Multi-criteria beam angle IMRT optimization with iCycle

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Introduction

An essential ingredient for making a good treatment plan for radiation therapy treatment is the selection of suitable beam angles. A sub-optimal beam angle configuration limits the possibilities of optimization. However, just as with normal IMRT optimization, the trade-offs between the PTV and OARs are not clear a priori. The introduction of multi-criteria optimization offered an intuitive planning approach.

Our work extends the concept of intuitive multi-criteria planning to the beam angle optimization phase of the planning. A prioritized prescription list (or 'wish-list') used for a priori multi-criteria optimization is also used to guide the beam angle optimization.

This results in an intuitive approach for automated beam angle optimization, where coplanar as well as non-coplanar directions can be considered. Significant improvement is found for the most important organ at risk.

Wish-list in IMRT optimization

A wish-list is a list with constraints (criteria which have to be met in any case) and objectives. Each objective has a priority of importance of meeting its goal. The multi-criteria optimization, which is a variant of the ϵ-constraint optimization, is performed in 2-steps [1]:

Step 1 Each objective is optimized in priority up to, but not less, than its goal. If the objective can reach its goal, the objective is constrained to its goal, otherwise the obtained optimal value is used as constraint. Then the next objectives are optimized according to this rule.

Step 2 Each objective which met its goal in the first step is optimized to its fullest.

This method assures a Pareto optimal solution which tries to meet more important objectives prior to meet lesser important objectives. It is not guaranteed that the goals will be met, hence the name 'wish-list'. The goal is usually set to a value below which the OAR is considered spared (e.g. $26\ Gy$ for a parotid gland).

An example wish-list for a patient with a sinus maximus carcinoma is given in table 1. This patient has 2 PTVs with prescribed doses of 46 and $66\ Gy$ respectively. Their maximum dose is limited at 107%. A ring of $1\ cm$ thick at $1\ cm$ distance of the PTV is constructed to enforce conformity, with a maximum dose of 85% of the prescribed dose.

The organs at the left side of the patient overlap with the PTV and can therefor not be spared. The highest priority objectives are those for the PTVs. The LTCP is to be minimized less than 1, which is the value corresponding to a homogeneous dose. An LTCP of 0.5 is considered *Sufficient* (for LTCP values < 1 the dose tends to be maximized beyond the prescribed dose). When the dose to the PTVs is maximized, the next priority is sparing of the right eye by means of an EUD, with parameter 15 to focus on the reduction of high dose. Then it is tried to spare the parotid gland, the submandibulary gland and the larynx.

If the EUD for the eye in the first step is less than $20\ Gy$, the limit is set to $20\ Gy$ and the dose to the right parotid is minimized. In the second step, the dose is the eye is minimized to its fullest. Otherwise, if the EUD for the eye in the first step cannot be minimized less than $20\ Gy$, the obtained result is used as a limit and further minimization is skipped in the second step.

At the end of the second step, the mean dose to the unspecified tissue is minimized to reduce unnecessary dose.

The advantage of such a wish-list is that the values are patient independent and the selection and ordering of criteria is intuitive. The same list for patients with identical tumour types can be used as a class-solution. [2]

Table 1: Wish-list for head-and-neck patient with 2 PTVs

Constraints

Nr	Volume	Type	Limit
1	PTV66	max	$70.62\ Gy$
2	PTV46	max	$49.22\ Gy$
3	PTV66Ring	max	$56.1\ Gy$
4	PTV46Ring	max	$39.1\ Gy$
5	Myelum	max	$50\ Gy$
6	Nerves†	max	$55\ Gy$
7	Eyes	max	$60\ Gy$
8	Unspecified Tissue	max	$72\ Gy$

Objectives

Priority	Volume	Type	Goal	Sufficient
1	PTV66	min LTCP	1	0.5
2	PTV46	min LTCP	1	0.5
3	Eye (R)	min EUD	$20\ Gy$	
4	Parotid (R)	min mean	$26\ Gy$	
5	Subman. Gland (R)	min mean	$35\ Gy$	
6	Larynx	min mean	$35\ Gy$	
7	Unspecified Tissue	min mean		

† Brainstem, Sella, Optic Chiasm, Optical Nerves

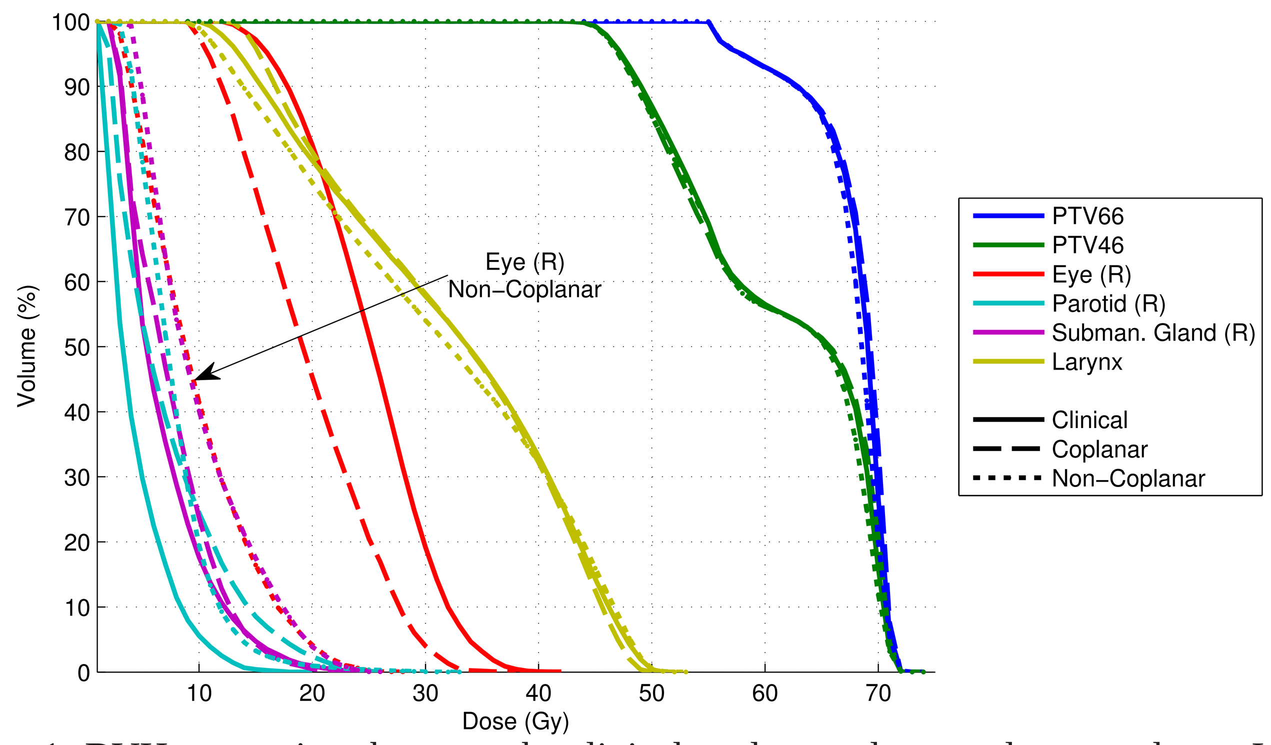


Figure 1: DVH comparison between the clinical angles, coplanar and non-coplanar. It is clear that with comparable tumour control, the dose to the right eye can be decreased significantly by using automated coplanar and non-coplanar beam selection.

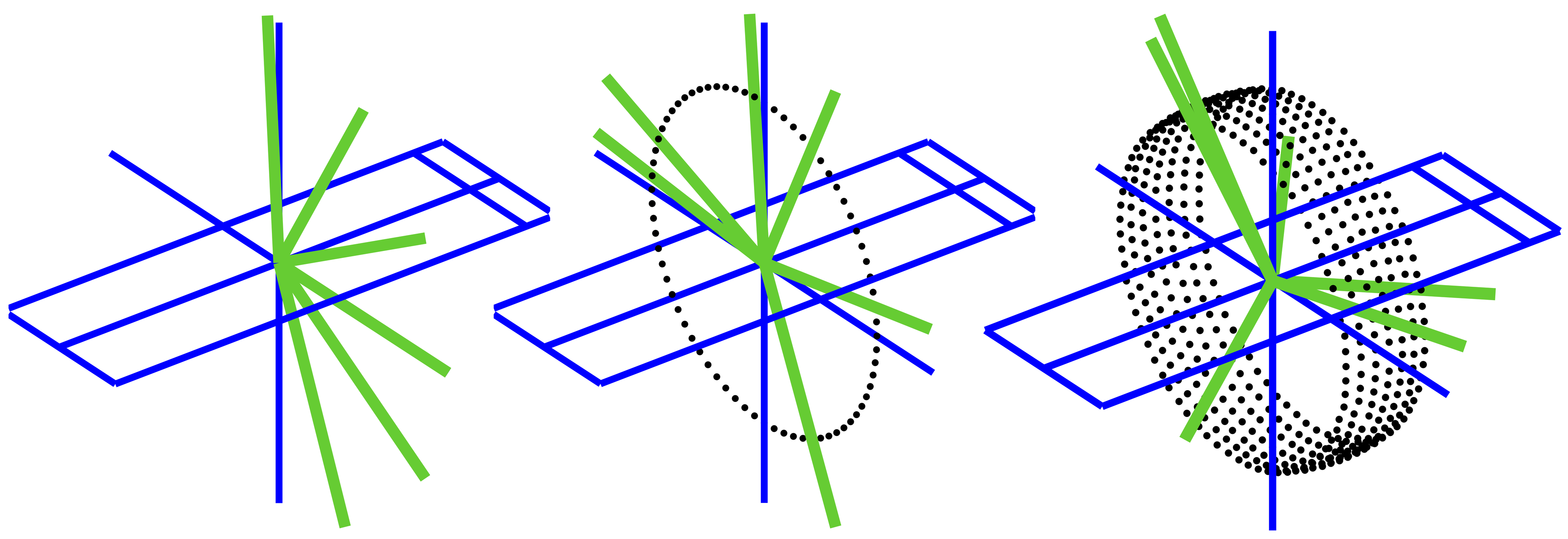
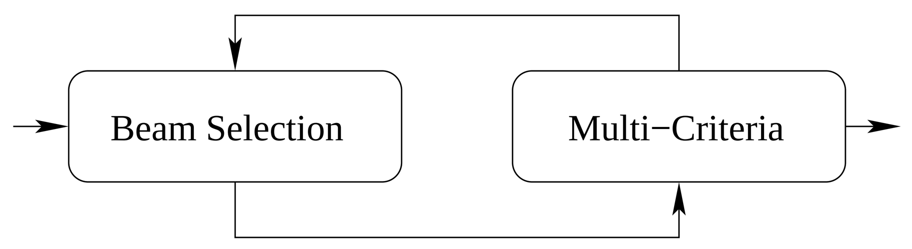


Figure 2: Beam directions for the clinical plan, coplanar and non-coplanar. The blue lines represent the treatment couch, with the location of the head at the double blue lines. The dots represent the beam candidate directions. The clinically used directions were selected by an experienced planner.

Beam angle optimization

The beam angle optimization is divided in 2 phases: the *beam selection* phase and *multi-criteria optimization* phase:



In the beam selection phase, all OARs are constrained and the dose to the PTVs is maximized. The constraints for the objectives result from the previous multi-criteria optimization (in the first iteration, all objectives are constrained to their goals). These optimizations are done with all previous selected beams plus a candidate beam direction.

The beam direction being able to deliver the highest dose to the PTVs is selected.

In the next phase, a multi-criteria optimization is done to obtain a Pareto-optimal solution and find new constraints for the next beam selection phase. From the result, new constraints are determined for the objectives to be used in the next beam selection phase. If the obtained value for an objective is lower than its goal, the constraint is set to its goal. Otherwise the constraint is set to the obtained value.

This strategy encourages that the dose contribution of the next selected beam is to the OARs which have not yet reached their (critical) goal value and minimizes additional dose to OARs which have already exceeded their limits.

Since it is not necessary to specify a maximum number of beams in advance, these steps can be repeated until the user is satisfied with the plan quality (or that the addition of an extra beam does not improve the plan quality enough to justify the prolonged treatment time). See table 2.

In the first 3 iterations, the prescribed dose for the PTVs is reduced because it is not possible to make a sane treatment plan with only 1 or 2 beams. Almost all OARs will be overdosed and it is not possible to make a good estimate which and how much the OARs can be spared. The reduction of the prescribed dose is set to 55%, 66% and 82% for 1, 2 and 3 beams respectively.

Results

To make a fair comparison with the clinical case, a multi-criteria optimization is done with the beams used in the clinical plan, using the wish-list. Then a coplanar and non-coplanar optimization was done, until an equal number of beam directions were used as in the clinical plan (6). The comparison is done using dose-volume histrograms in figure 1 and the selected beam directions, shown in figure 2. The improvement from 4 to 6 beams is given in table 2.

The tumour control improves with each beam added. The dose to the OARs generally decrease, but sometimes increases in favor of a higher order objective: the improved tumour control with 6 beams results in a slightly increased dose to the right eye.

Table 2: Numerical results for 4-6 coplanar beam directions.

		No. Beams		
Priority	Volume	6	5	4
1	PTV66	208.1	219.7	241.7
2	PTV46	0.5	0.5	0.5
3	Eye (R)	25.4	24.7	27.3
4	Parotid (R)	6.0	10.3	11.7
5	Subman. Gland (R)	6.3	4.8	4.0
6	Larynx	30.9	30.2	29.3
7	Unspecified Tissue	4.8	4.7	4.7
	Optimization Time (h)	9.0	6.7	4.3

Conclusions

The highest priority objective is irradiating the tumours. Here a strict improvement is seen for each beam added. In comparing clinical, copanar and non-coplanar beam angles, a clear improvement is seen for the right eye, the highest priority OAR. The parotid and submandibulary gland deteriorate slightly with automated coplanar selected angles and more for the non-coplanar setting, but the doses are still well within their limits of $26\ Gy$ and $35\ Gy$ respectively.

We conclude that automated beam angle optimization with iCycle can significantly improve treatment planning. Currently, iCycle is already in use for research on single vocal cord irradiation. [3]

References

[1] Breedveld S, Storchi P and Heijmen B 2009 Equivalence of multi-criteria methods *submitted*, [2] Breedveld S, Storchi P, Keijzer M, Heemink A and Heijmen B 2007 A novel approach to multi-criteria inverse planning for IMRT *Phys. Med. Biol.* **52** 6339-6353, [3] Osman S, Astreinidou E, Keskin-Cambay F, Breedveld S, de Boer H, Al-Mamgani A, Heijmen B and Levendag P 2009 IMRT In Image-Guided Single Vocal Cord Irradiation *ESTRO 2009*