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EPID

3D *in vivo* dose verification of entire hypo-fractionated IMRT treatments using an EPID and cone-beam CT

Leah N. McDermott, Markus Wendling, Jasper Nijkamp, Anton Mans, Jan-Jakob Sonke, Ben J. Mijnheer, Marcel van Herk*

Department of Radiation Oncology, Netherlands Cancer Institute – Antoni van Leeuwenhoek Hospital, Amsterdam, The Netherlands

Abstract

As radiotherapy becomes more complicated, dose and geometry verification become more necessary. The aim of this study was to use back-projected EPID-based 3D *in vivo* dosimetry and cone-beam CT (CBCT) to obtain a complete account of the entire treatment for a select patient group. Nine hypo-fractionated rectum IMRT patient plans were investigated. The absolute dose was reconstructed at multiple planes using patient contours and EPID images acquired for all fields during treatment. The meso-rectal fat (m-R) was re-delineated on daily CBCT scans, acquired prior to each fraction. The total accumulated dose was determined by mapping the m-R surface of each fraction to the planned m-R surface. Average planned and measured isocentre dose ratios were 0.98 (±0.01SD). 3D gamma analysis (3% maximum dose and 3 mm) revealed mean γ, $\langle\gamma_{mean}\rangle$ = 0.35 (±0.03 SD), maximum 1% of γ points, $\langle\gamma_{max1\%}\rangle$ = 1.02 (±0.14SD) and the percentage of points with $\gamma \leqslant 1$, $\langle P_{\gamma\leqslant1}\rangle$ = 99% (range [96%, 100%]), averaged over all patients. CBCT m-R volumes varied by up to 20% of planned volumes, but remained in the high dose region. Over-dosage of up to 4.5% in one fraction was measured in the presence of gas pockets. By combining EPID dosimetry with CBCT geometry information, the total dose can be verified in 3D *in vivo* and compared with the planned dose distribution. This method can provide a safety net for advanced treatments involving dose escalation, as well as a full account of the delivered dose to specific volumes, allowing adaptation of the treatment from the original plan if necessary.
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Keywords: EPID dosimetry; 3D verification; *In vivo* dosimetry; Cone-beam CT; Rectum TME

As dose prescriptions and the complexity of radiotherapy techniques increase, so too do the demands for accurate and efficient means of verifying the dose delivered to patients. This is especially true of hypo-fractionated treatments, where errors in a single fraction have a larger influence on the total dose than with lower dose-per-fraction schemes. For normal (2 Gy/fraction) fractionation schemes in our department, it is considered safe to perform a check after the first few fractions. It costs less work/time to check a number of fractions once, than to check every fraction daily [12]. Hypo-fractionated schemes, however, alter the safety versus workload balance in favour of safety, thus warranting daily checks.

Various strategies for verifying the dose in 3D based on EPID images have been reported over the past 11 years [1,3,13,15,17], however very few based their method on measurements during patient treatment and could be considered verification of dose *in vivo*. By using back-projection EPID dosimetry [19], we can determine the dose inside the patient in three dimensions based on transmission images acquired during treatment. Incorporating anatomical information obtained from images acquired in 3D minutes prior to treatment, both re-delineated structures and the dose can be verified at every fraction. If the total dose delivered to the patient over the entire treatment is measured, the impact of discrepancies can be determined and compensating effects quantified.

The treatment regime for this study was a hypo-fractionated IMRT treatment of rectal cancer. Radiotherapy (RT) plans consist of a 5×5 Gy fractionation schedule. Patients undergo a total meso-rectal excision (TME) within 10 days of the start of RT. A Dutch-led randomised international multi-centre trial compared patient groups undergoing TME surgery both with and without pre-operative RT. Patients receiving 5×5 Gy RT + TME surgery had a 5.6% local recurrence rate (LRR) after 6 years, compared with 10.9% in cases with surgery alone ($p < 0.001$) [14]. These results supported a Swedish rectal cancer trial report from 1997, with the pre-operative RT group having a 13% LRR, vs. 22% for the non-RT arm (involving only partial removal of the rectum). The survival rate also improved with pre-operative RT, having 58% 5-year survival compared with 48% [16].

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Survival rates, LRR (or tumour control probability) and side-effect prediction (or normal tissue complication probability), are only valid if the dose is delivered to the intended target region based on set planned parameters (within tolerance). Under-dosages will lead to increased recurrence rates, negating the benefits of pre-operative radiation treatment. Over-dosage to sensitive organs will increase the complication rate from RT and introduce additional complications during surgery. Given that we can now measure the patients' dose and position in 3D at the time of treatment with dosimetry and imaging tools currently available, the aim of this study was to develop a verification method using these tools, and to obtain a complete set of dose and geometry information for each treatment fraction.

Methods and materials

Patient treatment plans

Nine hypo-fractionated treatments for patients with rectal cancer were investigated. The clinical target volume (CTV) was defined as the volume encompassing the rectum, the meso-rectal fat (including the perirectal and presacral lymph nodes) and the lymph nodes along the internal iliac artery. The prescribed dose was 25 Gy to the planning target volume (PTV), defined as the CTV with a 1 cm uniform margin. Plans were delivered according to the 5×5 Gy fractionation scheme. All plans used step-and-shoot IMRT beams, four plans with seven beams and five with five beams. Each plan consisted of one 10 MV and four or six 18 MV photon beams. Dose distributions were optimised and calculated with the treatment planning system (TPS) Pinnacle 7.4f (Philips Medical Systems, Eindhoven, The Netherlands). The dose was calculated using the adaptive convolution algorithm on a grid of $0.4 \times 0.4 \times 0.4\ cm^3$ voxels.

EPID dosimetry

EPID images were acquired with an amorphous silicon flat panel imager (iViewGT, Elekta, Crawley, UK). Details regarding the imager design, image acquisition, stability and dosimetric characteristics have been reported extensively [2,8–10]. The back-projection algorithm designed in our department has also been described for 2D and 3D dosimetry [7,18,19]. The algorithm assumes a homogeneous patient and converts segment images to an absolute 3D dose matrix in the 'patient volume', i.e. the volume enclosed by the external contour of the patient. For better accuracy, the planning CT outer contour is used instead of the cone-beam CT (CBCT) contour for this patient group (see Discussion section for more details). Pixel values of the transit portal dose image are processed using scatter kernels (for scatter within the EPID and scatter from the patient to the EPID), the scatter-to-primary ratio (for scattered radiation within the patient), the inverse square law and the measured transmission. The latter is determined from the ratio of the primary portal dose image and open (no attenuating medium) portal dose image, acquired for each segment. The 2D images are back-projected to multiple planes within the patient dose volume to form a 3D matrix. A correction is also required to account for attenuation of the beam from each reconstruction plane to the exit surface. The external contour of the patient is used to obtain the ratio of geometrical path lengths, which is used to calculate the attenuation per pixel. The density of the transmission medium is assumed to be homogeneous, therefore the dose may be incorrect for locations corresponding to sections of the beam that passed through media of non-water equivalent density.

The reconstructed 3D dose distribution is the sum of the reconstructed dose distributions of all segments of each field. It should be noted that the accuracy of our EPID dosimetry method (±2% or 2 mm) has been published for 18 MV [18] in 2D and equivalent levels of accuracy have also been achieved for 3D verification, which will be submitted for publication in a separate report.

Cone-beam CT and re-delineation

A CBCT scan (Elekta Synergy 3.5) was made prior to each treatment according to an on-line set-up correction protocol. The planning CT scan for each patient was imported from the TPS to be used as a reference. A chamfer-matching algorithm was used to automatically localise the bony anatomy in the CBCT scans. Translations were used to correct the centre of mass of the PTV. The patient position was corrected for any translational displacement differences more than 1 mm. Since the CTV is not easily reproducible on CT scans, the delineated rectum plus surrounding the meso-rectal fat (m-R) was selected as the region of interest. The m-R was delineated on the planning CT scan and 5 CBCT scans for each patient (by a single observer). An example of the CTV and the m-R contours for one patient is shown in Fig. 1.

Mapping and comparison of dose distributions

To accumulate the dose over all fractions, the CBCT scans were all registered rigidly to the boney anatomy of the planning CT scan. The CBCT registration was used to consistently position corresponding m-R delineations and the measured dose distributions for each fraction. Since the treatments followed an on-line positioning protocol, the patients were shifted between imaging and treatment. The matched CBCT scan was assumed to represent the patient position during treatment *after set-up correction*. Since the on-line localisation protocol action level was accurate within 1 mm, it is assumed that matching the CBCT to the planning CT accurately represents the actual treatment position of the patient. The m-R volumes from CBCT scans were then virtually sliced, unfolded and mapped to the planning volume [5]. A line was selected from the apex, along the m-R on the dorsal side and used as the 'cut' line. In this way the 3D volumes were unfolded and mapped to a 2D surface and sampled on the corresponding measured dose distributions. The dose maps were summed over 5 days to represent the accumulated dose over the entire treatment for each patient. The surface dose distributions were used to make a dose-surface histogram (DSH) for the plan (whole treatment), each fraction and the accumulated dose distributions for the entire treatment course. Dose distributions were also compared using the gamma evaluation in 3D [20], with criteria of 3% of the maximum dose and 3 mm dis-