A multiobjective optimization framework applied to intensity-modulated radiation therapy

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Abstract. Radiation therapy treatment planning is inherently a multiobjective problem, aiming to balance delivering the prescribed dose to the tumor while minimizing exposure to surrounding healthy organs. Various multiobjective approaches have been developed to optimize radiation intensities for fixed beam irradiation directions. However, multiobjective beam angle optimization is rarely addressed. This paper introduces a novel multiobjective optimization framework that simultaneously considers both intensity and beam direction optimization. While multiobjective optimization of radiation intensities with fixed beam directions results in a single Pareto front, optimizing beam angles leads to multiple Pareto fronts, each Pareto front corresponding to a different set of beam angles.

Our framework suggests selecting a beam angle set by evaluating the corresponding approximation of the Pareto-front through a set of non-dominated solutions that are calculated using a tree-based approach. A performance indicator is used to assess each Pareto front overall quality within a variable neighborhood search metaheuristic.

Illustrated using head-and-neck cancer cases, this approach provides greater flexibility in treatment plan calculation and a deeper understanding of the trade-offs between different objectives. Although it has been developed for this particular application area, the developed framework has the potential to be applied to other problems.

1 Introduction

Radiation therapy (RT) is a primary treatment for cancer, prescribed to over fifty percent of cancer patients for either curative or palliative purposes. The objective of RT is to deliver a dose of ionizing radiation to the tumor sufficient to eradicate tumor cells while minimizing damage to surrounding healthy tissues, which are also inevitably exposed to radiation. Thus, the success of RT is closely linked to the ability to deliver the prescribed dose to the tumor while sparing healthy organs and tissues as much as possible. Consequently, planning RT treatments is inherently a multiobjective problem, requiring the best trade-offs between delivering the prescribed dose to the tumor and sparing healthy tissues. These compromises are patient-specific, as each patient has a unique anatomy, so individualized treatment plans need to be considered and individualized treatment decisions must be made.

External beam radiation with photons, namely intensity-modulated radiation therapy (IMRT), is the most common form of RT used for cancer treatment. A linear accelerator (linac) mounted on a C-arm gantry rotates around the patient, who is immobilized on a treatment couch that can also rotate. The radiation beams exit the head of the gantry, which is typically equipped with a multi-leaf collimator (MLC). The MLC consists of parallel metal leaf pairs that shape the beam to conform to the tumor by moving the leaves horizontally, blocking parts of the beam as needed. The movement of the MLC leaves discretizes the beam into a grid of smaller beamlets with independent intensities. By irradiating the tumor from different beam directions and modulating the beam, a high and conformal dose can be delivered to the tumor while preserving nearby tissues, which must receive a dose below the defined tolerance level. Treatment planning is the critical preparatory process conducted before a patient undergoes radiation therapy, typically using a treatment planning system (TPS). Several decisions need to be made: calculating the optimal beam directions, beam intensities, and collimator sequences to meet the clinical requirements for the treatment. The process begins with a radiation oncologist delineating all structures of interest on the patient's computed tomography (CT) scans. These structures include the planning target volumes (PTVs)—the tumor volumes expanded by a safety margin—and the surrounding organs-at-risk (OARs). The doses to be delivered to the PTV are usually specified as dose-volume desirable values whilst maximum tolerance dose-volume thresholds are defined for OARs.

Operations research has played a crucial role in addressing various decision-making problems in RT.

2 The developed methodology

The work here described has been published in [2]. In this work a new approach is presented for optimizing radiation therapy treat-

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ment plans in IMRT, explicitly considering beam angle optimization. IMRT treatment planning can be interpreted as a two-level decision making problem, where the irradiation directions are decided first (beam directions), and then the intensity patterns or "fluence maps" for those fixed beam directions are also optimized. However, the best optimal solution for the fluence map optimization (FMO) must be considered when optimizing the beams. One very interesting aspect of this problem is the fact that, when beam angles are fixed, the multiobjective fluence map optimization problem will produce a continuous and convex Pareto front. The Pareto-front can be iteratively built considering linear combinations of existing non-dominated treatment plans. This is possible because new non-dominated treatment plans can be calculated by a simple weighted average of the radiation intensities of other non-dominated plans. However, this is no longer valid when we allow beam configuration to be changed. While a multiobjective formulation for the optimization of intensities considering a fixed set of beam directions gives rise to a single Pareto front, including the beam directions in the optimization gives rise to multiple Pareto fronts. The developed framework is motivated by these multiple Pareto fronts that can be generated when beam angle optimization is considered.

The Beam Angle Optimization (BAO) framework proposed in this work employs a variable neighborhood search (VNS) metaheuristic for optimizing beam angles. This method involves constructing a branching tree for each beam angle set, where each node represents a different FMO problem, considering various compromises between PTV coverage and OAR sparing. To encourage the calculation of non-dominated solutions, each tree level imposes more demanding dosimetric requirements for one of the structures of interest compared to the previous level. The goal is for the leaves of each tree to potentially represent solutions on the Pareto front for a given beam angle set. Ultimately, only treatment plans corresponding to non-dominated solutions across all trees (beam angle set Pareto fronts) are selected. The VNS-tree based method for BAO and FMO can be summarized as follows:

1. Initial FMO Problem: At the root node of each tree, for a given beam configuration, solve the initial FMO problem aiming to meet the dose constraints specified by the medical prescription. If the prescription constraints are unattainable, relax some of the constraints.
2. Branch Creation: Whenever an admissible solution is found at a node, create branches equal to the number of objectives. For each new node at this lower tree level, set a more demanding threshold than the dose goals achieved in the previous level for one specific objective. Stop branching when no admissible FMO solution is found (see Figure 1 for an example).
3. Non-dominated Solutions: Save the current set of non-dominated solutions for the current beam angle configuration and update the overall set of non-dominated solutions across all trees.
4. Guide Optimization: Use the information from this tree to guide beam angle optimization in the VNS.

For the BAO VNS approach, it is essential to compare different beam angle solutions so that we can properly guide the optimization towards an optimal beam angle set. Given the multiobjective nature of the problem, directly comparing the values of a single objective function is inadequate. Actually, a set of non-dominated solutions approximating the Pareto-front will be associated with each beam angle set. So, we have decided to use a metric that is able to compare different sets of non-dominated solutions, namely the R^2 metric, as described by [1]. This metric is applied to the non-dominated solution set associated with each beam angle solution, which is generated by the corresponding branching tree.

By the end of the optimization process, a set of non-dominated treatment plans is obtained by considering the Pareto fronts across all the different beam configurations explored by the VNS. The approach is illustrated on head-and-neck cancer cases, showing it can identify beam configurations achieving better tradeoffs between target coverage and organ sparing compared to the equispaced beam angles typically used clinically.

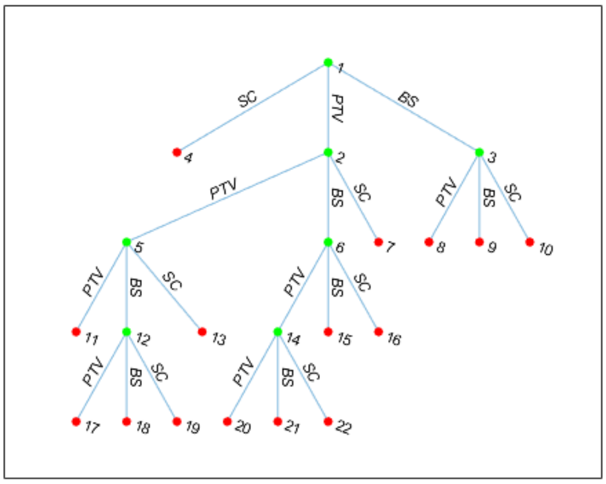

Figure 1. Example of a generated tree considering 3 objectives associated with 3 different strauctures

3 Conclusion

In summary, this work presents a multiobjective optimization framework that considers simultaneously the optimization of both the beam angles and fluence map intensities in IMRT planning, using a tree-based method to explore PTV-OAR tradeoffs and a beam angle optimization metaheuristic search (VNS) guided by evaluating non-dominated solutions sets. This approach was tested considering head and neck cancer cases and it was possible to conclude that it can be a useful tool for the planner to explore the existing trade-offs, without increasing the planner workload. This approach was able to generate high quality treatment plans, having the potential to improve treatment plan quality over standard approaches.

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References

[1] D. Brockhoff, T. Wagner, and H. Trautmann. On the properties of the $r2$ indicator. pages 465–472, 2012.

[2] J. C. de Freitas, D. R. Cantane, H. Rocha, and J. Dias. A multiobjective beam angle optimization framework for intensity-modulated radiation therapy. *European Journal of Operational Research*, 318(1):286–296, 2024.