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An in-vivo dosimetry procedure for Elekta step and shoot IMRT

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ABSTRACT

Purpose: The aim of this work was to extend an in-vivo dosimetry (IVD) method, previously developed by the authors for 3D-conformal radiotherapy, to step and shoot IMRT treatments for pelvic tumors delivered by Elekta linacs.
Materials and methods: The algorithm is based on correlation functions to convert EPID transit signals into in-vivo dose values at the isocenter point, D_{iso}. The EPID images were obtained by the so-called "IMRT Dosimetric Weighting" mode as a superposition of many segment fields. This way each integral dosimetric image could be acquired in about 10 s after the end of beam delivery and could be processed while delivering the successive IMRT beams. A specific algorithm for D_{iso} reconstruction especially featured for step and shoot IMRT was implemented using a fluence inhomogeneity index, FI, introduced to describe the degree of beam modulation with respect to open beams. A γ-analysis of 2D-EPID images obtained day to day, resulted rapid enough to verify the plan delivery reproducibility.
Results: Fifty clinical IMRT beams, planned for patients undergoing radiotherapy of pelvic tumors, were used to irradiate a homogeneous phantom. For each beam the agreement between the reconstructed dose, D_{iso}, and the TPS computed dose, $D_{iso,TPS}$, was well within 5%, while the mean ratio $R = D_{iso}/D_{iso,TPS}$ resulted for 250 tests equal to 1.006 ± 0.036. The same beams were checked in vivo, i.e. during patient treatment delivery, obtaining 500 tests whose average R ratio resulted equal to 1.011 ± 0.042. The γ-analysis of the EPID images with 5% 3 mm criteria supplied 85% of the tests with pass rates $\gamma_{mean} \leq 0.5$ and $P_{\gamma<1} \geq 90\%$.

Introduction

In-vivo dosimetry (IVD) is one of the major challenges in radiotherapy. The increase in complexity of radiotherapy treatments requires more and more accurate and efficient strategies to verify the dose delivered to patients. Inaccuracies in dose delivery may influence the outcome of any radiotherapy treatment, due to the steepness of dose–effect curves for both local tumor control and normal tissue complications. Pretreatment dosimetry by means of phantoms or the Electronic Portal Imaging Devices (EPID) [1] is commonly used to assess the accuracy of the computed TPS dose distributions. However studies about the implementation of IVD systems show that a relevant number of clinically unacceptable errors may remain undetected even when pretreatment verification is used [2–4]. Moreover, in the last years, several major incidents leading to significant complications and even to the death of patients, have been widely discussed by the media [5]. IVD protocols have been recommended by different organizations [6,7] and we believe they will become mandatory in many countries to fulfill legal requirements [8,9].

On this issue several researchers [10] have demonstrated the advantages of reconstructing the delivered dose by amorphous-silicon EPIDs (aSi-EPIDs) that present favorable characteristics such as fast image acquisition and high resolution [11]. Several methods have been successfully developed for dose reconstruction in patient in terms of point dose, 2D or full 3D dose distribution [12–17]. Nowadays the routine application of IVD is not widespread because of the workload involved and the effort to make existing technology more robust and simple [18].

One procedure recently developed by the authors [19] for the isocenter dose reconstruction has been generalized for the 3D

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conformal radiotherapy (3D-CRT) beams delivered by different linacs (Elekta, Varian and Siemens). In particular this generalized procedure adopts for an easy commissioning (i) a set of correlation functions between the transit signals and the doses at phantom mid-plane, parameterized by the beam quality index $TPR_{20,10}$ (ii) a simple calibration procedure for the different aSi-EPID models.

Moreover the procedure assures the use of the Record and Verify network of the center for a rapid access to the EPID images and the CT patient anatomical data to obtain the results in quasi real time. Using these strategies the present work reports the development of an IVD procedure for step and shoot IMRT beams delivered by Elekta linacs for the prostatic cancer treatment, that is the unique pathology treated with this technique in our center. However, for dosimetric purposes the EPID images acquired with step and shoot IMRT (unlike 3D-CRT) must be weighted according to the per-segment accumulated pixel values. This modality was tested and used not only for the isocenter dose reconstruction but also for 2D portal images comparisons obtained in different therapy sections to verify the treatment reproducibility. The easy commissioning of the method and the possibility to obtain the results in quasi real time are the reasons of the development of this procedure that can be used in clinical practice.

Materials and method

Linac units

Two Elekta Precise linacs (Elekta, Stockholm, Sweden), operating at the Fondazione di Ricerca e Cura "Giovanni Paolo II" of Campobasso, were used in this work. Both linacs were equipped with a standard multileaf-collimator (MLC) that consisted of two opposite banks carrying 40 leaves, of 1 cm width at the source axis distance (SAD equal to 100 cm). The two 6 MV X-ray beams used for the IMRT of prostatic tumors were characterized by the quality index, $TPR_{20,10}$, equal to 0.684 and 0.687 respectively. These values were representative of the $TPR_{20,10}$ interval range reported for the Elekta 6 MV X-ray beams [20].

EPID signals

The linacs were equipped with Elekta IviewGT EPIDs, based on aSi panels XRD 1640 AL5 (PerkinElmer Optoelectronics, Fremont, CA USA) operating as a two-dimensional photodiode array at the fixed source-EPID distance (SED) equal to 159 cm. This distance was adopted by the generalized procedure for the 3D CRT [19]. The sensitive layer consists of 1024 × 1024 pixels with a pitch of 400 μm, resulting in an active area of 409.6 × 409.6 mm^2 [11,20,21].

The EPID frame, generated in 434 ms, was defined as the raw signal $s'(x,y)$ in terms of arbitrary units (au), from one readout of the entire EPID panel, where x and y are the pixel coordinates in the 1024 × 1024 matrix.

The portal images for open or wedged beams, used by 3D-CRT, can be obtained by the integrated signals (over the total beam-on time) multiplied by a pixel scaling factor (PSF) [19,20]. Indeed an image acquired with 10 MU (Monitor Units) has roughly the same gray levels as an image acquired with 100 MU (i.e. the same normalized pixel values $s^*(x,y)$) and the PSF is supplied by the IviewGT software version 3.3 at the end of the irradiation. This way the un-normalized gray levels, i.e. the integrated pixel values $s(x,y)$, were obtained by subtracting the normalized pixel values from the number 65,535 ($2^{16}-1$) and then dividing it by the PSF

$$s(x,y) = \frac{65,535 - s^*(x,y)}{\mathrm{PSF}} \quad (1)$$

For the step and shoot IMRT beams the EPID uses the "IMRT Dosimetric Weighting" mode that is implemented as a Boolean variable (0/1) in the EPID configuration file (called sri.ini) [22].

It determines how IViewGT weights individual IMRT segment images collected during each treatment. By default, "IMRT Dosimetric Weighting" is disabled (its value is set to 0 in the sri.ini file) and individual segment images weighted equally when generating the final integrated composite image. This default behavior is appropriate, for example where it is intended that all individual segment shapes are visible in any final composite image, irrespective of the absolute segment doses. However for dosimetric imaging purposes the contributions from individual segments images must be weighted according to the persegment accumulated pixel values. This was implemented by enabling the "IMRT Dosimetric Weighting" variable in the sri.ini file i.e. the Boolean variable was set to 1. Then the EPID signal was processed by equation (1) using a PSF supplied for the integral dosimetric image. This result was available about 10 s after the end of the last segment delivery. This means that the successive steps of the linac, such as following the beam loading, the positioning of the new gantry angle and the MLC configuration (requiring about 60 s), were not interrupted by the acquisition of the integral IMRT image for processing. This way the IVD results can be supplied immediately at the end of the complete treatment.

Treatment planning system

The TPS used in this work was Oncentra Masterplan version 4.0 (Elekta, Stockholm, Sweden). Dose calculation was performed using the pencil beam algorithm with inhomogeneity correction and a dose grid resolution of 2 mm. The isocenter dose was named here as $D_{iso,TPS}$.

The Digital Comunication in Medicine (DICOM) RT-file supplied by TPS provided the MLC position and the MU number of each segment. This last information was used by an in house software developed in Matlab (Math Works, Inc., Natich, MA, USA) to obtain an integral intensity map (in terms of MU) for each beam, with a pixel resolution of 2 × 2 mm^2.

Simulated imrt-beams

In a recent paper, 9 X-ray beams of 6, 10 and 15 MV supplied by three Elekta Precise linacs operating in different centers, have been used to obtain a IVD procedure for 3D-CRT beams [19]. The method was based on correlation functions between the EPID transit signals and the doses at the isocenter point in solid water phantoms (SPs). The result of that work was the formulation of an algorithm useful for all open and wedged 3D-CRT beams.

In this work an IVD procedure for step and shoot IMRT 6 MV beams based on a general algorithm that takes into account the beam fluence modulation was developed. In particular the correlation functions have been obtained irradiating SPs of different thicknesses, w, with a set of simulated imrt-beams. Figure 1 reports the scheme followed to obtain square imrt-beams with size $L = 8$, 10, 12, 16 cm at the SAD. Rectangular fields of size, $L \times b$, (field 2, field 3, field 4) with $b = 2$ or 4 cm, were added to the square beams (field 1). This way for each square beam, 9 simulated imrt-beams were obtained for a total of 36 imrt-beams.

Figure 2 shows, for a square field equal to 16 × 16 cm^2, the EPID signal profiles along the x axis of the imrt-1, imrt-3, imrt-7 and imrt-9 beams (Table 1) compared with the open beam profile. Table 1 reports the MU used for each beam.

Fluence inhomogeneity index

The external boundaries of an integral IMRT beam are similar to those of conformed beams used for the 3D-CRT. The difference is in