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evaluate plan quality: Paddick conformity index (PCI), gradient index (GI), and BOT. Heat maps for each of the above metrics as a function of LD and BOT penalties were analyzed. An objective score matrix was calculated for each plan using a linear weighted combination of scaled and normalized GI, PCI, and BOT. An optimal solution space containing the 5 lowest values of the score matrix per patient was extracted. A frequency histogram was subsequently created in the LD-BOT coordinate space.

Results: The target volumes in the study ranged from 1.0 cc to 2.5 cc. For every patient, 121 plans were generated across the range of LD and BOT penalties, resulting in 3630 plans included in this analysis. The range of PCI, GI, and BOT across all plans were 0.71 to 0.95, 2.5 to 2.9, and 17.2 to 221 minutes, respectively. The variation of the LD/BOT penalties had a much larger impact resulting in a higher deviation about the mean for BOT (169%), followed by PCI (28%). Heat map analysis revealed that the plans that maximized PCI and minimized GI values occupied the upper triangular matrix of the LD/BOT penalty space, while plans that minimized BOT occupied the lower triangular space. The optimal solutions frequently occupied the diagonal space in between these zones. Specifically, the histogram analysis showed that 4 highest frequencies occurred at the user-inputted settings (LD, BOT) of (0.6, 0.5), (0.8, 0.6), (0.7, 0.5), and (0.7, 0.6), in order of plan quality.

Conclusion: In this study, the user-inputted variables (LD and BOT) were systematically varied to determine the optimal solutions to simultaneously maximize PCI while minimizing GI and BOT. The results of this study may permit SRS planners to generate single brain metastasis plans more efficiently using the study-defined optimal settings of LD and BOT.

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3305

Maximization of Peak-to-Valley Dose Ratio and Normal-Tissue Survival Fraction for Proton Minibeam Radiation Therapy

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Purpose/Objective(s): Proton minibeam radiation therapy (pMBRT) is a novel proton modality of spatially fractionated RT (SFRT). pMBRT can reduce the radiation damage to normal tissues via biological dose sparing of high peak-to-valley dose ratio (PVDR). This work will develop a new pMBRT treatment planning method that jointly optimizes the plan quality and maximizes the PVDR.

Materials/Methods: The new optimization method simultaneously maximizes the normal-tissue PVDR and optimizes the dose distribution at tumor targets and organs-at-risk (OAR). The PVDR maximization is through the joint total variation (TV) and L1 regularization with respect to the normal-tissue dose. That is, at beam-eye-view projected dose slices of several depths for each beam angle, the TV of dose is maximized, corresponding to the PVDR maximization, while the L1 of dose is minimized, corresponding to the minimization of the OAR dose and maximization of survival fraction (SF).

Results: The new IMPT method with TV and L1 regularization (TVL1) was validated in comparison with the conventional IMPT method (CONV) for pMBRT on several clinical cases. The results show that TVL1 provided larger PVDR and SF than CONV for biological sparing of normal tissues, with preserved plan quality in terms of physical dose distribution.

Conclusion: A new pMBRT treatment planning method is developed that can optimize and improve normal-tissue PVDR and SF, by incorporating TV and L1 dose regularization into IMPT.

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3306

3D Dose-Driven, Automatic VMAT Machine Parameter Generation with Deep Learning

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Purpose/Objective(s): Recent research efforts utilizing knowledge-based treatment planning for the prediction of 3D radiation dose distributions from planning structure sets have achieved positive results. Most ongoing efforts to generate deliverable plans from the predicted doses rely on full inverse optimizations using dose-volume histogram (DVH) objectives derived from these doses. In this study, we aim to leverage deep learning (DL) to rapidly generate machine delivery parameters for volumetric modulated arc therapy (VMAT) from predicted desired doses.

Materials/Methods: Data of 50 previously treated patients at our institution with prostate adenocarcinoma who received definitive radiotherapy were retrospectively obtained. All plans were generated with a one-arc VMAT technique, with conventional fractionation (78 Gy in 39 fx or 79.2 Gy in 44 fx to the prostate gland +/- seminal vesicles). A multi-task U-Net was constructed: it takes the 2D projections of the 3D dose and planning structures as inputs, and it predicts the numerical multi-leaf collimator (MLC) sequence and weights for the 178 control points. Five cases were randomly selected for testing only, and the remaining 45 formed the training set. The algorithm was implemented in Python 3.8 with PyTorch 1.7 as the DL framework. Model training was performed on a GPU. The DL-predicted plans underwent further inverse optimization with the 3D-dose-derived DVH objectives, utilizing only the last step of the Photon Optimizer (PO) in a treatment planning system. The optimization time and plan quality were compared to plans generated with one full PO optimization with the same objectives and clinical plans (all normalized to D95%=100% Rx dose).

Results: The DL model was trained for 200 epochs. On average, DL-predicted plans could be optimized in 22% (range, 18-26%) of the time required for full optimization plans. Dosimetric comparison (Table 1) demonstrated that the quality of the DL-predicted plans was comparable with clinical plans and full optimization plans, but the DL-predicted plans tended to have increased dose inhomogeneity within the PTVs.

Conclusion: We demonstrated the feasibility of rapidly generating deliverable VMAT plans from desired 3D doses with deep learning. Further work is needed to improve PTV dose homogeneity and generalize the method to multi-arc VMAT delivery.

Abstract 3306 - Table 1

Metric	Clinical plan	DL-predicted plan	Full Optimization plan
Time for optimization (seconds)	N/A	40+/-15	182+/-71
PTV, Max	109+/-2 % Rx dose	113+/-2 % Rx dose	108+/-1 % Rx dose
PTV, D95%	100% Rx dose	100% Rx dose	100% Rx dose
Rectum, D15% (Gy)	65.0 +/- 6.9	66.8 +/- 6.3	64.7 +/- 6.9
Rectum, D25% (Gy)	55.0 +/- 7.1	57.5 +/- 6.9	54.8 +/- 8.4
Rectum, D50% (Gy)	40.6 +/- 7.0	41.6 +/- 6.8	39.7 +/- 8.2
Bladder, D15% (Gy)	60.0 +/- 18.8	61.0 +/- 19.3	59.4 +/- 20.4
Bladder, D25% (Gy)	47.0 +/- 22.4	46.9 +/- 23.4	48.0 +/- 23.8
Bladder, D35% (Gy)	35.0 +/- 22.4	35.0 +/- 22.8	35.4 +/- 23.2
Penile bulb, Mean (Gy)	43.4 +/- 22.7	44.2 +/- 24.0	42.4 +/- 23.3

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3307

Patient-Specific Quality Assurance of Deformable Image Registrations Using Atlas for Adaptive Radiotherapy of Lung Cancer

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Purpose/Objective(s): Evaluating the uncertainty of deformable image registration (DIR) is challenging because the ground truth is often unavailable. We developed an automated method to create realistic deformations via an atlas and assess DIR algorithms on a patient-specific level for adaptive radiotherapy.

Materials/Methods: A library of deformations was created by extracting the longitudinal anatomical changes observed from an atlas of 60 locally advanced non-small cell lung cancer patients treated with IMRT (60Gy, 30 fx). The deformation vector field (DVF) between the planning CT (pCT) and last weekly CBCT of an atlas patient was derived via a free-form DIR algorithm and served as a ground truth pattern. An inquiry patient was first matched to an atlas patient on gross tumor volume (GTV) location and volume. The pCT of an inquiry patient was then deformably registered to that of an atlas patient to establish a voxel-based correspondence. Then, the deformation pattern of the atlas patient was transferred to the inquiry patient pCT by applying the known DVF to the corresponding voxels, resulting in a digital CT phantom. Subsequently, this CT phantom was appended with CBCT artifacts using a physics-based augmentation (Alam, PMB 2021) to imitate a weekly CBCT. To evaluate DIRs, a large deformation diffeomorphic metric mapping (LDDMM) algorithm, and two commercial systems (C1 C2) were used between the phantom (both simulated CT and CBCT) and actual pCT of the inquiry patient. Derived DVFs were compared to the ground truth. The voxel-level geometric and dosimetric uncertainties of DIRs were calculated using the DVF95% errors, fraction of volume with ≤1.5mm errors (V1.5mm) and mean dose errors (D_{mean}) for GTV and esophagus.

Results: In a retrospective evaluation of 10 paired inquiry and atlas patients, the actual deformations observed between the pCT and weekly CBCTs of inquiry patients were well-contained by the combined patterns from the matched atlas, validating the feasibility of an atlas. LDDMM performed consistently well, especially for the CT-CBCT registration ($p<0.01$, two-tailed t-test). GTV mean dose is less sensitive to DIR errors than esophagus mean dose.

Conclusion: It is feasible to augment anatomical changes for a particular inquiry patient using deformation patterns from matched patients in an atlas and evaluate the uncertainty of DIR algorithms in realistic simulations. Integration of such an automated program facilitates the clinical implementation of adaptive radiotherapy that involves longitudinal imaging studies.

Abstract 3307 − Table 1

		CT-CT			CT-CBCT		
DIR evaluation criteria		LDDMM	C1	C2	LDDMM	C1	C2
GTV	V1.5mm (%)	98±3	96±6	60±22	93±6	61±29	44±19
	DVF95% (mm)	0.9±0.5	1.5±1.4	4.4±2.1	1.6±0.6	4.1±2.3	5.1±1.9
	D_{mean} (cGy)	3±2	6±7	26±11	9±4	18±8	31±14
ESO	V1.5mm (%)	96±7	99±1	52±30	78±12	66±24	31±27
	DVF95% (mm)	0.7±0.4	0.5±0.2	3.2±1.1	2.9±1.5	4.8±3.8	5.3±1.6
	D_{mean} (cGy)	25±16	21±11	153±88	95±24	112±46	192±113

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3308

Feasibility of Using a Deep Learning Auto-Segmentation Software Trained with Planning CT for Iterative CBCT Based Online Adaptive Prostate Treatment

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Purpose/Objective(s): Cone-beam CT (CBCT) based organs-at-risk (OARs) delineation is the prerequisite of online adaptive therapy (ART) which can be time-consuming and inefficient. Auto-segmentation on CBCT would reduce the extra clinical resources required, however, it is labor-intensive to retrain the deep-learning auto-segmentation (DLAS) with CBCT contours that need to be labeled. Over standard CBCT, iterative CBCT (iCBCT) yields higher quality images with reduced noise and artifacts. This study aimed to comprehensively evaluate the feasibility of DLAS software trained with planning CT for iCBCT based online adaptive prostate treatment.

Materials/Methods: Total 25 male pelvis iCBCTs from corresponding prostate patients were selected for this study. An automated treatment planning process was established to simulate the online ART procedure by combining CT-based commercial DLAS software (i.e., trained with planning CT) and knowledge-based treatment planning used to eliminate human bias. Prostate and surrounding critical structures (i.e., bladder, rectum, and femoral heads) were delineated on iCBCT by a CT-based DLAS and by manual modification from corresponding planning CT registration. The geometrics metrics of OARs were computed between DLAS contours and manual contours. The prostate, considered as the gross tumor volume (GTV), was manually modified from DLAS to pursue accurate target dose coverage. For each iCBCT, two VMAT plans of 70 Gy with two full arcs were generated using the manual contour sets and DLAS contour sets respectively, which share the same modified prostate contour. Both plans were normalized to 100% of the prescription dose to cover 98% of the planning target volume (PTV) derived from GTV. The dose distributions from two plans were evaluated on the manual structure sets. The clinical appropriateness was evaluated by assessing D15(Gy), D25 (Gy), D35(Gy), and D50 (Gy) of critical structures following the RTOG-0815. The time required for the automated treatment planning process was recorded.

Results: Average dice agreement for bladder, rectum, femoral head_L and femoral head_R were 0.87 ± 0.10, 0.82 ± 0.08, 0.91 ± 0.12, and 0.93 ±0.07 respectively. DLAS generated a statistically significant of 0.39 Gy greater on bladder D_{25} than its counterpart. No statistically significant differences were found in other OARs dosimetric metrics. All unmodified OARs satisfied the dose constraints of RTOG-0815 even with some artifact cases involved. The average time needed for the automated treatment planning process simulating ART was 11.85 minutes including DLAS generated time (0.69 minutes), GTV modified time (0.9 minutes), and plan generated time on CPU (10.26 minutes).

Conclusion: The proposed DLAS trained with planning CT is a promising contouring solution for iCBCT-based intact prostate online ART in the clinic with labor shortage. Without modification needed, it can generate clinically acceptable OARs segmentation on iCBCT images within a limited time.

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