Development of a practical clinical application of NIPAM kV-CBCT dosimetry

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Abstract. We report our progress towards developing a clinical application of NIPAM kV-CBCT dosimetry. The goal is to develop a practical kV-MV isocenter verification test for which the measurement and analysis can be carried out quickly (within an hour), and that eliminates the need for separate readout (other than on board kV-CBCT) or extra analysis steps such as image registration. Isocenter verification is performed using a NIPAM 3D gel dosimeter which is irradiated with a small field to ~16Gy at eight unique couch/gantry angles. Pre- and post-irradiation kV-CBCT images are acquired and dose is manifest as the intensity difference between pre- and post-CBCTs due to radiation induced changes in density. Code was developed to detect the geometry of each beam in the kV-CBCT and quantify relevant parameters. We applied this technique to verify the isocenter for MLCs as well as for SRS cones. The measured radius to encompass all beams for 4mm, 6mm, 7.5mm, 12.5mm, and 15mm cones was 0.55±0.11mm. The efficiency, robustness to setup errors, and unique ability to visualize spatial uncertainties in the kV-CBCT coordinate system make the NIPAM kV-CBCT test a practical and unique tool for kV-MV isocenter verification.

1. Introduction
Advances in patient imaging have significantly improved the workflow of treating patients with stereotactic body radiation therapy (SBRT) and stereotactic radiosurgery (SRS). A major breakthrough in patient imaging is the use of a kilovoltage (kV) imaging system attached to the linear accelerator that is capable of acquiring cone-beam computed tomography (CBCT) images [1]. This is especially useful during SBRT/SRS for the verification of patient alignment [2] and the evaluation of organ motion [3] throughout the course of treatment. On-board kV-CBCT is also increasingly replacing external stereotactic frame systems, which require fixing the unit to the patient’s skull, by aligning a frameless mask using the imaging system [4].

Because of the critical clinical roles in which the kV-CBCT system takes part during patient treatment, the spatial accuracy of the radiation and imaging system is of high importance. This is tested and verified at regular intervals depending on the utilization of the linear accelerator [5]. Three-dimensional (3D) dosimetry systems may offer more comprehensive QA tests and provide information about the dose distributions achieved by techniques such as SBRT/SRS [6]. In this study, we demonstrate the use of kV-CBCT dosimetry to verify the spatial accuracy of the kV-MV isocenters. kV-CBCT dosimetry is enabled by N-isopropylacrylamide (NIPAM) polymer gel dosimeters. These are fabricated from radiation sensitive materials; when irradiated, a change in density occurs due to polymerization [7]. Visualization of the dose is made possible due to the change in density also causing...
a change in intensity [8] in the kV-CBCT image. Specific formulations of NIPAM gel dosimeters have been optimized for x-ray CT dosimetry, and are useful due to their reduced toxicity [9] and high sensitivity for x-ray CT [10]. Previous work [11] has demonstrated the use of NIPAM dosimeters for comprehensive verification of the radiation isocenter uncertainty and coincidence with the kV-CBCT imaging system using only three collimation systems.

Our purpose here is to report our progress towards developing a practical kV-MV isocenter verification test using NIPAM kV-CBCT dosimetry. We also apply this test for various clinical scenarios, including verification of all SRS cones, as well as before and after scheduled isocenter alignment maintenance of a Varian TrueBeam STx.

2. Materials and Methods

2.1. Isocenter verification test

NIPAM dosimeters were prepared at Duke University using an established formula [8]. The gel was poured into 16oz. Polyethylene Terephthalate (PET) plastic cylindrical jars (7.5cm diameter and 13.1cm height). To minimize oxygen effects, mineral oil was poured on top of the gel to displace oxygen and the top covered with parafilm prior to capping. The dosimeters are placed in a refrigerator to set (6-8 hours) and stored there until ready for use.

The isocenter verification test begins by immobilizing the dosimeter on the treatment table. In our initial tests, immobilization was accomplished by placing the dosimeter in a make-shift Styrofoam apparatus, and securing it further with masking tape. However, this was later replaced with a more secure thermoplastic immobilization in order to increase the spatial accuracy of the test. A CBCT image is then acquired. A slow-rotation CBCT scan is used to increase the number of projections from 895 (in a standard scan) to 5,330. The following settings were used: 125 kVp, 5130 mAs, 1mm slice thickness, smooth reconstruction. The dosimeter is then irradiated at eight unique gantry/couch angles, chosen specifically so that they do not overlap except at the isocenter. A post-irradiation CBCT is immediately acquired using the same settings as the pre-irradiation CBCT. All DICOM files are then exported to Matlab for analysis.

The Matlab code determines beam geometry using an iterative optimization process that maximized the contrast-to-noise ratio (CNR) of the high-dose regions relative to the low-dose (background). The CNR is calculated using a contrast and background weighting for each voxel of the CBCT image.

2.2. Clinical applications

The isocenter verification test was previously reported for three collimation systems: 4mm cone, 7.5mm cone, and 10mm diameter MLC field [11]. Here we perform the test on the remaining SRS cone sizes (6mm, 10mm, 12.5mm, and 15mm). Both automatic and manual analysis are performed using the Matlab code developed in house.

A second clinical application of the isocenter verification test is to detect kV-MV isocenter misalignment due to machine drift. Prior to maintenance of the isocenter alignment on a Varian TrueBeam STx, the comprehensive isocenter verification test was performed using 10mm diameter MLC fields. After maintenance was complete, the test was again performed using 5mm MLCs. For this specific test, the conformal thermoplastic radiotherapy mask was used (as demonstrated in Figure 3). The results were compared with the ISO lock measurements provided by the vendor.

3. Results and Discussion

3.1. Isocenter verification test

Figure 1 is a photograph of various dosimeters which illustrates the irradiation geometry for various collimation systems. Setup, irradiation, and imaging using the slow-rotation CBCT scan could be completed in approximately 50 minutes. While the slow scan does increase the number of projections,
it also greatly increases the time required for image acquisition (6 minutes per scan). Figure 2 shows the axial slice of the pre-irradiation CBCT, post-irradiation CBCT, and subtracted CBCT with a mask applied for the isocenter verification test performed using the 5mm diameter MLC field.

Figure 1. Unirradiated dosimeter (left) and irradiated dosimeters with increasingly larger field sizes.

Figure 2. Axial slices of the pre-CBCT (left), post-CBCT (middle), and subtracted CBCT with a mask applied (right) using 5mm diameter MLC field.

The creation of a custom thermoplastic immobilization better secured the NIPAM dosimeter as demonstrated in Figure 3. Dosimeter shift is more pronounced on the outer edge of the dosimeter immobilized in the Styrofoam apparatus when compared to the thermoplastic immobilization. Figure 3 also shows the improved image quality of slow-rotation CBCT versus a standard CBCT, due to increasing the number of projections.

Figure 3. Subtracted (pre-CBCT from post-CBCT) images of the NIPAM dosimeter. The edge artifact indicates dosimeter shift during irradiation, which is less pronounced with thermoplastic immobilization (right). Improved image quality for slow-rotation CBCT (left) is also apparent.
3.2. Clinical applications

Table 1 shows the results of the automatic analysis for the SRS cones performed in this report. In comparison, traditional star shots indicated a minimum tangent circle radius of 0.28mm for the same machine. Winston-Lutz images with MLCs indicated a 3D isocenter radius of 0.24mm, which also matched the isocenter size determined by the Varian MPC.

Table 1. Automatic analysis results of the isocenter verification test.

| Cone diameter | 6mm | 10mm | 12.5mm | 15mm |
|---------------|-----|------|--------|------|
| Dist. radiation iso to CBCT origin (mm) | 0.23 | 0.15 | 0.65 | 0.14 |
| Smallest radius intersecting all beams (mm) | 0.53 | 0.75 | 0.5 | 0.57 |
| Gantry accuracy mean differences (°) | 0.38±0.42 | 0.56±0.7 | 0.86±0.74 | 0.47±0.39 |
| Couch accuracy mean differences (°) | 0.01±0.45 | -0.08±0.66 | -0.29±1.53 | -0.07±0.55 |

Prior to maintenance, the machine isocenter diameter measured by the vendor was 0.976mm. After maintenance, this value decreased to 0.519mm. Our results using the NIPAM isocenter verification test with a 10mm MLC field before maintenance showed the radial distance from the radiation isocenter to the CBCT origin was 0.45mm. After repair, the isocenter verification test with 5mm MLCs showed this value to be 0.31mm. The smallest radius to intersect all beams decreased from 0.46mm to 0.43mm before and after maintenance, respectively.

4. Conclusion

This work demonstrates the clinical applications of using the comprehensive isocenter verification test with NIPAM kV-CBCT dosimetry. The fast acquisition and analysis, unique ability to directly visualize dose in the CBCT image, and comprehensive analysis of radiation uncertainty, coincidence with the kV-CBCT imaging coordinate system, and couch and gantry angle accuracy for all collimation systems, make NIPAM kV-MV isocenter verification a unique tool for a clinical radiosurgery program.

5. References

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