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Clinical Accuracy of Robotic Radiosurgery for Renal Lesions

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Abstract
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Abstract

Objective: Robotic stereotactic body radiotherapy is an emerging therapy for renal tumors. We assess intrafraction tumor motion patterns and accuracy of robotic renal radiosurgery with real-time respiratory tracking in order to derive appropriate planning target volume (PTV) margins.

Methods: We retrospectively collected delivery log files from 165 consecutive treatments of renal lesions between 02/2013 and 09/2019. All patients underwent placement of one to four radio-opaque gold fiducials in the affected kidney prior to treatment. A stereoscopic kV-X-ray system detects the three-dimensional position of the fiducials which is correlated with the patient breathing signal provided by up to three optical markers attached to the patient chest. This correlation model continuously predicts the tumor position and is updated with further image acquisitions throughout the treatment. A prediction algorithm for the breathing signal compensates the system latency of 115 ms and guides the robot motion during beam-on. To derive target motion characteristics, fiducial positions in X-ray images are utilized. The 5th to 95th displacement percentile in three dimensions is calculated to exclude erratic motion such as coughing. The error of respiratory tracking consists of four separate components: First, the model correlation error, i.e. the difference between the expected target position from the model and the actually measured position in current X-ray images. Second, the prediction error, i.e. the discrepancy between the predicted and the actual breathing pattern, which is only relevant during beam on. Third, we assume a total system accuracy of the treatment machine of less than 0.95 mm in accordance with quality assurance tolerance levels, including fiducial localization and registration errors. Fourth, kidney rotation introduces an error for non-spherical targets. We simulate the rotation of kidney lesions up to 15 degrees and compute their overlap with PTVs of different margins to assess required margins to account for rotation. To estimate final treatment margins, the 95th percentiles of these components are calculated.

Results: Most treatments were performed in a single session (85.5%), with 13.3% in three and 1.2% in five sessions. Mean fraction delivery time was 34 min with 10 min of beam on. Median tumor displacement was 10.5 (range 1.5 to 32.5) mm, 4.6 (0.6 to 14.7) mm and 2.4 (0.7 to 9.2) mm in superior-inferior (SI), anterior-posterior and left-right direction, respectively. The radial correlation error, i.e. the Euclidian distance of the correlation error, averaged over all treatments and its 95th percentile were 1.1 mm and 2.9 mm, respectively. The correlation error increased with tumor displacement and was therefore largest in SI direction (mean 0.8 mm, 95th percentile 2.0 mm). The mean prediction error and its 95th percentile were 0.3 mm and 0.6 mm. Simulation of rotation of eleven targets from different patients results in a required margin of 2 mm to achieve at least 95% coverage of the target volume. The root of squared sums of the total system accuracy, the 95th percentiles from prediction and correlation errors and the margin from rotation results in a minimum PTV margin of 3.7 mm.

Conclusion: The clinical accuracy of respiratory tracking in robotic radiosurgery can be derived from four sources of errors. For renal targets, the contribution is largest from the correlation model error, followed by influences from target rotation, total system accuracy and the breathing prediction error. Assuming optimal fiducial position and neglecting target deformation, we suggest a minimal PTV margin of 3.7 mm for renal lesions based on 95th percentiles of tracking errors.