used for the multiple 2D analyses of our pretreatment measurements will be extended to the 3D analysis based on a patient dose reconstruction. Because most differences found in individual beams will not add up to differences larger than 3% in the patient dose distribution, except if a consistent local problem is present in all beams, or a very large error is present in one or more beams, this is expected to increase the number of pretreatment measurements that can be approved fully automatically, thereby reducing the required workload.

Conclusion

A 3D reconstruction of the patient dose based on fluence maps measured with the EPID prior to the start of treatment was implemented. It allows for a more straightforward clinical evaluation of the results of pretreatment measurements than a multiple 2D comparison. Generally, the planned and reconstructed dose distributions show minor differences (less than 2%) in both DVH analyses and local dose comparisons.

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* Corresponding author. Mathilda van Zijtveld, Department of Radiation Oncology, Division of Medical Physics, Erasmus MC-Daniel den Hoed Cancer Center, Groene Hilledijk 301, 3075 EA, Rotterdam, The Netherlands. E-mail address: M.vanzijtveld@erasmusmc.nl

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