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Enhancing Patient-Specific QA in IGRT: Utilizing the OCTAVIUS Detector 1600 SRS with CyberKnife

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Abstract

Objectives:

The CyberKnife is a widely used robotic image-guided radiation therapy (IGRT) linac specifically designed for stereotactic radiosurgery (SRS) and stereotactic body radiation therapy (SBRT). This system has been effectively utilized for treating various disease sites, including intracranial, spinal, and trigeminal nerve targets. SRS and SBRT are characterized by high dose-per-fraction treatments, highly conformal target absorbed doses, rapid dose fall-off, a large number of non-coplanar beams, and small penumbra margins. Accurate tumor localization, patient immobilization, and image guidance are critical for ensuring patient safety and effective treatment.

Conventional dosimetry techniques for patient-specific QA are inadequate to account for the effects of small field dosimetry with CyberKnife cones (< 10 mm diameter). Film dosimetry can present challenges in accurately quantifying absolute absorbed doses due to the necessity of a separate absolute dosimetry calibration. Moreover, commonly used 2D diode detector arrays may lack the resolution required for small targets typical in SRS and SBRT, and they may exhibit angular dependence, complicating measurements further. Small field dosimetry is particularly challenging because of the loss of lateral charged particle equilibrium, volume averaging, detector-interface artifacts, and detector position/orientation effects. Currently, commercially available detectors are being developed with enhanced spatial resolution and more accurate dose measurement capabilities for small fields utilized in SRS/SBRT treatments. This work aims to characterize the performance and measurement uncertainties of the OCTAVIUS Detector 1600 SRS for patient-specific QA using the IGRT setup exclusively on a CyberKnife linac. Additionally, it explores the necessity of a cone-specific dose calibration depending on the size and shape of the treated field.

Methods:

Three patients treated at XXX with variable target size were selected for patient-specific QA evaluation. The first patient was diagnosed with spine metastases; PTV: T8-L1 (682.23cc); 30Gy in 5fx; CyberKnife cone diameters = 7.5, 10, 12.5, 20, 25, and 40 mm. The median cone size was 16.25 mm, so dose was calibrated to the output of a 15 mm cone. The second patient was diagnosed with brain metastases; PTV: right basal ganglia (49.97cc); 23.75Gy in 5fx; CyberKnife cone diameters = 7.5, 15, and 30 mm. The median cone size was 15 mm, so dose was also calibrated to the output of a 15 mm cone. The third patient was diagnosed with trigeminal neuralgia; GTV: left trigeminal nerve (0.01cc); 75Gy in 1fx; CyberKnife cone diameter = 5 mm. Dose was calibrated to the output of a 5 mm cone.

Treatments were planned in Precision (v3.3.0.0, Accuray, Sunnyvale, CA) and dose was delivered using a CyberKnife (G4, Accuray, Sunnyvale, CA) with a 6 MV linear accelerator, source-to-axis distance (SAD) of 80 cm, and fixed cones ranging in diameter between 5 – 60 mm. Dose was measured using an OCTAVIUS Detector 1600 SRS (PTW Dosimetry, Boonton, NJ) which includes 1521 liquid filled ionization chambers with an active volume of 2.5 × 2.5 × 0.5 mm3 spaced 2.5 mm apart covering a field size of 15 × 15 cm2. Detector array setup was based on CyberKnife's image-guidance system. Two ceiling-mounted kV x-ray sources and two corresponding in-floor image detectors are orthogonally positioned to automatically adjust the robot or table position as target motion is detected.

Patient specific QA was evaluated in VeriSoft (v8.1.1, PTW Dosimetry, Boonton, NJ) using a 2D gamma index with 1 or 2 mm distance to agreement (DTA), 1, 2, or 3% dose difference, and 10% of max dose threshold. Auto-alignment in VeriSoft was not utilized in order to make our comparisons purely image-guided. Dose calibration factors (kcross) for each plan comparison were applied based on the median cone diameter used

for treatment. Dose calibration factors for individual cone diameters were calculated as expected mean dose from the treatment planning system (TPS) divided by the value measured by the center chamber of the OCTAVIUS detector.

Results:

For the patient diagnosed with spine metastases, the 2D gamma passing rate was 98.1% (2% / 2mm / 0.1Dmax threshold) and 96.5% (3% / 1mm / 0.1Dmax threshold). The median, mean, and max absolute dose differences were 0.192 Gy, 0.234 Gy, and 1.122 Gy, respectively. For the patient diagnosed with brain metastases, the 2D gamma passing rate was 99.3% (2% / 2mm / 0.1Dmax threshold) and 99.6% (3% / 1mm / 0.1Dmax threshold). The median, mean, and max absolute dose differences were 0.060 Gy, 0.089 Gy, and 0.458 Gy, respectively. For the patient diagnosed with trigeminal neuralgia, the 2D gamma passing rate was 100.0% (2% / 2mm / 0.1Dmax threshold), 100.0% (3% / 1mm / 0.1Dmax threshold), and 96.7% (1% / 1mm / 0.1Dmax threshold). The median, mean, and max absolute dose differences were 2.900 Gy, 3.356 Gy, and 10.392 Gy, respectively.

One limitation of this work is that the results rely on the CyberKnife's capacity to correct submillimeter alignment inaccuracies. During treatment, patient positioning tolerance is < 10 mm translation (x, y, z), < 1° rotation (roll and pitch), and < 3° yaw. The robot will make real-time 6D beam-by-beam offset corrections if the position offsets observed by kV image alignment checks are all less than the above positioning tolerance. If any observed position offset exceeds the tolerance, the beam will stop, and the table position will be adjusted to correct large offsets. However, inherent system positioning errors (~ 0.5 mm), as measured by End-to-End testing, cannot be further reduced, and such sub-millimeter positioning errors will be reflected in the gamma analysis. Thus, adopting a 0.5 mm DTA in the gamma analysis may have questionable validity. Additionally, the quality of gamma analysis will depend on the alignment precision of our QA plan dose distribution with the central ionization chamber of the OCTAVIUS detector.

From our plan specific choice in dose calibration, it is postulated that the accuracy of our gamma analysis could be improved by separating dose delivery by cone diameter and calibrating absorbed doses individually for each collimator to account for small field dosimetry considerations. For conventional patient-specific intensity-modulated radiation therapy (IMRT) QA, a 10 × 10 cm^2 field is typically used for dose calibration, which is generally sufficient for large fields. However, for CyberKnife treatments utilizing multiple cone sizes, some as small as 5 mm, the effects of small field dosimetry must be considered. Dose calibration to the median cone diameter is insufficient for accurately measuring absorbed doses from treatments that use cone diameters < 10 mm.

Conclusion(s):

Our experience with the OCTAVIUS detector for patient-specific QA in SRS and SBRT treatments using CyberKnife highlights its value as an essential tool. We found good gamma pass rates with all three patient cases exceeding 95%, and the lowest pass rate being 96.7% at 1%/1mm for the trigeminal case. In comparison to conventional diode arrays, the OCTAVIUS detector has smaller detector size, higher resolution sampling, and reduced angular dependence, which may yield higher gamma passing rates and decreased dosimetric uncertainty. Additionally, the OCTAVIUS detector has greater reproducibility and is more user friendly than gafchromic film. Consequently, the OCTAVIUS detector significantly enhances the overall quality of patient-specific QA for SRS and SBRT treatments with CyberKnife, instilling confidence in our ability to deliver safe and precise doses to small targets.