Fast radiographic film calibration procedure for helical tomotherapy intensity modulated radiation therapy dose verification

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Film dosimetry offers an advantageous in-phantom planar dose verification tool in terms of spatial resolution and ease of handling for quality assurance (QA) of intensity modulated radiation therapy (IMRT) plans. A critical step in the success of such a technique is that the film calibration be appropriately conducted. This paper presents a fast and efficient film calibration method for a helical tomotherapy unit using a single sheet of film. Considering the unique un-flattened cone shaped profile from a helical tomotherapy beam, a custom leaf control file (sinogram) was created, to produce a valley shaped intensity pattern. There are eleven intensity steps in the valley pattern, representing varying dose values from 38 to 265 cGy. This dose range covers the most commonly prescribed doses in fractionated IMRT treatments. An ion chamber in a solid water phantom was used to measure the dose in each of the eleven steps. For daily film calibration the whole procedure, including film exposure, processing, digitization and analysis, can be completed within 15 min, making it practical to use this technique routinely. This method is applicable to film calibration on a helical tomotherapy unit and is particularly useful in IMRT planar dose verification due to its efficiency and reproducibility. In this work, we characterized the dose response of the KODAK EDR2 ready-pack film which was used to develop the step valley dose maps and the IMRT QA planar doses. A comparison between the step valley technique and multifilm based calibration showed that both calibration methods agreed with less than 0.4% deviation in the clinically useful dose ranges. [DOI: 10.1118/1.1924327]

Key words: film dosimetry, helical tomotherapy, IMRT treatment plan verification

I. INTRODUCTION

Helical tomotherapy presents a new approach to intensity modulated radiation therapy (IMRT).[1,2] Commercially available since 2003, the Hi-Art helical tomotherapy unit (TomoTherapy Incorporated, Madison, WI) integrates imaging, planning, delivery, and verification into one system. In many aspects, the Hi-Art helical tomotherapy unit is different from a conventional linear accelerator. In fact, the TomoTherapy unit looks more like a CT scanner. The couch is the only movable part one can see in the treatment room, while the linac and megavoltage image detector array are mounted on a ring gantry which is completely covered. The construction of the unit eliminates any gantry–couch collisions.[1] Contrary to a linac, there is no light field projection built in the treatment head; instead, the unit has an integrated laser system to facilitate patient setup. Three movable red lasers are used to define the patient treatment setup according to the treatment plan, and two stationary green lasers are used to define the virtual machine isocenter.

In a typical helical tomotherapy treatment, the patient positioning procedure consists of the following steps. Step one, patient is aligned with the red lasers, as defined from the patient's computerized treatment plan. Step two, a megavoltage computed tomography study (MVCT) is acquired and registered with the reference planning kilovoltage CT (KVCT). Step 3, treatment is delivered after positional adjustments are made (as calculated in step 2). The dose to the target is delivered in a helical fashion using continuous gantry rotations and simultaneous longitudinal translations, similar to motions in helical (or spiral) CT.[3] In addition to the treatment mode, the unit can also be operated in a calibration mode where one can drive the machine based on user specified parameters that were not derived from an inverse plan.[1–5]

In our clinical practice, we rely on film based dosimetry both for quantitative analysis of machine output characteristics, as well as patient specific IMRT QA. For a comprehensive IMRT dose verification, multidimensional measurements are required to quantitatively evaluate the dose distribution in steep dose gradient regions.[6] The helical tomotherapy unit is capable of generating highly conformal dose regions in the target volume with high dose gradient at the target boundary. The high spatial resolution that film offers, make it very desirable for both patient specific and routine machine quality assurance on the TomoTherapy unit.

In this work, we used the Kodak EDR2 film because of its large dynamic range and low sensitivity to processor chemistry variations.[7] Kodak EDR2 film has a sigmoid dose response curve that exhibits marked linearity in the dose range of 25–400 cGy, making it an excellent medium for IMRT dose verification.[12,13] Given that positioning accuracy is extremely important in dose-escalated IMRT treatment,[8–11] pla-

nar dose distribution verification by film dosimetry, in addition to ion chamber point measurement, are part of our IMRT QA protocol. To establish the correlation between film optical density (OD) and absorbed dose in film, one has to use an absolute dosimeter, such as an ion chamber, to calibrate the film and obtain the H-D curve. The conventional multifilm calibration procedure is neither cost effective nor time efficient. Characterizing the film response by delivering multiple fields on a single sheet of film, reduces the cost but can introduce errors unless the scatter dose is explicitly accounted for. Childress *et al.*[13] have proposed a method of rapid film calibration for a conventional linac, which delivers eight square fields (3×3 cm) at different dose levels on a single sheet of film. Ion chamber measurement of each field is taken while the reminder seven fields were irradiated, so that the scatter contribution could be quantified. Radiological Imaging Technologies (RIT) proposed a "step wedge" film calibration technique which was implemented in the RIT113 film dosimetry software. The step wedge creates a thirteen step distribution of dose in a wedge shape, using MLCs in a step and shoot mode. Both methods work very well for beams of conventional linac, but are not applicable to the helical tomotherapy unit because of the different MLC design and beam characteristics. Unlike conventional linac, helical tomotherapy unit does not have a flattening filter. Consequently, the beam spectrum is more narrow,[1] spatially invariant and the beam profile has the shape of an ice cream cone. Because of the unique "cone" shape profile, a specific beam modulation is needed in order to produce fairly uniform steps of dose within a single treatment delivery session. With that in mind, we created a special sinogram, which controls the binary MLC to produce a valley-shaped pattern. The beam parameters of the film calibration procedure are such that the gantry is stationary at the upright position and the couch does not move while the MLC leaves are modulating the beam. A single sheet of Kodak EDR2 is used for the film calibration. With the help of dedicated software we developed (EPIN, a shareware that can be downloaded from our ftp server, http://www.radonc.uams.edu/epin-np.asp), it takes less than 15 min to complete the patient specific QA process, including film calibration, plan delivery, film development, film digitization, and analysis.

II. METHODS AND MATERIALS

The step wedge film calibration method that we use in our clinic for linac based IMRT QA, delivers in a step-and-shoot fashion thirteen segments by opening leaves sequentially at a constant MU interval. The dynamic MLC file that is used for the step wedge calibration projects a rectangular area of 2 cm wide by 13 cm long at 100 cm source-to-film distance (SFD). The dose within each step exhibits a small gradient effect. This is because the adjacent higher dose step contributes more scatter than the adjacent lower dose step, creating a gradient across the field. Although a constant dose per step is preferred, the low dose gradient does not affect the ion chamber measurements needed to quantify the dose per step at the time of calibration.

If a similar step wedge like pattern could be devised for the helical tomotherapy unit, one could use it for film based dosimetry with tomotherapy. Unfortunately, the combination of the cone shaped beam fluence and lateral scatter transport makes only half of the dose steps usable (higher dose steps) and creates a dose gradient that is too large to obtain meaningful ion chamber readings. Unless it is modified by introducing beam modulation, the MLC control concept cannot be directly applied to the helical tomotherapy unit. A new step-wise dose distribution was developed based on the following hypothesis: Due to the cone shaped incident fluence, the steps further away from the beam's central axis receive lower dose than those closer to beam axis. One may arrange the dose steps in a valley pattern, so that lateral steps receive higher dose than central ones. The differential latter scatter contribution to adjacent steps can compensate for the reduced primary fluence and produce uniform dose steps, suitable for ion chamber measurements. Based on this hypothesis, a special sinogram was created using a stationary couch and stationary gantry configuration in order to get the required step valley intensity pattern (Fig. 1).

In tomography, we know that the sinogram is defined as a two-dimensional representation of the signal measured at a given angle in the imaging plane at varying or constant distances along the detector array. Usually the x axis represents the position of detector and y axis represents the projection angle. Similarly, in helical tomotherapy the sinogram that controls the binary MLC is indexed in a way that the x axis represents leaf position and the y axis the projection angle. The term projection is also borrowed from tomography and represents an MLC control cycle (or duration). A sinogram with 100 projections represents 100 control cycles. The number in the cell at a given leaf (x axis value) and projection (y axis value) represents the leaf open fraction (0.0–1.0 in float format) during the command cycle. For instance, 0.5 means the leaf is open 50% of the cycle time. The length of MLC control cycle varies according to the maximum required dose rate for the treatment. A shorter cycle stands for more frequent leaf status change (close or open). The MLC in helical tomotherapy unit contains 64 tungsten leaves, which implies that there are always 64 columns in a MLC sinogram.[4] There are 32 leaves on each of two opposing sides that can slide past one another.[4] Each leaf has the same width which projects to 6.26 mm at a distance of 85 cm from the source. At that distance, four adjacent leaves will cast a 2.5 cm$\times$5 cm rectangular area at the isocenter plane, which is a sufficiently large area for an ion chamber measurement to be made. There are total of 320 projections in the sinogram shown in Fig. 1. Leaves 1–10 and leaves 55–64 are open all of the time, and they are used only to provide lateral scatter to the inner steps. The remaining 44 leaves were grouped into 11 leaf bands to form the step intensity pattern. The delivery procedure uses a stationary gantry at an upright angle and stationary couch, 5 cm jaw opening, 160 projections per rotation and 20 s per rotation. Based on those settings, each projection lasts one-eighth of a second (160 projections/20 s). It takes only 40 s to finish the procedure with 320 projections.

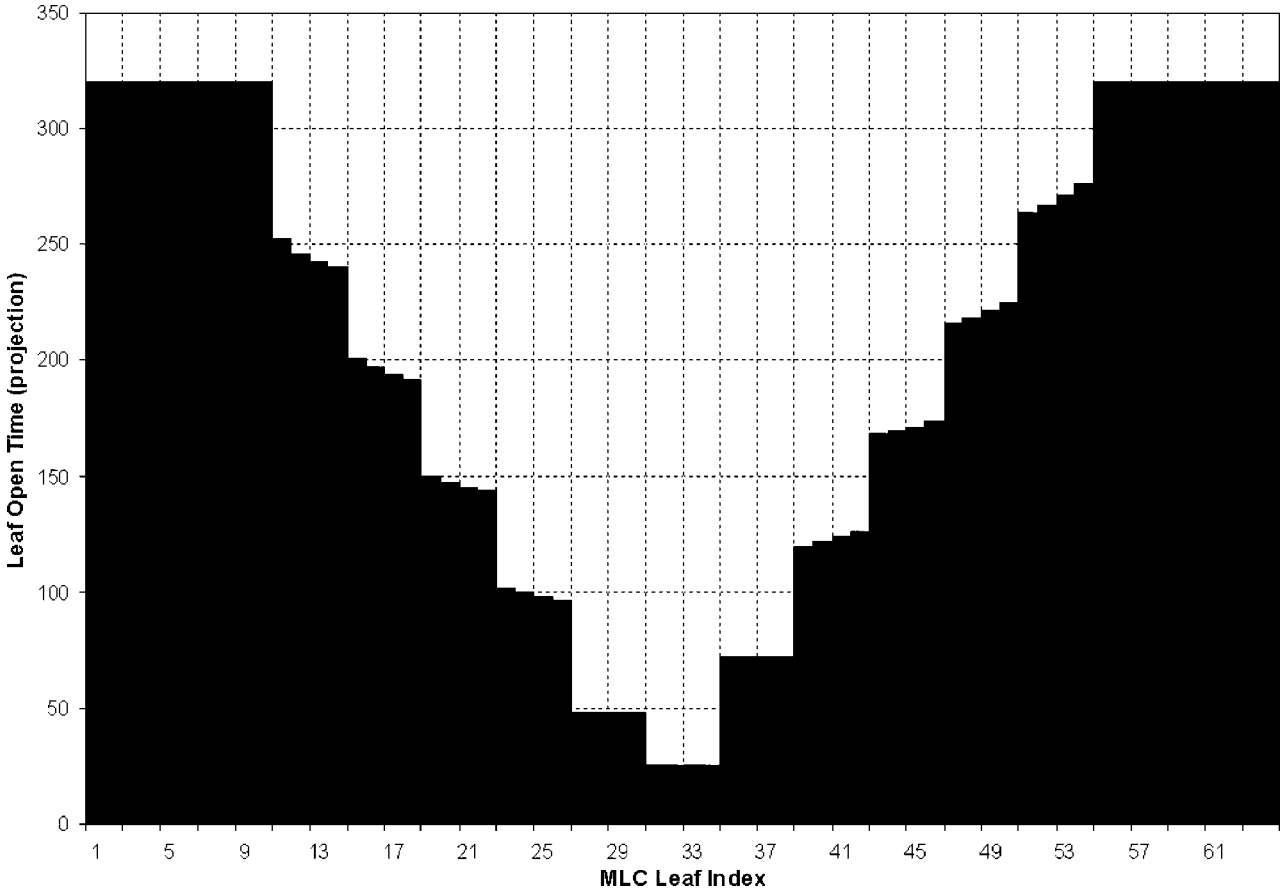

FIG. 1. Representation of valley-shaped sinogram. Black means open and white represents closed status of each MLC leaf during the procedure. The actual values (control cycles) in the order of leaf index are: 320, 320, 320, 320, 320, 320, 320, 320, 320, 320, 252, 246, 243, 240, 201, 197, 194, 192, 150, 147, 145, 144, 102, 100, 98, 96, 48, 48, 48, 48, 25, 25, 25, 25, 72, 72, 72, 72, 120, 122, 124, 126, 168, 169, 171, 174, 216, 218, 221, 225, 264, 267, 271, 276, 320, 320, 320, 320, 320, 320, 320, 320, 320.

In this study we placed the film at a depth of 6 cm which is well beyond the electron contamination range of the 6 MV photon beam from the tomotherapy unit. A rectangular Virtual Water™ phantom (MedCal, Verona, WI) was used as the scatter medium for the measurements and each slab measured 55 cm long and 15 cm wide. One sheet of Kodak EDR2 ready-pack was sandwiched between solid water slabs at a depth of 6 cm from the top and was aligned with the horizontal green lasers at a source to film distance of 85 cm.

To establish the relationship between dose in a step and optical density, dose values at each step have to be measured. The absolute dose at each step was measured using a calibrated ion chamber. The "step valley" procedure was executed with the chamber placed in the center of each intensity step in the same irradiation geometry as the film. The procedure has to be delivered eleven times, one for each dose level. The chamber reading is reflective of the dose from its positional dwelling step as well as the scatter dose from the remaining ten dose steps. Based on those measurements, a calibration curve was established to relate film optical density (OD) and dose. To obtain the film response curve on a different day, one only has to measure the output of the unit and scale accordingly the dose in each of the "step valley" dose steps if the output is different from the day of the original film calibration. The ion chamber measurements need only be made once, at the time of the commissioning of the calibration procedure. In order to minimize errors the film for the daily calibration and the film for the patient IMRT QA should be from the same film box and should be developed sequentially.

A second method of film response calibration was also implemented, where a single film was exposed to a certain dose level using a rectangular fixed beam aperture. Six films were used that were individually exposed to doses ranging from 55 to 255 cGy. This is the conventional multifilm based H-D calibration method.

III. RESULTS

The dose map from a "step valley" procedure delivery and a profile across it is shown in Fig. 2. The dose in the steps varies from 39 to 260 cGy, with a maximum dose gradient of 0.4 cGy/mm. The dose range can be changed to higher or lower dose, by scaling the times in the sinogram accordingly. Figure 3 shows the H-D curves for the step valley method and for the conventional multifilm method.

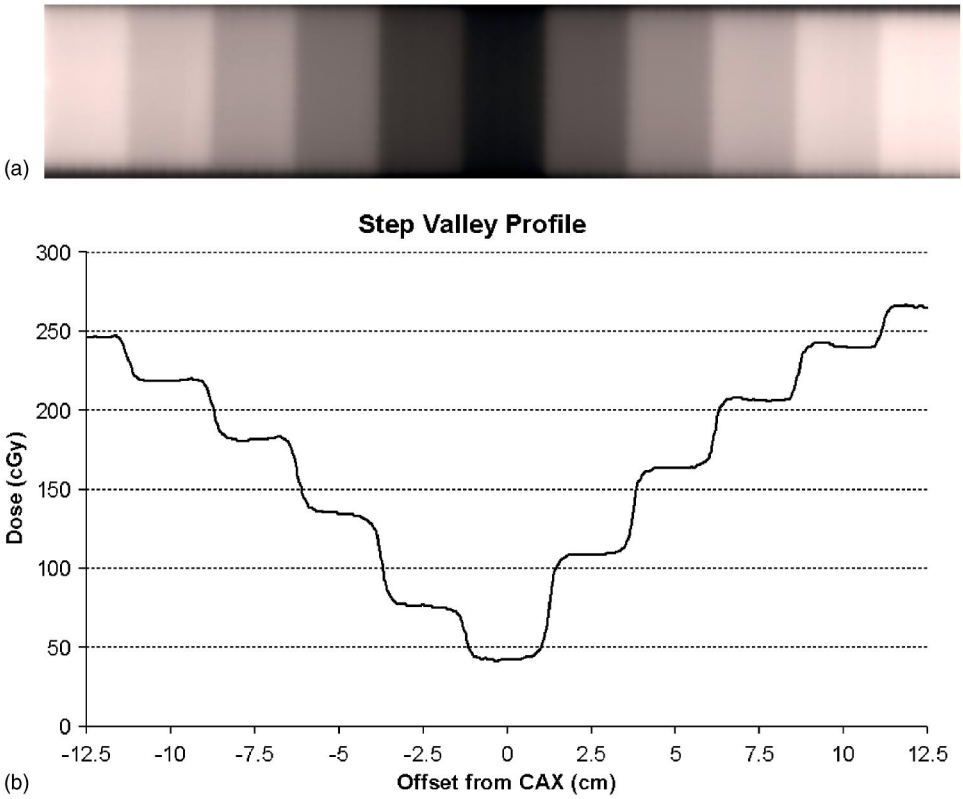

FIG. 2. Step valley dose distribution pattern delivered by Hi-Art Helical tomotherapy unit (a), and transverse dose profile along the dotted line (b).

The two methods are in very good agreement and show a maximum deviation of 0.15% throughout the whole clinical dose range.

An example of a clinical application of our method for a patient specific IMRT QA measurement is shown in Fig. 4. The treatment was developed for a brain tumor where the GTV was prescribed to receive 2 Gy a day for 25 fractions while the nearby critical structures (left and right eye, left and right optic nerve, chiasm and brainstem) were kept below tolerance doses. Once the clinical plan was completed, a calculation of dose, using the patient derived sinograms, was performed in a cylindrical phantom. The calculation was done in a high resolution grid so that we could minimize resolution discrepancies when the film and QA plan dose were compared. The "step valley" calibration technique for the EDR2 film was then performed at the tomotherapy unit as described earlier, while accounting for the daily output variation of the machine. The same cylindrical phantom that was used to calculate the dose in the planning station was used to expose a film that was placed at the equator of the

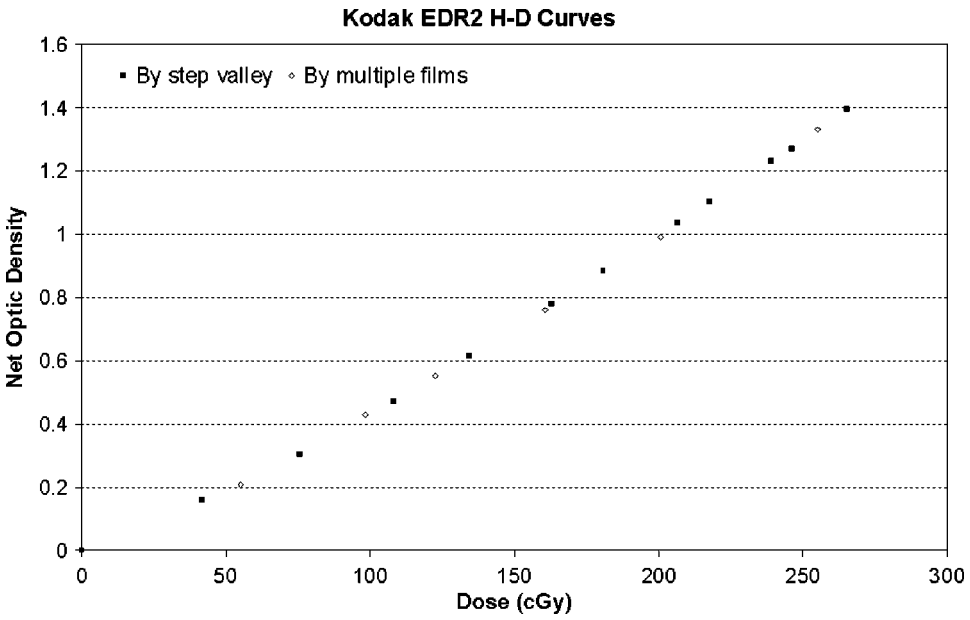

FIG. 3. Comparison of H-D curves measured by step-valley method and multiple films method.

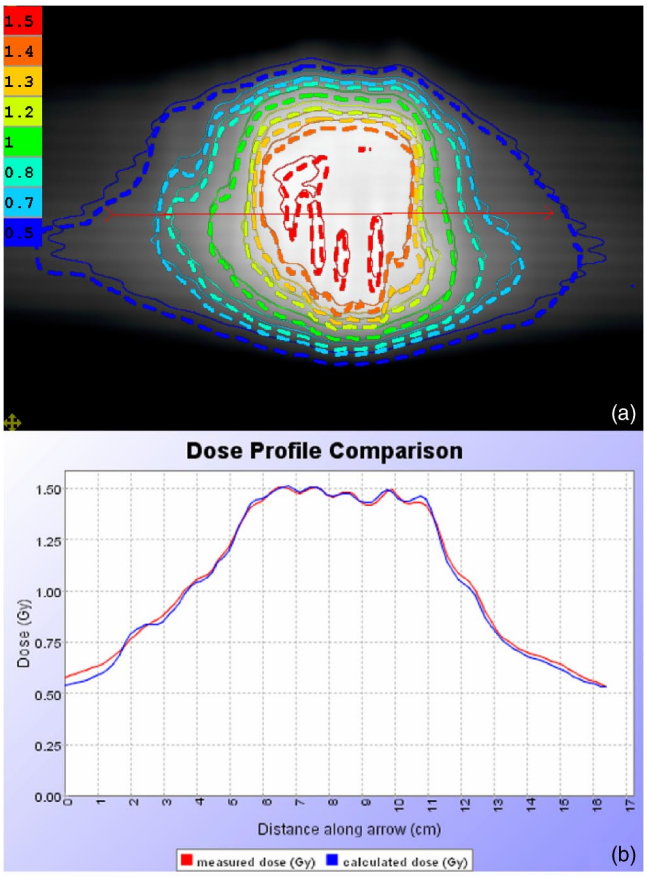

FIG. 4. Clinical patient-specific IMRT QA example. (a) Two-dimensional dose distribution compassion at central coronal plane in cylindrical Virtual Water™ phantom. Computer calculated dose distribution is represented in thick isodose lines; film measurement is represented in thin isodose curves (from inner higher dose to outer lower dose, 1.5, 1.4, 1.3, 1.2, 1.0, 0.8, 0.7, and 0.5 Gy, respectively). (b) Dose profiles along the arrowed line shown in (a).

phantom (coronal plane). An ion chamber measurement was obtained simultaneously at a user defined depth. The chamber placement was based on the dose distribution calculation in the phantom and is typically chosen to be at an area of high dose and low dose gradient. Once the procedure was executed, the "step valley" film and the patient QA film were processed and analyzed. We developed an in-house software program that automatically analyzes the "step valley" film and produces the H-D curve that was used for the film analysis. The results of the isodose distribution comparison for the brain case are shown in Fig. 4.

IV. DISCUSSION AND CONCLUSIONS

Helical tomotherapy is a new modality of radiation therapy treatment delivery. The machine delivers highly conformal intensity modulated fields in a helical fashion. Film dosimetry, coupled with point dose measurements are the tools available at this point for dosimetric verification of the machine characteristics, including patient plan verification. We have developed a fast and accurate technique for film response calibration that can be used with the helical tomotherapy unit. The "step valley" technique uses a custom sinogram that drives the binary MLC of the unit. The sinogram is designed so that it takes advantage of the conical shape of the photon fluence of the unit and the lateral scatter transport between steps in the delivered field. The result is a "step valley" dose pattern on the film with eleven distinct dose levels. There is very little dose gradient in each step, but there is a sharp dose gradient between steps. This technique is very easy to implement and can account for daily machine output fluctuations.

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