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Improving Aperture Control Methodologies for Optimization of Volumetric Modulated Arc Therapy (VMAT)

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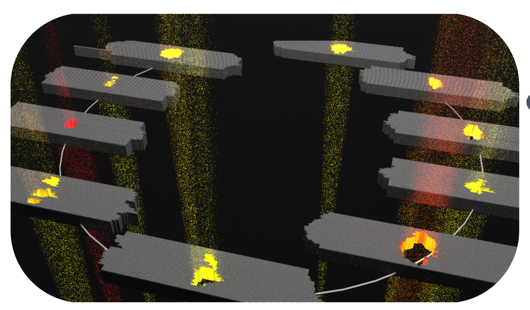
External Beam Radiation

Radiation Therapy is used in the treatment of cancer. The challenge is to deliver a prescribed dose of radiation to tumors while simultaneously protecting healthy organs from toxic dose levels.
In VMAT, the gantry and couch rotate describing a sphere of beams around the patient. Radiation is delivered through a dynamic multi-leaf collimator.

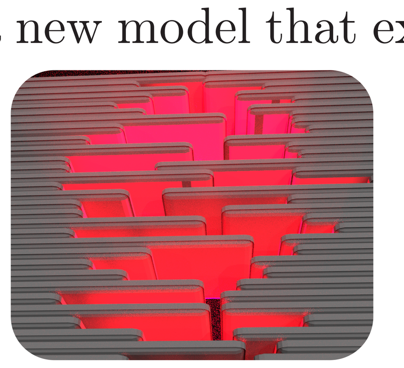
Modeling Delivery:



- Gantry path is discretized into control points
- At each control point we specify multi-leaf collimator (MLC) leaf positions, gantry rotation speed and dose rates
- Structures are discretized into voxels in order to calculate doses, given intensities and aperture shapes
- Built-in software extrapolates leaf positions and rotation speed between control points in order to deliver continuous treatment

Aperture Shape Irregularities

Conventional models sometimes produce apertures with irregular shapes. Aperture shape irregularity results in decreased dosimetric accuracy. We propose a new model that explicitly controls aperture quality.



- We prefer "round" and "big" apertures
- We propose an optimization model that explicitly penalizes irregular aperture shapes

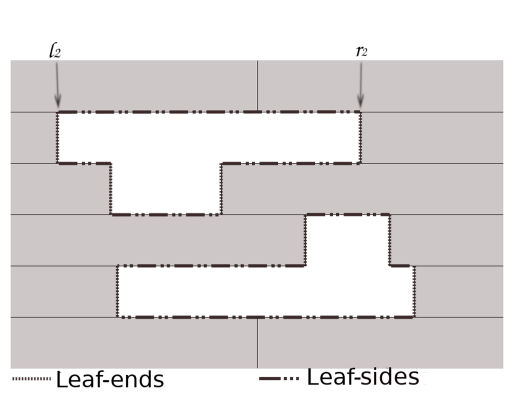
Aperture Quality Measures

- Younge's Measure of Aperture A [1]:

$$\mathscr{P}(A) = \frac{\tilde{C}_1\mu(A) + \tilde{C}_2\lambda(A)}{\text{area}(A)}$$

- Our Measure:

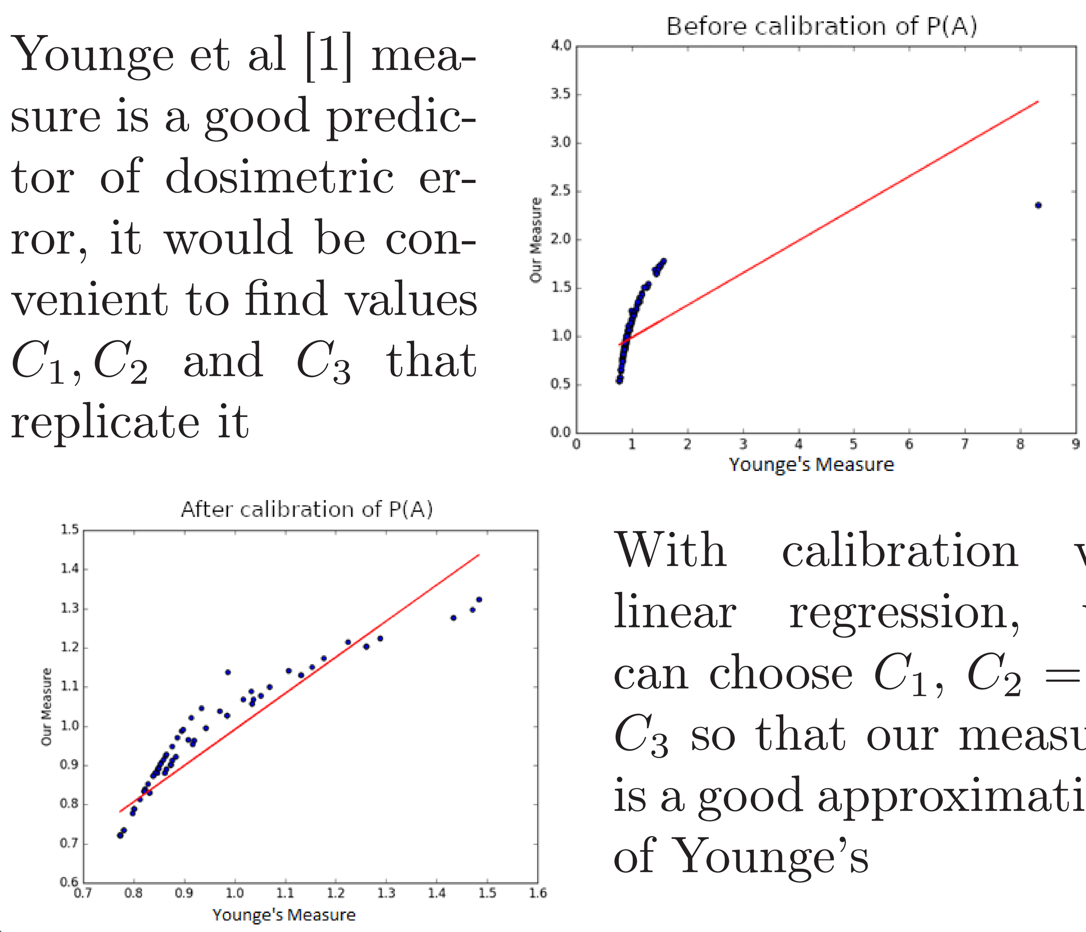
$$P(A) = C_1\mu(A) + C_2\lambda(A) - C_3\text{area}(A)$$



where $\mu(A)$ and $\lambda(A)$ are the lenghts of the aperture perimeter defined by the leaf-ends and sides

Parameter Calibration

Younge et al [1] measure is a good predictor of dosimetric error, it would be convenient to find values C_1, C_2 and C_3 that replicate it



With calibration via linear regression, we can choose C_1, $C_2 = 0$, C_3 so that our measure is a good approximation of Younge's

Proposed Model

$$\begin{aligned}
\underset{\substack{y_k, z_v, A_k \\ k\in\{1,\ldots,K\} \\ j\in\mathcal{V}}}{\text{minimize}} \quad & F(z) + C\sum_{k=1}^{K} P(A_k)y_k \\
\text{subject to} \quad & z_v = \sum_{k=1}^{K} D_{kv}(A_k)\delta_k y_k,\ v\in\mathcal{V} \\
& y_k \in [0, Y^U],\ k = 1,\ldots,K \\
& S^L \le S^U_{k,k+1}(A_k, A_{k+1}),\ k = 1,\ldots,K \\
& A_k \in \mathcal{A},\ k = 1,\ldots,K.
\end{aligned}$$

Parameters:
- $\mathcal{A}$: Set of admissible apertures
- Y^U: Intensities upper bound
- δ_k: Angular length between control points
- S^L: Lower bound on gantry speed

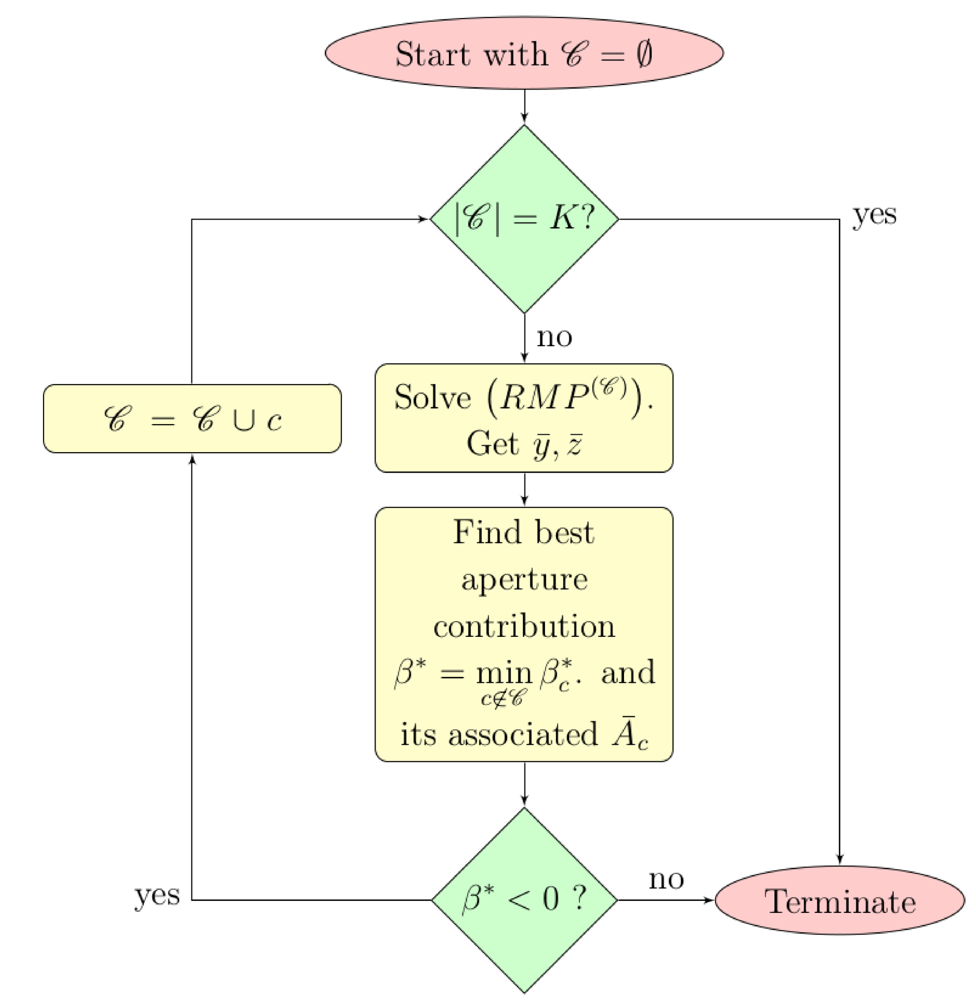
Variables:
- z_v: Dose to voxel v
- y_k: Intensity at control point k [a]
- A_k: Aperture choice at control point k

Model Components:
- $D_{kv}(A_k)$: Contribution to dose at v from aperture A_k
- $F(z)$: voxel-based convex piece-wise quadratic penalty function reflecting quality of dose distribution z
- $S^U_{k,k+1}(A_k, A_{k+1})$: Maximum gantry speed that allows MLC transitions from A_k to A_{k+1}
- $P(A_k)$: Aperture shape penalty
- $\mathcal{C}$: Set of selected apertures

[a] Intensity = dose rate / transversal time between Control Points

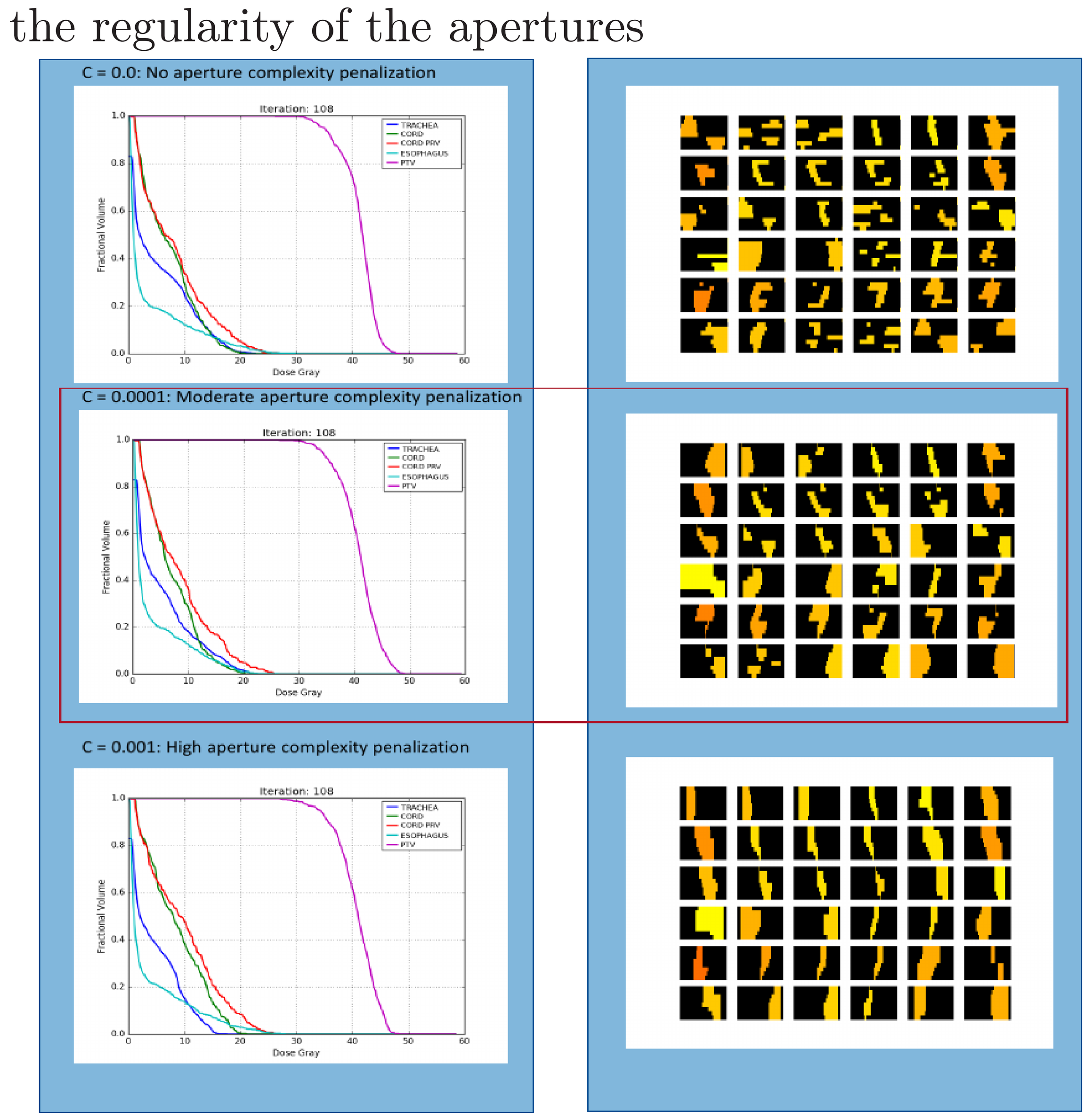
Column-Generation Heuristic

The proposed problem is not convex and it is difficult to solve exactly; therefore, we propose a greedy column-generation-based heuristic to solve the problem approximately:



Impact of $C \ge 0$ on Plan Quality and Aperture Shapes

In this spine case: As penalization increases so does the regularity of the apertures



Results

- Our model's penalization (P) is directly related to our goal (Younge et al., 2012): $\mathscr{P} = \frac{\tilde{C}_1\mu(A) + \tilde{C}_2\lambda(A)}{\text{area}(A)}$; "adding this edge penalty to the optimization cost function dramatically reduces the number of pixels failing dose difference criteria" The table below shows values of Younge's penalization for plans computed with different values of our penalization weight (C) for the spine case:

Penalization Weight	$C = 0$	$C = 10^{-5}$	$C = 10^{-4}$	$C = 10^{-3}$
$(\mathscr{P})$ Avrg. Edge Penalization	6.37	5.87	5.16	4.61

Younge,et al. show that $(P) \approx 6\%$ reduces 10% inaccuracies by $\approx 60\%$

We are able to achieve 19% improvement in edge metric penalization, preserving treatment quality

- Similar results were obtained in a Head and Neck, a Lung, a Spine and a Brain case.

Conclusions

- We incorporated aperture complexity penalization within a complex VMAT optimization heuristic
- Experiments demonstrate that our model can create plans that are less complex and therefore suffer from less delivery errors, with minimal changes in plan quality
- This approach can be used in a clinical setting
- Future work will extended this approach to different treatment sites

References

1. Younge K., Matuszak M., Moran J., McShan D., Fraass B., Roberts D. Penalization of aperture complexity in inversely planned VMAT. Medical Physics. 2012. 39, 11. 7160-70.
2. Peng F., Jia X., Gu X., Epelman M. Romeijn E., Jiang S. A new column-generation-based algorithm for VMAT treatment plan optimization. Physics in Medicine and Biology. 2012. 57, 14. 4569-4588.
3. Peng F. Jiang S., Romeijn E., Epelman M. VMATc: VMAT with constant gantry speed and dose rate. Physics in Medicine and Biology. 2015. 60, 7. 2955-2979.
4. Romeijn E., Ahuja R., Dempsey J., Kumar A. A Column Generation Approach to Radiation Therapy Treatment Planning Using Aperture Modulation. SIAM Journal on Optimization. 2005. 15, 3. 838-862.