MULTI-CRITERIA OPTIMIZATION IN RAYSTATION

A constant difficulty encountered in radiation therapy treatment planning is the patient-specific tradeoff between ensuring appropriate tumor coverage and avoiding excessive radiation to healthy structures. Such tradeoffs are conventionally resolved by manually altering an optimization problem formulation and re-optimizing the treatment plan multiple times. Trial and error of this form is time consuming and even if a treatment plan deemed satisfactory is found, it is not clear if better treatment options exist for the current patient. Multi-criteria optimization (MCO) provides an alternate workflow where explicit (i.e., fixed) importance weights to planning objectives are avoided. A comprehensive representation of all relevant treatment plans is instead navigated in a continuous fashion, thereby allowing tradeoffs between conflicting objectives to be explored in a more intuitive manner.

PARETO SURFACE REPRESENTATION

MCO identifies the set of relevant treatment plans as those that are Pareto optimal with respect to the user-specified set of tradeoff objectives and constraints. A plan is Pareto optimal if it is feasible with respect to all constraints and no objective can be improved without impairing at least one other. The infinite number of plans that satisfy this criterion is approximated by a discrete set of plans that give different emphasis to the considered planning objectives.

Algorithmic details: Pareto surface approximation algorithm
- Pareto optimizations are performed using beamlet intensities, resulting in fluence-based dose distributions
- The first $N$ plans, where $N$ is the number of objectives, are called anchor plans and generated by optimizing each objective individually
- The $(N+1)$th plan is called the balance plan and gives equal emphasis to all objectives
- Additional plans beyond the $(N+1)$th are called auxiliary plans and constructed towards improving the current Pareto surface representation as much as possible
- When the number of objectives is below ten, auxiliary plans are generated towards minimizing the distance between an inner and outer approximation of the image of the Pareto set in objective function space [1]

Algorithmic details: navigation algorithm
- For ten objectives and more, auxiliary plans are generated by giving emphasis to pairwise combinations of objectives, with pairs selected according to maximum degree of anti-correlation

NAVIGATION

Navigation of the Pareto surface is performed by continuously forming combinations of plans from the discrete Pareto surface representation. The navigation algorithm takes input from a set of slider controls corresponding to each tradeoff objective.

Algorithmic details: navigation algorithm
- User input from the slider controls is converted into movements along smooth trajectories in objective function value space that connect the best possible point for the associated tradeoff objective with the corresponding worst possible point
- The navigated dose is updated in real-time by interpolation over the dose distributions associated with the Pareto optimal plans
- The navigation trajectories are computed by solving linear programs with convex coefficients of the plans in the discrete Pareto surface representation as variables.

Anchor plans represent extreme tradeoffs
GENERATING A DELIVERABLE PLAN
A navigated dose distribution corresponds to a linear combination of fluence-based dose distributions. To obtain a deliverable treatment plan, the best approximation of the navigated dose is determined by direct machine parameter optimization. The goal is here to minimize the error in dose volume histogram (DVH) between the navigated solution and the deliverable plan. The DVH curve error is summed over a user-specified set of regions of interest, with the default being all structures associated with at least one tradeoff objective or constraint.

Algorithmic details: “dose-mimicking” algorithm
- The objective function during generation of a deliverable plan is a weighted sum of reference DVH functions that impose a one-sided quadratic penalty on DVH curve error
- Functions associated with organs at risk (OARs) are given unit weight while functions associated with targets are given a weight equal to a user-defined target priority
- Reference DVH functions associated with OARs penalize overdosage with respect to the navigated DVH over the entire volume interval, whereas reference DVH functions associated with targets penalize overdosage for relative volumes in the interval [0, 0.5) and underdosage in the interval [0.5, 1.0]

IMPACT ON THE TREATMENT PLANNING WORKFLOW
Ultimately, MCO seeks to decrease manual planning time, to provide better understanding of tradeoffs between conflicting planning goals, and to improve treatment plan quality. These goals have been critically assessed in a series of studies conducted at Massachusetts General Hospital (MGH), Boston. In a comparative study between standard inverse planning and MCO for treatment of patients with glioblastoma or pancreatic cancer, it was reported that MCO leads to an average reduction in treatment planning time from 135 minutes to 12 minutes [2]. Blind tests conducted during this study also revealed that physicians judged the treatment plans generated by MCO as superior to the conventionally optimized plans. It is important to note, that physician involvement time did increase from 5 minutes to 10. However, benefits described above outweighed this increase, producing better plans in a much more efficient time frame for the planner. In an analysis of 10 anal cancer patients, the MGH team showed that physicians navigate to plans with much higher sparing of the small bowel compared to the as-treated (non-MCO) plan [3]. This study echoed the paper by Craft et al., [2] in showing that when physicians perform the Pareto surface navigation, they select plans with higher DRR sparing at the expense of slightly more target underdosing. A retrospective planning study of nine prostate patients again showed that MCO yielded intensity-modulated radiation therapy (IMRT) plans which were preferred by the physicians in blinded tests [4]. For this study, two physicians were asked to score each MCO plan and each traditionally derived plan, and in all cases the MCO scores were superior to the non-MCO scores.

THE FUTURE
Multi-criteria optimization is a module in RayStation, which is a fully featured Treatment Planning System available in North America, Europe and Asia. The future of multi-criteria optimization holds many possibilities in other areas such as volumetric-modulated arc therapy planning and proton planning. RaySearch is working towards DMCO (Direct Multi-Criteria Optimization), where one could navigate segmented base plans which would further improve the efficiency of the planning process. Another future improvement is prioritized optimization tradeoffs that would result in a stronger “balance plan” or starting point. RaySearch Laboratories is committed to continually advancing this technology to make IMRT planning more controllable, intuitive and efficient.

CONCLUSION
Multi-Criteria Optimization is a new way of approaching intensity-modulated radiotherapy planning. In essence, planners and physicians will be able to find solutions they didn’t know existed previously and they will be able to do so in an efficient manner.

REFERENCES

MCO has a great potential to change how clinical radiotherapy treatment planning is done. By allowing physicians and planners to interactively navigate the solution space, the tradeoffs inherent in radiation dose shaping are precisely conveyed, allowing for better patient care and more efficient use of oncology center resources.