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Research Paper

Optimizing the CBCT Technique and Analysis for LINAC Synchronized NIPAM 3D Dosimetry

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Abstract

Linac Synchronized NIPAM (LS-NIPAM) 3D dosimetry utilizes on-board CBCT to read 3D dosimeters, while the measured dose is inherently synchronized with the on-board imaging coordinate system. The main issues are the limited signal strength and the lack of reliable and widely available analysis tools. Our goal is to develop a practical LS-NIPAM 3D dosimetry system that is applicable on a wide scale for accurate 3D dosimetry. An initial irradiation consisted of a simple 3-field plan (6 MV-FFF, 25 Gy), then an AAPM TG119 C-Shape plan was used as a clinical verification. We compared iterative and standard reconstruction algorithms as well as the impact of a variety of imaging metrics on NIPAM image quality. VistaAce (v 0.7) was used for data analysis. The Contrast to Noise Ratio (CNR) increased considerably when the iterative reconstruction algorithm was used (4.7 to 11.8). The measured dose agreed with the dose from the treatment planning system for the 3-field plan, with a pass rate of 95.6% for 3%3mm and 94.5% for 5%2mm. The results from VistaAce were verified via a second analysis using MATLAB and 3D Slicer with both analyses methods in agreement. The initial analysis of the TG119 C-Shape plan shows promising agreement. The developed CBCT technique demonstrated high CNR and high agreement with TPS dose which uses averaged pre-irradiation CBCTs subtracted from averaged post-irradiation CBCTs and using an iterative reconstruction technique. The VistaAce software shows promise as a robust and widely applicable 3D dosimetry analysis tool, including for LS-NIPAM 3D dosimetry.

Keywords: 3D polymer gel dosimetry; NIPAM gel; Iterative reconstruction; Cone Beam-CT.

Introduction

Radiation therapy is one of the primary treatment modalities for treatment of cancer[1], whether for curative or palliative goals. With the transition from 3D External Beam Radiation Therapy (3D EBRT), to advanced techniques such as Intensity modulated Radiation Therapy (IMRT) and Stereotactic Radio-Surgery (SRS and SBRT), the main goals of radiation therapy remain the same: to safely increase the amount of radiation dose a tumor receives, and to protect the surrounding healthy tissues from radiation induced toxicity. With the implementation of these techniques incorporating small fields and high dose gradients, 1D/2D quality assurance methods (ion chambers, TLDs, films) are bounded by the limited sampling in measurements and the missed planning and delivery errors, which is insufficient to provide a truly comprehensive and convenient dose measurement in 3D [2,3]. Recent studies focused on radiation sensitive gels for validating 3D dose distribution [4,5]. Polymer gel dosimeters indicate a radiation induced polymerization when exposed to high energy ionizing radiation, and this reaction can be readout using, MRI, x-ray CT or optical CT.

X-ray CT is a promising option for 3D dosimeter readout, due to its availability in the radiation oncology facility and high image quality, but the fact that the dosimeter must be moved before and after irradiation is a limitation. In IMRT, VMAT and SRS/SBRT, the slightest movement can have large clinical impact and the margin for error can be very tight. Thus, eliminating the need to move the dosimeter between irradiation and readout, and thus "register" the planned and measured dose distributions, would be a significant advantage for 3D dosimetry. Linac-Synchronized CBCT NIPAM based 3D dosimetry system (LS-CBCT NIPAM) is a promising option, as the readout is carried out using on board kV-CBCT instead of a separate diagnostic CT scanner[6,7]. However, the decreased image quality of kV-CBCT is an added challenge. In addition, while kV-CBCT is widely available, there are few sophisticated analysis tools for 3D dosimetry that are as widely available, as MATLAB in-house scripts that can be time consuming and difficult to adjust to each clinic's needs, thus still limiting the potential applicability of LS-NIPAM 3D dosimetry.

Since basic properties of NIPAM dosimeter readout using X ray CT or CBCT were investigated in previous studies[4-8], the goal of this study is to develop a practical LS-NIPAM 3D dosimetry system that is applicable on a wide scale for accurate 3D dosimetry. We accomplish this through the following sub-goals: (a) improve the image quality of LS-NIPAM by optimizing a slow rotation CBCT technique, (b) develop a practical analysis workflow for a newly developed 3D dosimetry analysis software, and (c) demonstrate feasibility via clinical application of LS-CBCT NIPAM based on a treatment plan from TG119.

Material and Methods

For the current study, two 3D NIPAM dosimeters were fabricated at the 3D dosimetry laboratory (Department of Radiation Oncology, Duke University, Durham NC, USA). The first dosimeter (10 cm diameter), was used to investigate (a) the performance of the slow rotation CBCT technique/configuration, (b) the optimal reconstruction algorithm (Standard vs Iterative) and the reliability of VistaAce (Modus QA) as an analysis tool. The second dosimeter (15 cm diameter) was a direct clinical application of the TG119 C-Shape plan.

NIPAM gel fabrication

The NIPAM gel formula used in this study is based on a previously established fabrication process that has been previously optimized for CT based NIPAM 3D dosimeters [2,3]. It consists of using: 75.5% of deionized water, 5% gelatin (Sigma-Aldrich, Oakville, ON, Canada), 15% N-isopropylacrylamide (NIPAM, TCI America, Portland, OR, USA), 4.5% N, N′-methylenebisacrylamide (BIS, Sigma-Aldrich) and 5 mM tetrakis hydroxymethyl phosphonium chloride (THPC, Sigma-Aldrich). The fabrication process is illustrated in Figure 1. For a safe preparation of the gel, safety measures were taken while interactiong with NIPAM and THPC.

Dosimeter irradiation

A simple 3-field irradiation[9] plan was used as a test of both the gel response to irradiation (polymerization process) and the CBCT imaging technique to be used in subsequent studies (clinical applications). The gel was allowed to set to room temperature prior irradiation, then it was positioned on the table for pre-post images and plan delivery. 25 Gy was delivered to a 10 cm jar (1L of NIPAM gel) using an energy of 6 MV and a field size of 3x7cm^2 as shown in Figures 3A, 3B and 3C.

A second irradiation was delivered based on TG119 C-shape IMRT commissioning plan[10] [TG119 ref]. The target is a C-shape that surrounds a central avoidance structure. The center core is a cylinder 1.9 cm in radius. The gap between the core and the PTV is 0.5 cm, so the inner arc of the PTV is 1.5 cm in radius. The outer arc of the PTV is 3.7 cm in radius. The PTV is 8 cm long and the core is 10cm long. A 15 cm jar was used (2L of NIPAM gel) for this irradiation and 25Gy was delivered using 6 FFF MV.

Dosimeter imaging

Pre- and post-scans were acquired using the on-board imager on the Varian TrueBeam Linac. Previous study [11] showed that, unlike the normal rotation CBCT mode, the slow rotation CBCT mode (increased imaging dose) provides accurate visualization and detection, especially for SRS treatments. The CBCT scan configuration used in this study was based on the slow rotation technique and used the following settings for both reconstruction algorithms: exposure of 1065 mAs, tube current of 100 kV, 5327 projections, 1 degree per second gantry speed, 1mm slice thickness, 512 pixels matrix and smooth filter for reconstruction. Once irradiated, we waited for 35 to 40 minutes, as recommended in a previous study[7], so that the polymerization process (as a response to irradiation) can be fully completed.

Iterative reconstruction algorithm (iterative_CBCT) uses a finite element solver (AcurosCTS)-based scatter correction and a statistical (iterative) reconstruction[12], which improves image quality for both phantom and clinical patient dataset. A comparison between iterative_CBCT and standard_CBCT was carried out while optimizing the imaging technique for the LS-CBCT

NIPAM 3D dosimetry system, and accordingly 6 pre- and 6-post-scans were acquired for image averaging[7].

Analysis process

Image quality was investigated through a Contrast to Noise Ratio calculation using an in-house MATLAB code. Dosimetric analysis was done using VistaAce v0.7.4 (Modus QA), which is a commercial software, designed for 3D dosimetry, and is currently under development. It can perform registration of a dose plan with an optical scan and perform various analytics on the registered results[13]. Since it was mainly developed for radiochromic 3D dosimeters readout by optical CTs, it had to be modified in collaboration with the vendor as part of this work to handle NIPAM dosimeters readout by LS-CBCT. The pre- and post-scans were uploaded to VistaAce for analysis (DICOM image format). As shown in the detailed analysis diagram (Figure 2), the first step, after importing the DICOM images, was to average the images then subtract the pre-averaged-scan from the post-averaged-scan (background subtraction). A spatial registration was as applied to verify that the planned and the measured data use the same coordinate system and adjust the dosimeter's positioning as shown in Figure 2. The radiation induced polymerization is translated to HUs, which needs to be converted to dose in order to proceed with the analysis. Therefore, a best fit calibration was applied by selecting several points inside the region of interest of the gel, which excludes the jar walls and lid. The software, then, provides an automatic calibration equation that can be changed and validated by the user

After calibration, 3D gamma comparison was performed and line profiles were extracted from the data. A separate analysis verification was performed using an in-house MATLAB code in association with 3D Slicer v4.13.0.

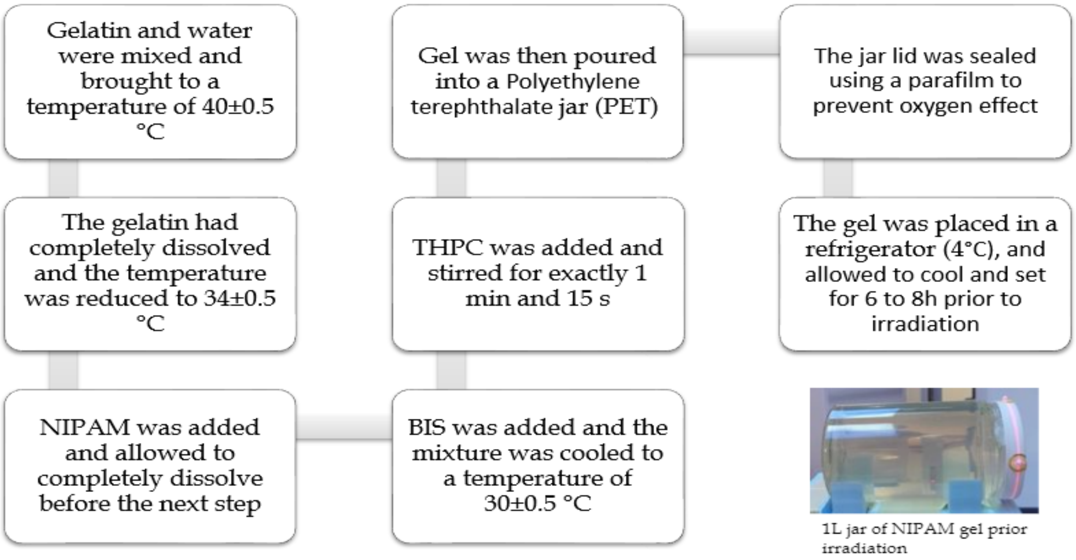

Figure 1. Step by step fabrication process of a 1L jar of NIPAM 3D dosimeter.

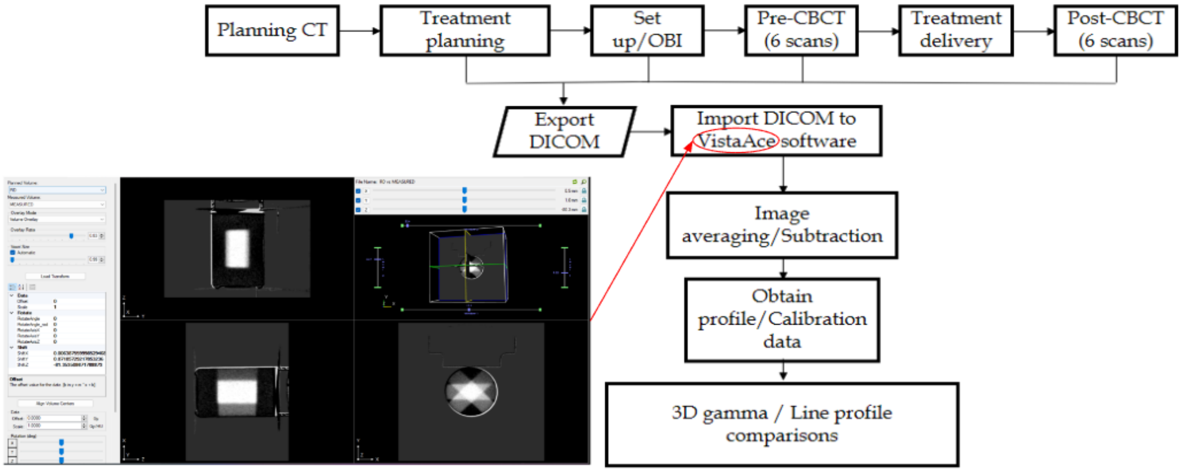

Figure 2. LS-CBCT NIPAM 3D dosimeter data analysis diagram. The screenshot shows VistaAce manual registration interface, with volumes overlaid (planned and measured).

Results

The impact of the slow rotation CBCT technique along with the iterative reconstruction algorithm, on the image quality, can be noticed visually, as shown in Figures 3D, 3E and quantified through the contrast to noise ratio calculations. The CNR of 6 images reconstructed by the standard algorithm (CNR=4.7) was not even equivalent to the CNR of one single image reconstructed by the iterative algorithm (CNR=10.3).

As a part of this project, VistaAce was modified in collaboration with the vendor, so it can handle NIPAM dosimeter data. The modifications were mainly applied to the manual registration, calibration process and data import/export.

The best fit calibration confirmed the proportionality between the polymerization chain and the delivered dose (Figure 4) which results in a linear calibration equation.

As shown in Table 1 and Figure 5A, the 3D gamma analysis of the 3-field irradiation data showed an agreement between the measured data and Eclipse treatment plan for both reconstruction methods. In comparison, data analyzed using MATLAB and 3D Slicer agreed with the treatment planning system with a Gamma index passing rate of 96.52% and 92.82% using 3%/3mm and 5%/2mm criteria, respectively with an average uncertainty of 0.184%. Line profiles in Figure 5B confirm the agreement between the TPS and the measured data. The difference between the two plots can be due to analysis artefact (Calibration), or oxygenation effect. This will be investigated in future studies.

Initial analysis of the TG119 C-shape plan presents promising results. The gel response was as expected in Figure 7, the density change followed the target volume's shape, and the initial series of 3D gamma analysis for 3%3mm was over 90%.

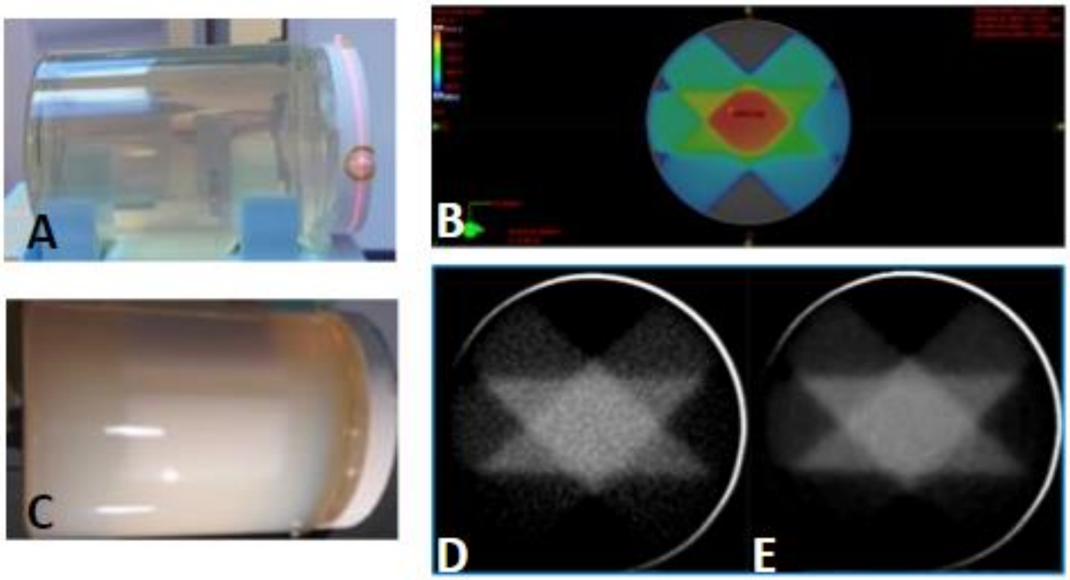

Figure 3. (A) NIPAM gel jar prior irradiation (B) Eclipse treatment plan of the 3-field irradiation (C) NIPAM gel after 3-field irradiation (D) Central axial slice of NIPAM 3D dosimeter reconstructed using standard algorithm. (E) Central axial slice of NIPAM 3D dosimeter reconstructed using iterative algorithm..

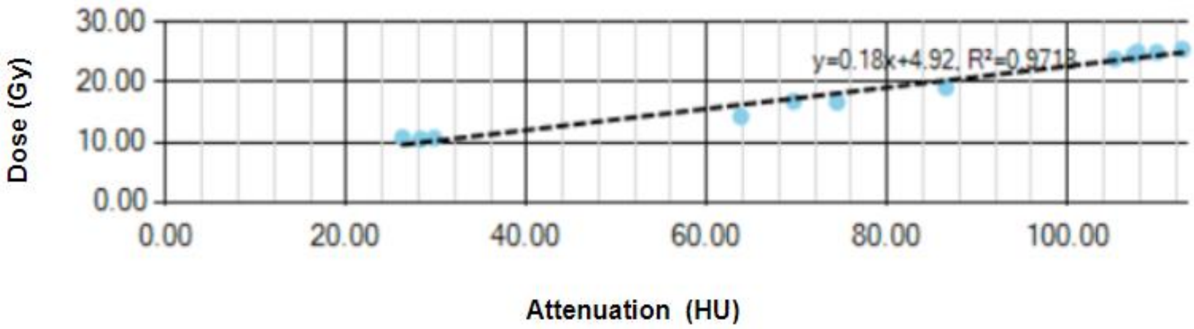

Figure 4. Calibration Curve of the NIPAM jar used in this study.

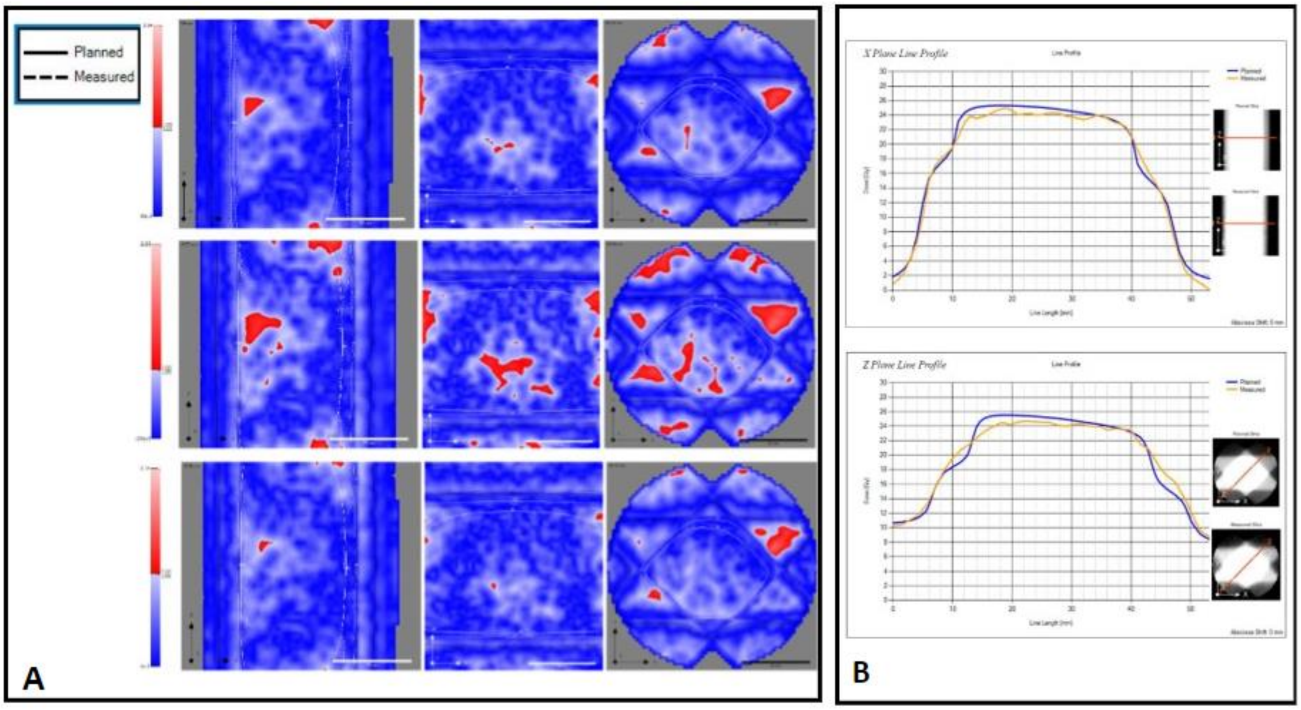

Figure 5. A: Gamma maps (iterative_CBCT data) for 3%/3mm (Top), 3%/2mm (Middle) and 5%/2mm (Bottom). B: Line Profiles across X plane (Top), and Z plane Bottom).

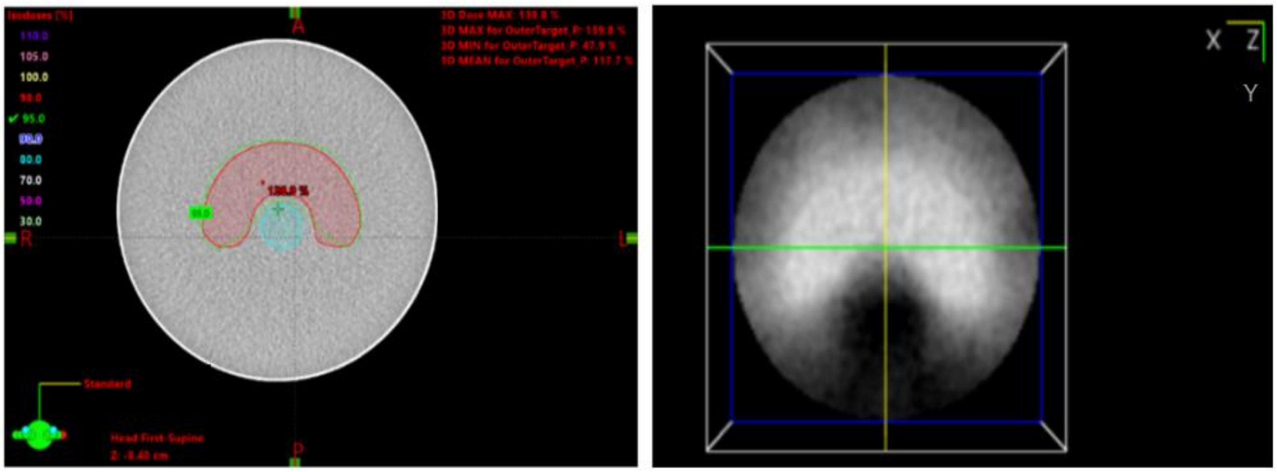

Figure 6. (Left) Eclipse treatment plan of the TG119 c-shape plan, (Right) NIPAM dosimeter response after the TG119 C-shape plan delivery.

Table 1. Gamma pass rates of iterative and standard reconstruction data analyzed with VistaAce software

	Iterative Reconstruction	**Standard Reconstruction**
3%/2mm	88.89%	80.452%
3%/3mm	95.626%	95.889%
5%/2mm	94.48%	86.832%

Conclusions

This work introduces a 3D dosimetry technique with potential wide-spread adoption – requiring common imaging equipment available in typical RadOnc departments with CBCT capability. An optimal CBCT technique includes slow rotation CBCT all along with iterative reconstruction.

Abbreviations

Linac: Linear Accelerator; CBCT : Cone Beam CT; NIPAM: N, N′-methylenebisacrylamide; FFF: Flattening Filter Free; AAPM TG-119: American Association of Physicists in Medicine Task Group-119; CNR: Contrast to Noise Ratio; PTV: Planning Target Volume.

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Author Contributions

All authors contributed to this study. All authors gave their final approval.

Competing Interests

We declare no competing interests.

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