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An Inverse Treatment Planning System for Robotic Seed Brachytherapy

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Seed-Brachytherapy (BT) is a guideline-conformal therapy for low-risk prostate cancer, which relies on the implantation of small radioactive sources (seeds) by interstitial needle placement. However, due to its complex workflow and the lack of proper education programs the number of interventions is steadily declining. Introducing robotic navigation assistance tools to position the implantation needle and better image modalities could improve the intervention procedure in terms of reduced complexity and higher safety while decreasing costs by higher time efficiency. It could then broaden the access of patients with prostate carcinoma as well as other cancer types.

This thesis focuses on three treatment scenarios. Scenario 1 is the treatment of a liver metastasis with a navigation tool for trans-percutaneous needle implantations. Scenario 2 is the transrectal treatment of prostate seed-BT using a navigation tool for MRI-guided needle implantations. Scenario 3 in contrast treats intra-prostatic lesions in a focal treatment approach or as a dose escalation scenario in combination with External-Beam Radiation Therapy. A novel Treatment Planning System (TPS) is presented as part of an adaptive robotic workflow. It automates the needle path- and treatment planning by inverse optimization. In scenario 1, the path planning algorithm determines all suitable injection points to reach the target volume by circumventing risk structures. In scenario 2 and 3 however, all needle trajectories meet in the rotation point coordinate of the robot's needle guide. The needle candidate domain then structures all combinations of injection and tip points to benefit the inverse optimization as pre-processed data in terms of reduced computational cost during the treatment planning. A greedy optimizer generates an initial treatment plan, which is then further optimized to fulfil the planning constraints. The feedback of the needle or implanted seed coordinates to the TPS enables to adapt the remaining needles to compensate a loss of dose coverage. Implantations (SI)s were simulated to compare them to novel needle-adaption algorithms. The workflow's feasibility for the transrectal approach is tested with an implantation experiment using an anthropomorphic pelvis phantom.

A TPS-calculated dose plane showed a 98.5 % pass rate for the gamma 1 %, 1 mm test indicating a nearly equivalent dose distribution as the same plan's dose plane implemented in a commercial Brachytherapy TPS. The path planning is shown to avoid needle candidates through the organ at risks (OARs) automatically such as the ribs and the liver in scenario 1 and the urethra in scenario 2. The treatment plans matched the planning constraints for all scenarios. The V100 (mean $\pm$ std) for each ten plans yielded (99.1 ± 0.3) % for scenario 1, (95.8 ± 0.5) % for scenario 2 with $\mathrm{D_{pr}} = 145\ \mathrm{Gy}$ and (99.2 ± 1.2) % together for the lesions L1/3/4/5 in scenario 3. In scenario 2, the treatment plans were clinically acceptable, fulfilling as well the dose constraints for the OARs similarly, as interstitial seed-BT. The SIs showed a decrease of the V100 due to needle displacements, which could be partly compensated by the needle adaption algorithms in all scenarios. The implantation experiment showed a needle guide placement accuracy of $0.58 \pm 0.22\ \mathrm{mm}$ and the spatial displacement between the approved needle trajectory and registered seed position was 2.62 $\pm$ 1.24 mm.

Altogether, the TPS enables robotic seed-BT in a more flexible and automated workflow of the prostate as well as other tumour sites or metastases in a fully automated planning process. The physician may benefit from the direct seed implantation feedback and the possibility to correct displacement errors in a way that the learning curve is flattened and the quality of implant is quickly raised.