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Online combination of EPID & Cherenkov imaging for 3D dosimetry in a liquid phantom

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Abstract

Online acquisition of Cherenkov and portal imaging data was combined with a reconstruction scheme called EC3D, providing a full 3D dosimetry of megavoltage X-ray beams in a water tank. The methodology was demonstrated and quantified in a single static beam. Furthermore, the dynamics and visualization of the 3D dose reconstruction were demonstrated with a volumetric modulated arc therapy (VMAT) plan for TG-119 C-Shape geometry. The developed algorithm combines depth dose information, provided by Cherenkov images, with the lateral dose distribution, provided by the electronic portal imaging device (EPID). The strength of our approach lies in the acquisition of both imaging data-streams with sub-millimeter theoretical resolution at 5 Hz frame-rate, which can be concurrently processed by Fast Fourier Transform-based analysis, thus providing means for an efficient real-time 3D dosimetry.

Index Terms

Cherenkov imaging; portal imaging; real-time 3D dosimetry; image reconstruction; EPID; VMAT

I. Introduction

Increasing demand for high-definition intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) procedures put stress on patient-specific plan quality assurance (QA) resources. While there are several strategies for pre-treatment plan

QA, there remains a need for a tool that can provide complete and accurate verification in a fast enough timeframe for it to be useful in every procedure. In fact, the IMRT plans are often verified in air using EPID measurement, as a simple and efficient way to ensure that the treatment is deliverable as planned. Typically referred to as portal dosimetry, the treatment plan is delivered without any object in the treatment area. The plan is verified by comparing the “in air” recorded cumulative EPID image with a predicted one. Additional tools based upon diode arrays can be employed, but concerns surround the lack of tissue equivalence and sparse data sampling [1]. Recently, an EPID-based computational method for online 3D dose verification has been developed [2]. However, the depth dose distribution is calculated rather than independently measured. Due to reported deficiencies in existing planar dosimetry tools [3], it would be ideal to have a high resolution (< 3 mm) 3D dosimetry tool that provides measurement of the 3D dose distribution in real time during the beam delivery and dose deposition process. In this study, the concept of online (5 Hz) sampling of dose delivery was prototyped and its reconstruction demonstrated by the combined data sets of EPID and Cherenkov imaging of the same beam.

Using modern dose calculation algorithms, dose prediction in treatment planning is highly accurate, however verification of delivery is especially important in dynamic delivery such as IMRT or VMAT, where failure to deliver dose as planned has resulted in disastrous results. These plans use small beams and steep gradients rendering conventional detectors such as a farmer ionization chamber inadequate. Gel dosimetry has become a tool for moderately accurate dosimetry in a tissue equivalent or anthropomorphic geometry, however the material-specific and readout errors [4] as well as long readout times [5] prevail. Diode array based systems are perhaps the industry standard for verification of individual plans but these have distinct limits on spatial resolution [1][6]. Transit dosimetry based upon reconstructing the dose inside a phantom portal can achieve images [7][8], but still require a simulation-based scatter correction for accuracy and/or other assumptions about the beam depth dose curve in the media.

Cherenkov imaging has been recently demonstrated in water tank dosimetry as a way to image the depth dose profile for a 2D projection view through one wall of a water tank [9]. Additionally, fully reconstructed 3D images can be acquired [10], but require many angles of view for accurate filtered back-projection reconstruction. So while Cherenkov beam imaging has the strengths of real time acquisition [11][12] and a clear view of the depth dose profile, it is limited by the single 2D view of a 3D dose distribution.

In this work, we investigated the feasibility of performing online (near real-time) 3D dosimetry using a combination of transit dosimetry from EPID imaging with orthogonal front-facing projection views from Cherenkov imaging. Our approach uses the portal image as primary information of transverse dose distribution, while the Cherenkov image serves for scatter correction and depth dose distribution. The two complement each other because of their similar time frame of readout, and they compensate for their respective weaknesses (see Table 1). At each time point, an orthogonal pair of portal and Cherenkov images was acquired and combined by a specially designed reconstruction algorithm, yielding a time-resolved 3D relative dose distribution of each beamlet. This proof-of-principle 3D

Cherenkov-EPID dosimetry was tested on a series of static beams using a custom VMAT plan in the AAPM Task Group 119 (TG-119) C-Shape geometry [13].

II. Methods

A. Experimental setup

The schematic experimental setup and basic procedural steps are outlined in Figure 1. The experiment was performed on a Varian TrueBeamTMLINAC (Varian Medical Systems, Palo Alto CA, USA), equipped with an HD120TMhigh definition multi-leaf collimator (MLC) and an AS1000 EPID detector (pixel pitch 0.384 mm). As a target we used a 30×40×30 cm water tank filled with a solution of tap water and 1.0 g/L Quinine Sulfate (99% Quinine hemisulfate monohydrate, Alfa Aesar, Ward Hill, MA). The quinine fluorophore was used to increase the isotropic emission of Cherenkov radiation through absorption of UV light and fluorescence re-emission in the blue wavelengths [9]. Compared to the Cherenkov emission from undoped water, the combined effect of Cherenkov wavelength shifting and scintillation of quinine increased the detected signal by a factor of two. The phantom was centered in horizontal x-y plane to the isocenter, and the water level was set to $z = 120$ mm above the isocenter. The EPID was located at a source-to-imager distance of $SID = 150$ cm during both static and VMAT delivery. Both static and VMAT plans were delivered with a 10 MV beam. Cine-mode EPID images were acquired with 10 fps and saved in DICOM format. The Cherenkov images were captured by a time-gated Intensified Charge-Coupled Device (ICCD) camera PI-MAX4 1024i (Princeton Instruments, Acton, MA). The camera was located on the rotational axis of the LINAC gantry at a distance of 3 m from isocenter. Using a 135 mm $f/2$ lens we achieved a theoretical resolution of 0.257 mm/pixel. An experimental spatial resolution of 1.3 mm was measured at the center of Cherenkov image field of view. The intensifier gate of 3.8 μ s duration was triggered by the target current (“TargI”) signal of the LINAC. The CCD was cooled to -20° C and operated at 50 accumulations-on-chip, resulting in a 5 fps video stream. A VMAT plan in TG-119 C-Shape geometry was created in the Eclipse treatment planning system (TPS) (Varian Medical Systems, Palo Alto CA, USA) and normalized to deliver 200 cGy at the point of maximum dose (D_{max}).

B. Dose reconstruction

The approach used to combine the portal image and the frontal Cherenkov image into 3D volume can be divided into three steps. First, a perspective projection of EPID image generates an initial dose volume, which is also projected along y-axis to get an image which is comparable to the Cherenkov image. Second, the algorithm extracts the depth-dose distribution and lateral scatter correction factors by comparing the initial dose volume projection with Cherenkov image. Third, the correction factors are extended to 3D and applied to the initial dose volume, yielding the final 3D dose distribution. The reconstruction algorithm was based on spatial frequency spectral analysis and filtering via Fast Fourier Transform (FFT), and can be described by the diagram in Fig. 2.

The reconstruction algorithm starts with a perspective transformation P of the portal image $E(x', y')$ onto a 3D coordinate system, defined within the physical extent of the phantom, yielding a portal image-based volume $E(x', y', z')$. A frontal view, $E_F(x', z')$, of the portal

image-based volume was then created by summing the values along the y-direction. This frontal view closely resembles the Cherenkov image (see Fig. 3.a and Fig. 3.c), but it also contains the erroneous EPID X-ray scatter signal in the penumbra regions and lacks the depth dose distribution. It is our hypothesis that once the relation between the portal image-based view $E_H(x', z')$ and Cherenkov image $C(x', z')$ is found, one may extend this relation into the third dimension and use an extended 3D relationship to correct the errors in portal image-based volume, $E(x', y', z')$. Since the correction of the portal image-based volume was done by FFT spatial frequency manipulation, the aforementioned portal–Cherenkov image relation has taken the form of a convolution kernel. Both the depth dose distribution and scatter correction factors were encoded in the kernel, allowing the correction of the 3D portal image-based volume. The detailed frequency analysis is described in the following paragraph. Without the loss of generality, the frequency analysis in 1D separates from the dependence on z' dimension. This separation allowed the FFT analysis and filtering of the two-dimensional transverse (x', y') dose planes in an iterative manner along the z' -axis (radiation beam axis). Following the formation of the portal and Cherenkov frontal view pairs, we performed a 1D forward FFT of these images along the x-dimension. The 1D FFT yielded Fourier spectra of portal and Cherenkov frontal images $\hat{E}_H(u', z')$ and $\hat{C}_H(u', z')$, respectively (see Fig. 3.b and Fig. 3.d). A series of 1D integral convolution kernels $\hat{S}_H(u', z')$ was then calculated as a complex magnitude of the ratio $|\hat{E}_H/\hat{C}_H|$ for each z (Fig. 3.e). Next, a set of 2D convolution kernels $\hat{S}(u', v', z')$ were reconstructed from $\hat{S}_H(u', z')$. The distributive property of this convolution allowed reconstruction of the real-space 2D radial convolution function from its integral projection $\hat{S}_H(u', z')$ using the inverse Abel transform. The radial 3D convolution kernel $\hat{S}(u', v', z')$ was reconstructed by performing a series of inverse Fourier, inverse Abel, and forward first-order Hankel transforms on $\hat{S}_H(u', z')$:

$$\hat{S}(u', v', z') = HA^{-1}F^{-1}\hat{S}_H(u', z') \quad (1)$$

The 3D convolution kernel $\hat{S}(u', v', z')$ represents a spatial frequency filter, which carries both depth dose distribution and scattering relation between the portal image and Cherenkov image. It is straightforward, that the final 3D dose distribution $D(x, y, z)$ can be calculated by piecewise multiplication of portal image-based spectrum $\hat{E}(u', v', z')$ by the spatial frequency filter $\hat{S}(u, v, z)$ (Fig. 4):

$$\hat{D}(u', v', z') = \hat{S}(u', v', z') \circ \hat{E}(u', v', z'), \quad (2)$$

followed by a partial inverse Fourier transform:

$$D(x', y', z') = F^{-1}\hat{D}(u', v', z'), \quad (3)$$

and by a mapping of the dose distribution D to the (x, y, z) coordinate system.

III. Results

The profile of a reconstructed beam for an 8×8 cm square beam is shown in Fig. 5, with the input RAW data from Cherenkov and EPID as well as the manufacturer's reference dosimetric dataset known as the Golden Beam Data (GBD, Varian Medical Systems) [14]. The GBD constitutes a set of the commissioning beam data required by treatment planning system, and the LINACs are verified to deliver the dose within 1% accuracy compared to the GBD. The reconstructed EC3D result shows the best agreement to the GBD profile in both the top of the beam as well as in the penumbra wings. The scatter present in the raw EPID data can be clearly observed in the wings outside the beam profile. To quantify the agreement between the reference GBD profile and reconstructed crossbeam profile, we used the Gamma index method as proposed in [14]. The cross-beam profile Gamma analysis using a 3%/3mm distance-to-agreement criteria is shown in the graph below the profiles, indicating 100% pass rate ($\Gamma = 1$ for all data points). The 3% dose difference was measured relative to the point of maximum dose. A custom VMAT plan for the TG-119 C-shape geometry was used as a dynamic treatment to visualize the EC3D capabilities. Images of the Cherenkov lateral depth dose images (top) and the EPID transit images (bottom) are shown in Fig. 6 a) for 40 time points during the delivery. The entire stack of image data was processed in the algorithm, and individual time-integrated points of the 3D recovery are shown in Fig. 6 b). To assess the spatial accuracy of Cherenkov imaging, we performed a global Gamma analysis between the integrated Cherenkov image (Fig. 7 b) and the lateral projection of the TPS calculated dose distribution (Fig. 7 a) using a 3%/3mm agreement criterion. The measured integrated Cherenkov image was normalized to the Eclipse plan. The analysis reported 85.4% pass rate, with the largest mismatch in the inner low dose, high gradient area (Fig. 7 c).

IV. Discussion

The presented results confirmed the feasibility of online 3D dose reconstruction of dynamic and intensity-modulated plans from cine EPID and Cherenkov image data streams. The EPID image was used primarily for geometric 3D beam definition, while the Cherenkov image served for correction of the depth dose and X-ray scatter distribution. The uniqueness of our approach lies in an efficient FFT algorithm that was used for merging orthogonal images. Despite the sparsity of the dataset and proof-of-concept stage of the EC3D method, we achieved 100% Gamma pass rate of the cross-beam profile of a square-profile static beam, when compared with reference dosimetric dataset. Gamma analysis with more stringent 1%/1mm criteria yielded pass rate of 85.5%, indicating possible usability of EC3D for reference dosimetry. The Gamma analysis of laterally-projected VMAT dose distribution revealed discrepancies in the low dose, high gradient areas distant from the isocenter. The possible explanations include geometrical aberrations of the Cherenkov imaging system or incorrect depth dose distribution due to energy dependency of the Cherenkov emission mechanism [16]. The latter case might lead to decreased intensity in the buildup region due to the rejection of low-energy photons and electrons [17]. Furthermore, the reconstruction of diagonal beams delivered to a rectangular phantom might be less accurate due to a slightly different propagation depth across the cross-beam profile. This issue could be mitigated by using a rotationally symmetric phantom. Importantly, the presented 3D reconstruction

algorithm may also be readily employed in the 3D plastic and liquid scintillator imaging modalities [18].

V. Conclusion

A methodology to achieve dynamic volumetric dose reconstruction from combined EPID and Cherenkov images has been demonstrated for the first time. The reconstruction algorithm was described and the approach was experimentally demonstrated indicating feasibility of a real-time EPID-Cherenkov dosimetry technique. We have illustrated the reconstruction of cumulative dose deposited to a water phantom by a VMAT plan for TG-119 C-Shape geometry. This preliminary development has interesting potential for translation to a system for real time verification of treatment plans in patients, once fully developed and optimized for acquisition and image recovery.

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Fig. 1.

a) Schematic experimental setup for the EPID-Cherenkov 3D dosimetry; b) illustration of the portal and Cherenkov imaging geometry; c) measured 3D cumulative dose map produced by a custom TG-119 C-Shape VMAT plan (6MV, 200 cGy) X-ray beam in a water phantom. The coordinate system of the water tank is (x, y, z) . The coordinate system of the X-ray beam is (x', y', z') , where axis z' is coincident with the beam axis.

Fig. 2.

Schematic diagram of the reconstruction algorithm. The algorithm processes input portal and Cherenkov frames $E(x', y')$ and $C_F(x, z)$, respectively, after each readout event, and returns the reconstructed dose volume $D(x, y, z)$.

Fig. 3.

Input images and intermediate results produced by the reconstruction algorithm. a) The integral frontal view of the portal image-based volume $E_F(x', z')$ and b) the magnitude of its 1D partial fourier transform $\hat{E}(u', z')$; c) the acquired Cherenkov image and d) the magnitude of its 1D partial fourier transform $\hat{C}(u', z')$; e) the portal (red) and Cherenkov (blue) spectral magnitudes at depth $z = 100$ mm, and their ratio $\hat{S}(u')$ (black); f) a single slice of the 3D convolution kernel $\hat{S}(u', v', z')$ at depth $z = 100$ mm.

Fig. 4.

The $E(x', y')$ image subsets of the portal image-based volume $E(x', y', z')$ are iteratively 2D convolved with subsets of 3D convolution kernel $S(x', y', z') = F^{-1}\hat{S}(u', v', z')$, yielding the 3D dose distribution $E(x', y', z')$. This convolution is an equivalent representation of the $\hat{D}(u', v', z') = \hat{S}(u', v', z') \circ \hat{E}(u', v', z')$ multiplication in the presented algorithm.

Fig. 5.

The comparison of the reconstructed cross-beam dose distribution with GBD [13], Cherenkov image, and portal image profiles. All cross-beam profiles were normalized. The transverse beam size at the isocenter was 8×8 cm, beam energy was 10 MV. Bottom graph shows reconstructed cross-beam profile Gamma pass rate (3%/3 mm criterion).

Fig. 6.

a) The temporal evolution of the C-shape VMAT plan delivery, captured by Cherenkov images and portal images during the first (top) and second (bottom) field delivery; b) snapshots of the reconstructed cumulative dose at five different time points of VMAT plan delivery.

Fig. 7.

Lateral projection of the cumulative dose distribution in the water phantom at the end of Field 2 of C-shape VMAT plan delivery, as calculated by Eclipse treatment planning system (a), and as recorded by the Cherenkov camera (b). The global Gamma analysis (c) of the planned vs. Cherenkov projected dose distributions reported 85.4% pass rate with 3%/3mm criteria.

TABLE I

General characteristics of portal and Cherenkov imaging modalities

	Portal imaging	Cherenkov imaging
Equipment	Standard equipment	Additional equipment
Linearity	Linear with dose	Linear with dose
Readout speed	Fast readout (> 10 fps)	Fast readout (> 10 fps)
Resolution	High resolution (< 1 mm)	High resolution (< 1 mm)
Geometry	Beam's eye view of transmitted dose ¹⁾	Side view of deposited dose ²⁾
Target	Water equivalent target	Water equivalent target
Main limitations	Penumbra scatter error ²⁾	No depth resolution ¹⁾