final reported dosimetric indices are computed on 500,000 DC points, the standard setting in Oncentra Brachy.
Bi-objectively optimized plans are compared to clinical plans obtained by experienced planners using IPSA/HIPO, followed by graphical optimization, in 30 to 60 minutes.

Results

For all cases, a trade-off curve of plans similar to or better than the clinical plan was found. The clinical plans satisfied all clinical criteria for only 4 cases. Our optimization found plans satisfying all clinical criteria for 15 cases, including these 4. Optimizing for more than 30 seconds did not substantially improve results.
Figure 1 shows plans generated in 30 seconds by the bi-objective planning for 3 patients.
In Table 1, we highlight selected plans for the same patients. Plans with maximum coverage while satisfying all sparing constraints were selected. To satisfy the clinical constraint on the urethra for patient 2, dose to rectum and bladder are increased compared to the clinical plan. For patient 3, all dosimetric indices of the optimized plans are better than the clinical plan.

Conclusion

Bi-objective planning allows for insightful plan selection from a large set of high-quality plans, each with a different trade-off between target coverage and organ sparing. We can now generate such sets computer-aided in as little as 30 seconds by applying GPU acceleration, which permits use in clinical practice.

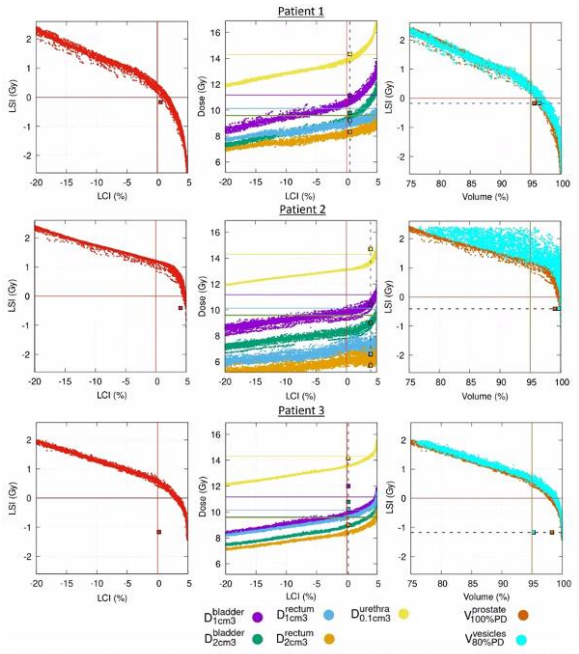

Figure 1: All optimized plans of 30 runs (to show variation) of bi-objective planning for 30 seconds. Leftmost figures show the LCI and LSI for all plans. Plans with positive LCI and LSI satisfy all clinical coverage and sparing constraints, respectively. Middle figures show each plan in 5 different colors, aligned parallel to the dashed line, to indicate the 5 different dose indices for a plan with a given LCI. Rightmost figures show each plan in 2 colors, and corresponding volume indices for a given LSI. Clinical constraints are shown as solid lines in corresponding colors. The clinical plan is shown as a square in all plots, colored corresponding to the displayed dosimetric index.

***Planning-aim Dose (PD)** = 13.00 Gy*

		$V^{prostate}_{100\%PD}$	$V^{vesicles}_{80\%PD}$	$D^{bladder}_{1cm3}$	$D^{bladder}_{2cm3}$	D^{rectum}_{1cm3}	D^{rectum}_{2cm3}	$D^{urethra}_{0.1cm3}$
Protocol		*> 95%*	*> 95%*	*< 11.18 Gy*	*< 9.62 Gy*	*< 10.14 Gy*	*< 9.62 Gy*	*< 14.30 Gy*
P1	*Clin.*	*95.5*	*96.4*	*11.15*	*9.79*	*9.22*	*8.33*	*14.35*
	Bi-obj.	*96.5±0.3*	*97.3±0.6*	*10.80±0.10*	*9.55±0.06*	*9.12±0.17*	*8.30±0.17*	*14.20±0.11*
P2	*Clin.*	*99.0*	*99.7*	*10.42*	*9.01*	*6.58*	*5.70*	*14.70*
	Bi-obj.	*99.8±0.1*	*100±0.0*	*11.03±0.14*	*9.42±0.11*	*7.26±0.44*	*6.29±0.36*	*14.13±0.17*
P3	*Clin.*	*98.3*	*95.2*	*12.02*	*10.79*	*10.22*	*9.01*	*14.16*
	Bi-obj.	*98.3±0.6*	*98.6±0.9*	*10.56±0.11*	*9.55±0.08*	*10.08±0.05*	*8.84±0.06*	*14.07±0.11*

Table 1: Dosimetric indices of selected, bi-objectively optimized plans (Bi-obj.) for 3 patients (P1-3), compared to the clinical (Clin.) plans. The clinical protocol for HDR prostate BT at our medical center is listed, and dosimetric indices violating the protocol are marked in red. Means and standard deviations of 30 runs are displayed.

OC-0396 Robust HDR prostate brachytherapy planning accounting for organ reconstruction settings

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Purpose or Objective

Recently, a bi-objective optimization model has been introduced, to automatically create a set of clinically good HDR prostate brachytherapy (BT) plans. The model uses separate objectives for target coverage and organ sparing, based solely on dose-volume indices (DVIs). To calculate DVIs, a reconstruction algorithm is used to determine the 3D organ shape from 2D contours, containing settings that influence the result. In this work, we augment the automatic planning model to find plans that are robust to differences in 3D reconstruction. We investigated the impact on the resulting plans.

Material and Methods

The original model is based on the clinical protocol (Table). DVIs of the protocol are combined into two objectives: Least Coverage Index (LCI) and Least Sparing Index (LSI), and a hard optimization constraint value C. Studied reconstruction settings were:
1.The urethra is considered as part of the prostate, or not.
2.Contours fill the volume spanned by their slice, or interpolation is used.
3.Top/bottom contours span the half-slice-thickness towards the other contours, or the full-slice-thickness.
Combinations of these settings yield 8 possible 3D organ reconstructions per patient, hence 8 combinations of (LCI_i, LSI_i, C_i) per plan. We define the robust model as
$LCI = \min_{i=1,\dots,8}\{LCI_i\}$, $LSI = \min_{i=1,\dots,8}\{LSI_i\}$, $C = \min_{i=1,\dots,8}\{C_i\}$.
Both models were tested on data of 5 prostate cancer patients consecutively treated with HDR BT, with contours delineated on axial MRI scans (slice thickness: 3.3mm). For the original model, settings were based on the standard of our TPS (Oncentra Brachy version 4.5: urethra as part of the prostate, interpolation, half-slice-thickness). Plans were optimized using the evolutionary algorithm GOMEA, which previously obtained excellent results for the original model. Optimization was performed on 20,000 dose-calculation points, and re-evaluation on 500,000 points. To compare the two models, all optimized plans were re-evaluated both in the original, and in the robust model.

Target coverage		Organ sparing		
Prostate	**Vesicles**	**Bladder**	**Rectum**	**Urethra**
$V_{100\%} > 95\%$ $D_{90\%} > 100\%$ $V_{150\%} < 50\%$ $V_{200\%} < 20\%$	$V_{80\%} > 95\%$	$D_{1cm3} < 86\%$ $D_{2cm3} < 74\%$	$D_{1cm3} < 78\%$ $D_{2cm3} < 74\%$	$D_{0.1cm3} < 110\%$

$$LCI = \min\{V^{prostate}_{100\%} - 95, V^{vesicles}_{80\%} - 95\}$$
$$LSI = \min\{86 - D^{bladder}_{1cm3}, 74 - D^{bladder}_{2cm3}, 78 - D^{rectum}_{1cm3}, 74 - D^{rectum}_{2cm3}, 110 - D^{urethra}_{0.1cm3}\}$$
$$C = \min\{50 - V^{prostate}_{150\%}, 20 - V^{prostate}_{200\%}\}$$

Table: The DVIs and the clinical protocol for HDR prostate BT used at our center, and the original bi-objective optimization model used. The unit of each DVI is either percentage of total organ volume for volume indices V, or percentage of planning-aim dose (13Gy) for dose indices D. During optimization, only plans with a positive constraint violation index (C) are considered feasible. For feasible plans, the clinical protocol is satisfied if the two objectives Least Coverage Index (LCI) and Least Sparing Index (LSI) are positive.

Results

Re-evaluated in the original model, differences were negligible for all patients between plans optimized using the original model (fig.(a)), and plans optimized using the robust model (fig.(b)), hence the cost for robust optimization as observed in the original model was negligible. Re-evaluated in the robust model, the difference between the original model (fig.(c)) and the

robust model (fig.(d)) was large for 2 of the 5 patients (2,5), hence the benefit of robust optimization could be large. For patient 2, plans that appeared good when optimized in the original model, often violated the clinical protocol when considering different settings. This was not the case for robustly optimized plans.

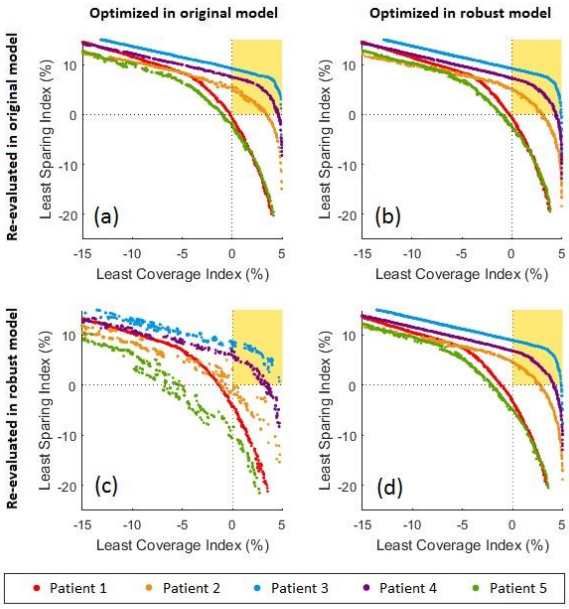

Figure: Original and (new) robust bi-objective HDR prostate BT planning results for 5 patient cases. All plans, optimized with either the original (a, c) or robust (b, d) bi-objective model, are re-evaluated in the original (a, b) or the robust (c, d) bi-objective model. Plans in the yellow rectangle where the LCI and LSI are both larger than zero satisfy the clinical protocol.

Conclusion

Different settings for organ reconstruction can have a non-negligible impact on automatically optimized plans. Robust optimization generated plans of high quality, irrespective of organ reconstructions, and therefore offers a solution to accounting for dosimetric uncertainties.

OC-0397 Intensity modulated brachytherapy for prostate cancer: plan quality, robustness and delivery time

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Purpose or Objective

Intensity modulated brachytherapy (IMBT) is a novel high dose rate brachytherapy (HDR-BT) technique which incorporates rotating metallic shields inside brachytherapy catheters to dynamically direct the radiation towards the tumor and away from healthy tissues. A delivery system that can enable IMBT for prostate cancer was proposed in a previous study. The purpose of this study is to evaluate the plan quality, robustness and delivery time for IMBT.

Material and Methods

The IMBT delivery system dynamically controls the rotation of platinum shields placed inside interstitial catheters (Fig. 1). The platinum shield partially collimates the radiation emitted from an ^{169}Yb source to produce a highly anisotropic dose distribution. The shield contains an emission window of 180° and a groove which guides the translation of the source through the catheter. The device can be connected to the standard 6F transfer tubes for interstitial brachytherapy. Conventional ^{192}Ir-based HDR-BT and ^{169}Yb-based IMBT plans were generated for 12 prostate cases using an in-house column generation-based optimizer coupled to a Geant4-based dose calculation engine, RapidBrachyMC. The optimized treatment plans were normalized to match the same PTV D_{90} coverage as the original clinical plans. A sensitivity analysis was performed to evaluate the impact of longitudinal source positioning errors (±1 mm, ±2 mm and ±3 mm) and rotational errors (±5°, ±10° and ±15°) on plan quality indices (PTV D_{90} and urethra D_{10}).

Results

The platinum shield reduced the dose on the shielded side at 1 cm off-axis to 18.1% of the dose on the unshielded side (Fig. 2a). For equal PTV D_{90} coverage, the urethral D_{10} was reduced by 12.9%±4.6%, without change to other plan quality indices (Fig. 2b). The maximum decrease for a single case was 21.3%. Delivery times for IMBT using a 3.1 Ci ^{169}Yb source, which has the same dose rate at 1 cm off-axis as a 10 Ci ^{192}Ir source, were, on average, 35% higher compared to conventional HDR-BT. Systematic translational and rotational shifts led to a decrease (increase) in PTV coverage (urethral dose). In general, the PTV D_{90} was more sensitive to source positioning errors, while the urethral D_{10} was more sensitive to rotational errors (Fig. 2cd). For a typical range of delivery errors (±1 mm, ±5°), the plan quality indices varied by <2%.

Conclusion

A system was developed to deliver IMBT for prostate cancer. IMBT has the potential to create a low dose tunnel within the urethra. Delivery times for IMBT with a 4 Ci ^{169}Yb source are comparable to that of conventional HDR-BT with a 10 Ci ^{192}Ir source. Treatment plans are robust with respect to delivery errors.

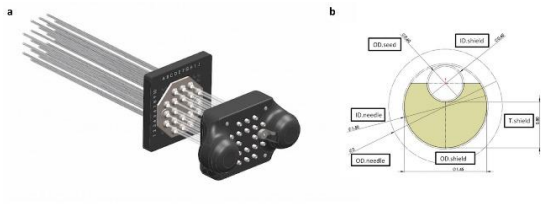

Figure 1: (a) IMBT system. (b) Transverse cross section of the shielded needle with dimensions.

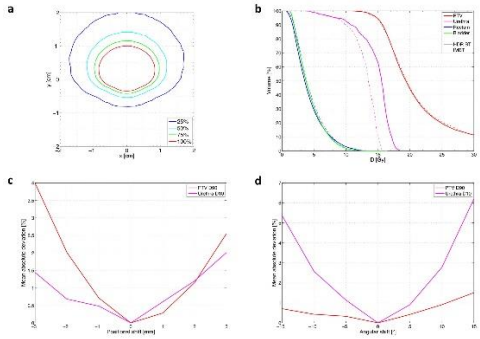

Figure 2: (a) Relative dose distribution in the transverse plane of a shielded 169Yb source. (b) Average DVH for prostate cancer treated with conventional HDR-BT and IMBT. Impact of (c) source position errors and (d) rotational shield errors on plan quality indices.

OC-0398 Clinical introduction of 3D printed applicators for endocavitary and interstitial brachytherapy.

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