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Real-time 3D dose imaging in water phantoms: reconstruction from simultaneous EPID-Cherenkov 3D imaging (EC3D)

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Abstract. Combination of electronic portal imaging device (EPID) transmission imaging with frontal Cherenkov imaging enabled real-time 3D dosimetry of clinical X-ray beams in water phantoms. The EPID provides a 2D transverse distribution of attenuation which can be back-projected to estimate accumulated dose, while the Cherenkov image provides an accurate lateral view of the dose versus depth. Assuming homogeneous density and composition of the phantom, both images can be linearly combined into a true 3D distribution of the deposited dose. We describe the algorithm for volumetric dose reconstruction, and demonstrate the results of a volumetric modulated arc therapy (VMAT) 3D dosimetry.

1. Introduction

Using visible Cherenkov radiation as a surrogate of the dose distribution in water phantoms is a promising method to perform fast quality assurance (QA) and relative dosimetry of megavoltage photon and electron beams [1,2]. Since the first demonstration of direct visualization of dose deposition in a clinical setting [3], Cherenkov imaging has been tested in many applications of clinical radiation dosimetry [4,5]. In a previous study [6] we demonstrated a tomographic 3D reconstruction of dose in a water phantom via tomographic acquisition of the Cherenkov light distribution in a 180° scan. This required several minutes of acquisition time which is prohibitive for imaging dynamic beam modalities such as volumetric modulated arc therapy (VMAT).

We have addressed the challenges of fast 3D dosimetry [7] by developing a technique that allows for real-time dose imaging in water phantoms. As shown in Figure 1, the method – EPID-Cherenkov 3D dosimetry (EC3D) – relies on simultaneous acquisition of EPID images and lateral Cherenkov images. While the EPID provides a 2D transverse distribution of transmitted beam, the Cherenkov imaging provides an accurate lateral view of the dose. Assuming a homogeneous density and composition of the phantom, as true in water tanks, both images can be linearly combined into a consistent 3D distribution of the deposited dose. Most importantly, both EPID and Cherenkov techniques provide images with high frame rates (~10 fps) which permits real-time 3D beam reconstruction. In this contribution we present the means of dynamic volumetric dose reconstruction by combining the EPID and Cherenkov image information in a straightforward manner. The reconstruction is demonstrated using a custom VMAT plan for the AAPM Task Group 119 (TG-119) C-Shape geometry [8].
2. Methods

2.1. Experimental setup
The experiment was conducted in a clinical radiotherapy setting using a Varian TrueBeam™ LINAC (Varian Medical Systems, Palo Alto CA, USA), equipped with an HD120™ high definition multi-leaf collimator (MLC) and an AS1000 EPID detector. As a target we used a 30x40x30 cm water phantom, consisting of 1.0 g/L solution of Quinine Sulfate (99% Quinine hemisulfate monohydrate, Alfa Aesar, Ward Hill, MA) solution in tap water. 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 [6]. The EPID was positioned at a source-to-EPID distance of \( SED = 150 \text{ cm} \) during both static beam and VMAT delivery. Cine-mode EPID images were acquired with 10fps and saved in DICOM format. The EPID featured a symmetric pixel pitch of 0.384 mm in the detector plane. The Cherenkov images were captured by a time-gated intensified Charge-Coupled Device (ICCD) camera PI-MAX4 1024i (Princeton Instruments, Acton, MA) equipped by 135 mm f/2 lens, yielding a 0.257 mm/pixel theoretical resolution. The camera was located on the rotational axis of the LINAC gantry at a distance of 3 m from isocenter. The intensifier gate of 3.8 \( \mu \text{s} \) 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 for TG-119 C-Shape geometry was created in the Eclipse treatment planning system (TPS) (Varian Medical Systems, Palo Alto CA, USA) and was designed to deliver 200 cGy at \( D_{\text{max}} \).

2.2. 3D image reconstruction
As illustrated in Figure 2, the 3D reconstruction consisted of three consecutive steps. First, a 3D perspective projection of the EPID image was generated by mapping the EPID intensity onto a perspective-transformed 3D coordinate system (shown in Fig 2a). Second, a 3D correction factor was created from the ratio of projected EPID and Cherenkov images (shown in Fig 2b). Third, the EPID projection was multiplied by the correction factor yielding a relative dose distribution (shown in Figure 2c). The reconstruction was performed for each frame of the EPID and Cherenkov image pair.
Figure 2. Steps involved in the 3D dose reconstruction process. 1) A 3D EPID volume is created (a) and piecewise multiplied by Cherenkov correction factor (b), yielding a 3D dose volume (c).

2.2.1. EPID perspective projection

The 2D EPID image, represented by values $E(x, y)$, as well as the true spatial coordinates $(x, y)$ and gantry angle $\alpha$ were read from the individual EPID images. To prepare the EPID image for 3D transformation, a 3D EPID volume $E(X) = E(x, y, z)$ was created by replicating the EPID image normal to its plane at incremental $z$ distances. Then, a perspective transform $T : (x, y, z) \rightarrow (x', y', z')$ was applied to $E(X)$ by forward-mapping its coordinates $X$ via transformation matrix $T$

$$X' = TX$$

yielding a perspective-transformed EPID volume:

$$E(X') = E(TX)$$

The transformation matrix $T$ must include the setup geometry (source-to-EPID distance $SED$, source-to-isocenter distance $SSD$, and size of the EPID volume) as well as the gantry rotation $\Theta$ relative to the horizontal $(x', y')$ plane. The matrix was thus composed of sub-matrices $T_1$ to $T_5$:

$$T = T_5 T_4 T_3 T_2 T_1$$

whose order follows the logical steps during reconstruction. These steps include $T_1$, translation of the geometrical center $(x_c, y_c)$ of EPID image to the geometric origin; $T_2$, perspective projection towards a point at the source-to-EPID distance $SED$; $T_3$, translation to the center of gantry rotation ($SED-SSD$), $T_4$, rotation around gantry rotation axis $y$ by angle $\Theta$, and $T_5$, translation to the isocenter $(x_c, y_c, z_c)$:

$$T_1 = \begin{bmatrix} 1 & 0 & 0 & -x_c \\ 0 & 1 & 0 & -y_c \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & SED-SSD \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_3 = \begin{bmatrix} \cos \Theta & 0 & -\sin \Theta & 0 \\ 0 & 1 & 0 & 0 \\ \sin \Theta & 0 & \cos \Theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_4 = \begin{bmatrix} 1 & 0 & 0 & x_c \\ 0 & 1 & 0 & y_c \\ 0 & 0 & 1 & z_c \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$
A cubic interpolation between neighboring points was used to calculate the final voxel intensity values.

2.2.2. Cherenkov correction

The Cherenkov correction factor acts on the projected EPID volume. It was defined for each voxel row in superior-inferior (y) direction, and its magnitude was defined as an intensity ratio of the Cherenkov image and summed EPID image:

\[ C(x', z') = I_{ch}(x', z') \left( \sum_y E(X') \right)^{-1} \]  
(5)

The ratio results from the fact that the Cherenkov image represents a measured dose, summed in y-direction. The resulting 2D correction factor \( C(x', z') \) was then replicated along the y-axis over the range of the EPID volume. A piecewise multiplication of EPID volume and 3D correction factor finally yielded the 3D dose distribution within the reconstructed volume:

\[ D(X') = C(X') \circ E(X') \]  
(6)

Here the \( \circ \) operator symbolizes a Hadamard product.

3. Results

To demonstrate the feasibility of our technique, we acquired and reconstructed a dynamic 3D dose map from the delivery of a VMAT plan in TG-119 C-Shape geometry. In Figure 3 we present the intermediate results of EPID back projection, raw Cherenkov images and Cherenkov correction factors, as well as the final 3D accumulated dose volume for 10 out of 320 frames from the VMAT plan delivery.

![Figure 3](image_url)

**Figure 3.** Sample of 10 intermediate and final results from the full course of VMAT delivery. Rows top to bottom: a) lateral view of back projected EPID; b) Cherenkov image; c) lateral view of Cherenkov calibration factor; d) final 3D view of accumulated dose.

4. Conclusions and discussion

We presented a dynamic volumetric dose reconstruction by combining information from EPID and Cherenkov images. Namely, this process described the means of 3D post-processing, and demonstrated the feasibility of our technique. Known issues of EPID image fidelity due to internal scattering and readout artifacts [9] are being addressed. In future work we will validate the EC3D technique further by quantitative comparison with ionization chamber measurements, as well as simulated dose distribution from the treatment planning system and Monte-Carlo calculations. It is hypothesized that the proposed
technique may have a large impact in clinical pre-treatment plan verification and quality assurance due to the high spatial and temporal resolution of the measured 3D dose distributions it provides.

5. Acknowledgement
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