Robotic brachytherapy demonstration: Implant of HDR brachytherapy needle configuration computer-optimized to avoid critical structures near the bulb of the penis

Needle planning is an implicit step in the high dose rate brachytherapy (HDR-BT) workflow, performed mentally by the physician during needle insertion. In both template-based and freehand techniques, the physician attempts to evenly distribute needles around the target. To maximally utilize robots for HDR-BT, a computerized needle planning system should be employed to determine an optimized needle configuration before insertion. We have (1) formulated the needle planning problem as a set cover integer program and (2) adapted the Acubot-RND [2] needle insertion robot for an HDR-BT workflow. This system was used by a novice to execute the workflow on phantoms with sufficient quality to meet clinical dose objectives. As control, an experienced physician implanted a nearly-identical phantom using TRUS guidance. We believe this study is a significant step towards clinical acceptance of HDR robots.

A candidate needle set (CNS) consisting of parallel and angulated needles (Fig. 2) was generated for each phantom using CT images. Needles intersecting organs other than the prostate (urethra, bladder, rectum, pubic arch, and CSNB) were removed from the set. The entry plane segment (red box Fig. 1, 2) of the CNS was centered on the CT marker, defined the extent of the CNS geometry, and ensured every needle was within the robot workspace. A subset of the CNS to be implanted was chosen using the custom built Needle Planning by Integer Program (NPIP) optimization engine. This planned needle configuration (PNC) was passed to the dose optimization engine IPIP [1] for verification that the PNC supports a clinically viable dose plan. NPIP was formulated as follows. For target voxel $P_i$ and for a user-specified $\delta > 0$ mm, let $J_k = \{ j : D_j$ is a dwell position in needle $k \}$. Then $C_{ik} = 1$ if and only if $\exists j \in J_k$ s.t. $||P_i - D_j||_2 < \delta$. $C_{ik}$ denotes whether a needle could cover $P_i$. For each needle in the CNS, a binary variable $x_k = 1$ if needle $k$ was chosen to be in the implant and 0 otherwise. NPIP minimizes the number of needles chosen from the candidate needle set $(\min(\Sigma x_k))$ such that every $P_i$ is covered. Here, $\delta$ was chosen to achieve a 16 needle implant to match that used clinically.

The CT marker was used to calibrate the phantom–robot positioning and register the digital and physical coordinate systems. Acubot was originally designed to insert a single needle by manual joy-stick input. This was modified to allow for automated insertion based on two cartesian coordinates: the entry point of the needle on the perineum and the final tip location inside the phantom. Needle stylets were deposited so the single insertion needle could be reused. The robot geometry was used to calculate an analytic inverse kinematic solution to map every point in the robot workspace: from the 3D coordinate system of the planner to the 7D coordinate system of the robot.

Fig. 4 superimposes the PNC (red) and INC (blue) for one phantoms. The root-mean-square (RMS) of the distances between the endpoints of all the needles in the PNC and INC (endpoints = first and last dwell positions within the prostate) were calculated. P1-A1 (P2-A2) had an RMS error of 2.4 (3.5) mm. Some systematic placement error can be accounted for by (1) calibration and registration uncertainty and (2) lack of a perfectly steady hand during the manual step of retracting the needle over the stylet.

We have conducted initial experiments towards robot-assisted insertion of computationally-generated needle configurations for HDR-BT. We emphasize that a complete workflow of HDR-BT was demonstrated—puncture of critical structures avoided and clinical dose coverage achieved—by a novice human operator.
