necessary, modified based on additional information from high resolution CT or MRI.

Proffered Papers: Physics 2: Dose planning: on automation and robustness

OC-0069

Automatic interactive optimization for volumetric modulated arc therapy planning of head and neck cancer

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Purpose/Objective: Intensity modulated radiotherapy treatment planning for sites with many organs-at-risk (OARs) is a complex and labor-intensive process, making it hard to obtain consistent and high quality plans. As a solution, an automatic interactive optimizer (AIO) was developed to be used in conjunction with the Eclipse treatment planning system. AIO performance was benchmarked against clinical plans of 20 head and neck cancer (HNC) patients treated recently at our department using volumetric modulated arc therapy (RapidArc).

Materials and Methods: Our institutional approach to HNC planning uses 3-4 optimization objectives per OAR, evenly placed along the displayed dose-volume histogram (DVH) curve. During the optimization process, the planner attempts to maintain a fixed distance between the objectives and the DVH curve, while weighting factors (optimization priorities) are kept constant. AIO scans the optimization window and uses color-coding to differentiate between OAR DVH-lines, allowing it to automatically adjust the location of optimization objectives far more frequently and consistently, again using fixed priorities. The summed cost function for all OAR objectives is therefore held constant throughout the optimization process, allowing the optimizer to balance sparing of the included OARs. Because planning target volumes (PTVs) are assigned higher priorities than OARs during optimization, AIO can gradually push the OAR objectives to lower dose values at each iteration without underdosing the PTVs.

AIO plans were compared to clinical plans on the basis of i) Mean dose to the oral cavity (D_{oc}), individual and composite salivary glands (D_{sal}) and swallowing muscles (D_{swal}). ii) Boost/elective PTV (PTV_B/PTV_E) volumes receiving more than 95% (V95) and less than 107% (V107) of the prescribed dose. A head and neck radiation oncologist performed blinded evaluation of the clinical and AIO plans.

Results: Planning results were averaged over all 20 patients and are summarized in the Table. Dosimetric parameters in the AIO plans differing significantly (two-sided Student t-test) from the clinical plans are indicated by '†' in the table. Clinically acceptable maximum doses to the brainstem and spinal cord were achieved in all plans. AIO reduced D_{oc}, D_{sal} and D_{swal} by 2.6, 0.8 and 4.3Gy, respectively, while also improving PTV_B/PTV_E V95 and PTV_E V107. 19/20 AIO plans were judged as the superior plan by the radiation oncologist, while quality of the remaining AIO plan was considered similar to the clinical plan. AIO only required a single optimization of 20-35 minutes, whereas clinical plans could have required multiple iterative optimizations.

	Plan		Clinical	AIO
	Boost PTV	V95 (%)	99.1 ± 0.3	99.4 ± 0.4
		V107 (%)	2.0 ± 2.8	1.3 ± 1.3
	Elective PTV	V95 (%)	98.2 ± 1.0	98.0 ± 0.7
		V107 (%)	16.5 ± 9.2	12.0 ± 6.0 †
Mean Dose (Gy)	Contralateral Parotid Gland		20.6 ± 8.3	19.8 ± 7.8 †
	Ipsilateral Parotid Gland		28.1 ± 8.8	27.4 ± 8.8
	Contralateral Submandibular Gland		33.6 ± 11.8	32.1 ± 12.7 †
	Composite Salivary Glands		26.5 ± 7.6	25.7 ± 7.5 †
	Composite Swallowing Muscles		29.5 ± 8.1	25.2 ± 9.2 †
	Oral Cavity		29.0 ± 12.5	26.4 ± 13.0 †

Conclusions: The present results show that AIO can automate treatment planning for complex HNC patients, increasing efficiency while improving quality over manually created plans. AIO has been clinically implemented at our clinic for HNC treatment planning.

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OC-0070

Automatic dose painting workflow: from tumor segmentation to optimization

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Purpose/Objective: Dose painting becomes a popular strategy to increase tumor local control in radiotherapy. However, only a few research centers have developed the tools to apply it to patients. Our aim is to develop an automatic workflow for dose painting, which is integrated in a commercial treatment planning system (TPS).

Materials and Methods: A set of MATLAB® functions (GTVPETCT) are called through scripting from RayStation (RaySearch Laboratories, research version 3.99) to segment the primary tumor (GTV_{PET}) in $^{18}FDG_{PET}$ images, using an automatic gradient-based method. The user selects the lower and upper limits (Gy) for dose escalation. The FDG uptake in each voxel is linearly converted to dose (Gy), starting from the median uptake to avoid background contamination. Optimization can be performed using either a number N of sub-volumes (N selected by the user) or directly on the voxel scale thanks to a customized function developed with the RaySearch research package (C++). The N contours can be used to drive the optimizer towards a dose painting by number prescription (DPBN) or either to perform sub-volume boosting (dose painting by contours) if uniform dose is prescribed inside each contour.

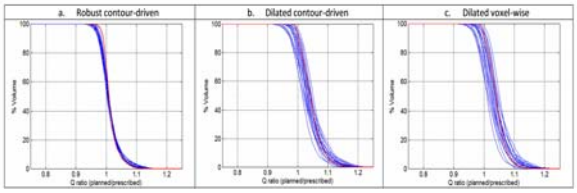
The workflow can be applied for IMRT and proton therapy, but in this work we considered only the latter. To ensure robustness against setup (and range) errors, two strategies are implemented: 1) integration of margins in a dilated prescription; and 2) robust optimization, but only for contour-driven optimization. Work is in progress to extend this feature to voxel-wise optimization.

Plan quality was assessed with Quality Volume Histograms (QVH), where quality (Q) is the ratio of the planned dose to the prescribed dose in each voxel. Robustness is evaluated by calculating the dose perturbed by setup errors (and range errors for protons) gathered in a set of scenarios.

As an illustration, the workflow was applied to a H&N patient, aiming at reproducing a DPBN prescription. Direct voxel-wise optimization and 7 non-uniform dose levels were used for Proton Pencil Beam Scanning.

Results: The DPBN prescription was reproduced successfully for both contour-driven and voxel-wise optimizations: more than 99% of the PTV_{PET} received at least 95% of the prescribed dose ($V_{Q=95\%}$>99%) and less than 1% received more than 105% ($V_{Q=105\%PET}$ achieved perfect target coverage ($V_{Q=95\%}$=100%) and slight overdosing ($V_{Q=105\%}$=9%). Dilated prescriptions yield high

overdosing in GTV_{PET} ($V_{Q=105\%}$>35%) and are not sufficient to be robust against setup errors in proton treatments. Voxel-wise optimization was twice faster than with contours.



Conclusions: This automatic workflow for dose painting can be directly implemented in clinics since it is integrated in a commercial TPS. Voxel-wise optimization was simpler and faster. Surprisingly, robust optimization with protons yields dose escalations that are robust for both target coverage and overdosing.

OC-0071

Real Time Interactive Treatment Planning (RTIP) with prioritized goal matching

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Purpose/Objective: Create a planning platform for real-time dose manipulation and prioritized goal matching. **Materials and Methods:** A real-time interactive planning (RTIP) system was developed for deriving achievable patient specific dose distributions. It may be used by the radiation oncologist or treatment planner to navigate through potential 3D dose distributions and determine a clinically optimal dose distribution. The RTIP system was developed on the hypothesis that the process of evaluating potential dose distribution options and deciding on the best clinical trade-offs may be separated from the derivation of the actual delivery parameters used for the patient's treatment. For this purpose a novel high speed dose calculation algorithm was developed to derive an Achievable Dose Estimate (ADE). The ADE incorporates the limits of what can be achieved in practice thereby ensuring that the calculated dose is deliverable. The resulting speed increase permits real-time changes in 3D dose distributions (using isodoses, DVHs, EUD etc.) which provides a more intuitive understanding of the available trade-offs for each patient. The system may also function in an automated fashion where predefined dosimetric goals guide where changes to the dose distribution are applied. Unlike conventional plan optimization the goals are presented as a prioritized list, so that each goal is attempted separately and in turn. If a goal is not achieved the clinician has the option of proceeding to the next goal or constraining the dose at the current dose level. **Results:** Full 3D dose distributions are calculated in ~2-20 milliseconds. Including graphics processing overhead, clinicians may visually interact with the dose distribution and display updates of the dose distribution at a rate of more than 20 times per second. Through automatic goal matching the clinician may directly visualize how each dosimetric requirement impacts the 3D dose distribution. Furthermore, because the system is fully automated, a complete list of 10 to 20 goals may be attempted in ~5 to 30 seconds, depending on the complexity of the case and how challenging the goals are.
Conclusions: RTIP is a novel system for manipulating and updating achievable dose distributions in real-time. Preliminary studies show that it can be used interactively by the clinician to generate a 3D dose distribution and treatment plan in ~1-5 minutes. Dosimetric trade-offs are evaluated by direct manipulation of DVHs, isodoses, EUD or any other dose metric. Efficiency is further improved using automatic prioritized goal matching. A final off-line optimization step is used to derive treatment delivery parameters. An important application of the technique is in adaptive RT where strict time constraints are the norm.

OC-0072

Quantification of modulation degree for VMAT

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Purpose/Objective: The aim of this study is to present a modulation index for volumetric modulated arc therapy (VMAT) based on the speed and acceleration analysis of modulating-parameters such as multi-leaf collimator (MLC) movements, gantry rotation and dose-rate, comprehensively. In addition, texture analysis on fluence maps was performed to evaluate the degree of modulation for VMAT plans. **Materials and Methods:** In this study, modulation index for VMAT (MI_t) was designed as follows.

Gantry speed & dose rate at each control point: $GS_i = \frac{Gantry\ angle_i - Gantry\ angle_{i+1}}{Time_i}$, $DR_i = \frac{MU_i - MU_{i+1}}{Time_i}$

Gantry acceleration & dose rate variation: $GA_i = |GS_i - GS_{i+1}|$, $DRV_i = |DR_i - DR_{i+1}|$

Weighting factors: $W_{GA,i+1} = \frac{\beta}{\left\{1+(\beta-1)\cdot e^{-\frac{GA_i}{\gamma}}\right\}}$, $W_{MU,i+1} = \frac{\beta}{\left\{1+(\beta-1)\cdot e^{-\frac{DRV_i}{\gamma}}\right\}}$

$$z_{total}(f) = \left(\frac{1}{(N_{cp}-2)}\right)\cdot\sum_{i=1}^{N_{cp}}\{N_i\left(f;\ \begin{matrix} MLC\ speed_i > f\sigma_{MLC\ speed}\ or \\ MLC\ accel_i > af\sigma_{MLC\ accel}\end{matrix}\right)\cdot W_{GA,i+1}\cdot W_{MU,i+1}\}$$

$$individual\ MI_t = \int_0^k z_{total}(f)\,df \quad (k = 0.2, 0.5, 1 \text{ and } 2)$$

$$MI_t = \sum_{n=1}^{120} individual\ MI_{t\,n}$$

A total of 40 VMAT plans were retrospectively selected. To investigate the deliverability of each VMAT plan, gamma passing rates and differences in modulating parameters (MLC positions, gantry angles, and MUs at each control point) between VMAT plans and dynamic log files registered by the linac control system during delivery were acquired. Furthermore, differences between the original VMAT plan, and the plan reconstructed from the dynamic log files were also investigated. A total of 6 textural features including angular second moment (ASM), inverse difference moment (IDM), contrast, variance, correlation and entropy were calculated for fluence maps generated from VMAT plans (particular displacement distances, d = 1, 5 and 10). To test the performance of the MI_t and textural features as indicators for the modulation degree of VMAT plans, Spearman's rank correlation coefficients (r_s) with the plan deliverability were calculated. For comparison purposes, conventional modulation indices for VMAT including the modulation complexity score for VMAT (MCS_v), leaf travel modulation complexity score (LTMCS) and modulation index supporting station parameter optimized radiation therapy (MI_{SPORT}) were calculated, and their correlations were analyzed in the same way.
Results: In the case of textural features, contrast (d = 1) and variance (d = 1) generally showed considerable correlations with every type of plan deliverability. These textural