ROBUST OPTIMIZATION IN RAYSTATION

Setup errors, density errors, and organ motion can lead to delivered dose distributions that deviate highly from the planned distributions in radiation therapy. The conventional method to take errors into account during treatment planning is to plan with margins such as when using PTVs. For cases of heterogeneous density, and especially in particle planning, conventional margins often cannot provide the intended robustness against uncertainties.

ROBUST METHOD

To enable the creation of robust plans for cases where conventional margins do not work, RayStation implements a robust optimization method that explicitly considers the effects of possible errors. RayStation can simulate setup and density errors, as well as utilize multiple images in the optimization of organ motion. The optimization then strives for plans that are robust against these effects. The basis of this method is minimax optimization, in which the optimization functions that have been selected to be robust are considered under the worst case scenario [1]. The worst case scenario is the realization of uncertainty under which a robust function attains its highest value. If several functions are selected to be robust, their weighted sum in the worst case scenario is considered. Minimax optimization of n functions $f_1,\ldots,f_n$ which are all required to be robust over the scenarios enumerated by the set S, and which have non-negative importance weights $w_1,\ldots,w_n$, can be formulated as an optimization problem on the form

$$\min_{x\in X} \max_{s\in S} \sum_{i=1}^{n} w_i f_i(d(x;s)), \quad (1)$$

where X is the set of feasible variables (e.g., MLC leaf positions and segment weights for IMRT or spot weights for IMPT), and $d(x;s)$ is the dose distribution as a function of the variables x and the scenario s. Functions considering the dose in the nominal scenario only can also be added to the objective. Moreover, nominal and robust constraints can be used in combination with formulation (1). RayStation supports robust optimization for step-and-shoot IMRT, DMLC, VMAT, Tomotherapy, and actively scanned protons and carbon ions.

UNCERTAINTIES

The set of scenarios forms a discretization of the errors against which the plan should be robust. Each scenario determines a specific combination of a setup and a range error and a patient image. Setup uncertainties are specified like an expansion of an ROI, range uncertainty is specified as a percentage, and organ motion uncertainty is specified by the inclusion of multiple CT images, see Figure 1. The setup uncertainty can be the same for all beams, independently affect beams with different isocenters, or independently affect each beam. The latter cases can be used to create robustly matched fields. The inclusion of multiple CT images in the robust optimization process addresses situations where there is significant motion of internal organs, for example in the thorax during free breathing or partially gated treatments, where robust optimization on the CTV can be used in place of an ITV. The image data may originate from any source, such as a 4D-CT, or from simulation of the organ motion performed in the Deformable Registration module of RayStation.

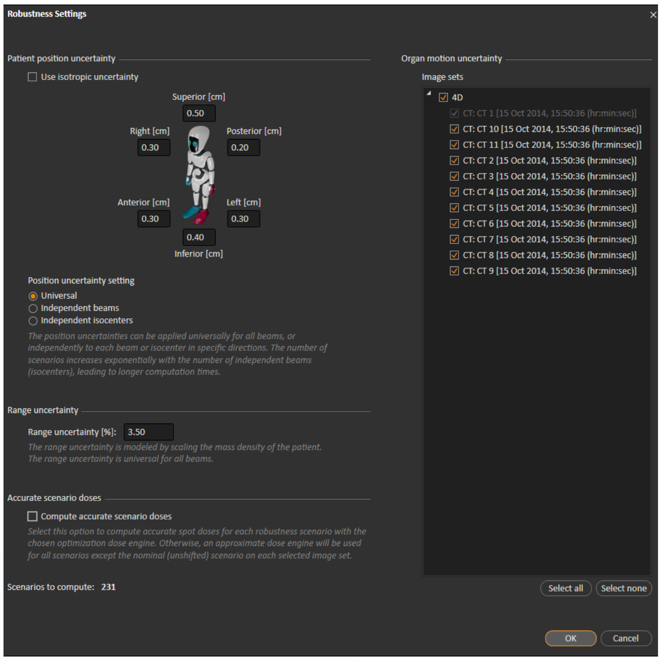
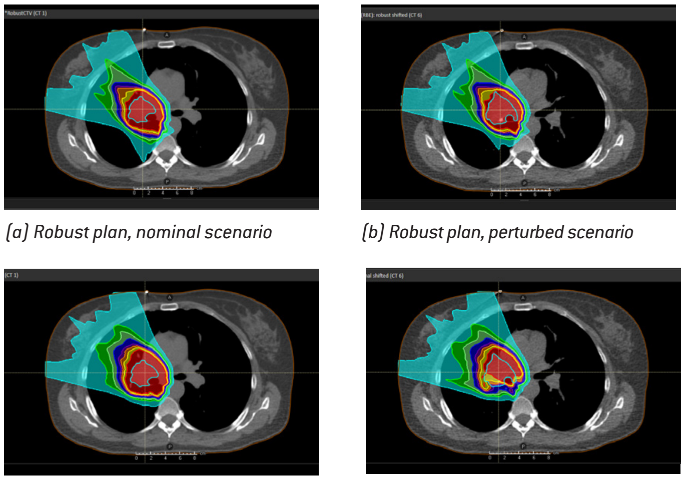


Figure 1. *In the robustness settings dialog, the user can specify the maximum magnitude of the uncertainties to take into account, and the images to consider.*

Example 1 (Figure 2)
Robust optimization for IMPT applied to a 4D-CT lung case subject to at most 0.5 cm setup errors and 3.0 % density errors was compared to margin-based planning. The ten phases of the 4D-CT were included in the robust optimization. Transversal slices of the planning CT (CT 1) under the nominal scenario and of a non-planning CT (CT 6) under a perturbed scenario are shown in Figure 2. The figure illustrates that robust optimization can lead to improved robustness at the same time as decreased integral dose compared to conventional margins.

Figure 2.



(a) Robust plan, nominal scenario

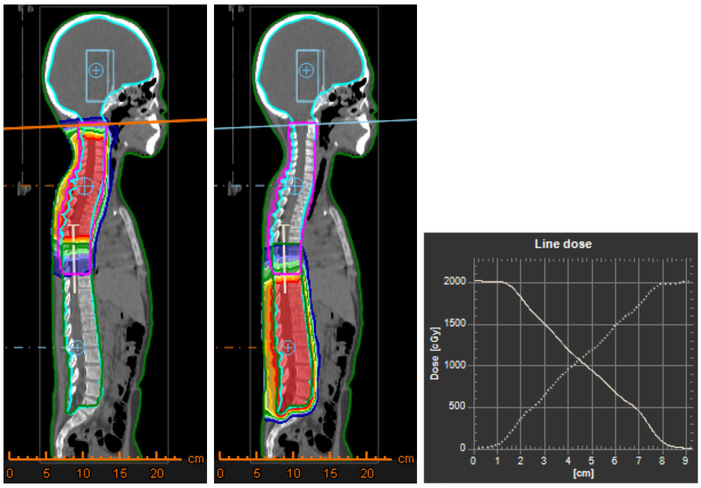
(b) Robust plan, perturbed scenario

(c) Margin-based plan, nominal scenario

(d) Margin-based plan, perturbed scenario

Example 2 (Figure 3)
Robust optimization was applied to a craniospinal case treated with IMPT. Setup uncertainty along the craniospinal axis affecting the beams independently was assumed for the optimization to yield robustly matched fields. Figure 3 shows the resulting field junction between the lower and upper spine fields.

Figure 3.

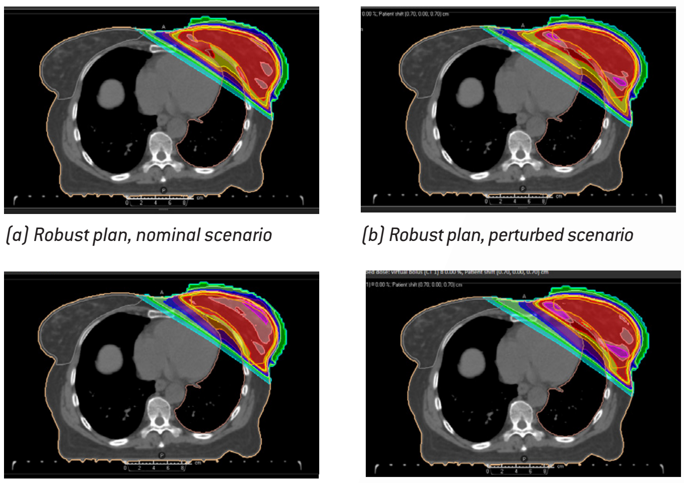


(a) *(b)* *(c)*

Beam doses of the beams irradiating (a) the upper and (b) lower spine.
(c) The line dose over the field junction.

Example 3 (Figure 4)
For a breast case treated with IMRT, robust optimization was used to achieve target coverage in the case of setup variations. It was compared to the virtual bolus method, in which the PTV is extended into the air anterior to the patient, and a virtual bolus is used during planning to prevent optimization to air. Figure 4 shows that robust optimization resulted in more homogeneous target dose and lower skin dose than the virtual bolus method.

Figure 4.



(a) Robust plan, nominal scenario

(b) Robust plan, perturbed scenario

(c) Virtual bolus plan, nominal scenario

(d) Virtual bolus plan, perturbed scenario

STUDIES

RayStation's robust optimization applied to treatment planning for IMPT has been found to improve robustness compared to margin-based IMPT planning, also when the margin-based planning uses the single-field uniform dose technique [1,2]. For VMAT, RayStation's robust optimization has been found to provide greater stability in dose variations compared to other techniques for mitigating motion effects in lung [3], and for step-and-shoot IMRT, it has been shown to be an effective means of achieving superficial target coverage in breast [4] and to deliver more conformal plans with superior cortical sparing than conventional planning in glioblastoma patients [5].

CONCLUSION

Robust optimization in RayStation provides robustness in cases where conventional margins fail. This ensures that the precision of particle therapy can be utilized even in the presence of uncertainties. In photon planning, the method can yield less dose variations, more conformal plans, and reduced OAR doses compared to convetional methods. Moreover, it can be used to solve other problems in radiation therapy, such as robust field matching and skin flash.

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