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Intelligence-guided beam angle optimization in treatment planning of intensity-modulated radiation therapy

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ABSTRACT

An intelligence guided approach based on fuzzy inference system (FIS) was proposed to automate beam angle optimization in treatment planning of intensity-modulated radiation therapy (IMRT). The model of FIS is built on inference rules in describing the relationship between dose quality of IMRT plan and irradiated region of anatomical structure. Dose quality of IMRT plan is quantified by the difference between calculated and constraint doses of the anatomical structures in an IMRT plan. Irradiated region of anatomical structure is characterized by the metric, covered region of interest, which is the region of an anatomical structure under radiation field while beam's eye-view is conform to target volume. Initially, an IMRT plan is created with a single beam. The dose difference is calculated for the input of FIS and the output of FIS is obtained with processing of fuzzy inference. Later, a set of candidate beams is generated for replacing the current beam. This process continues until no candidate beams is found. Then the next beam is added to the IMRT plan and optimized in the same way as the previous beam. The new beam keeps adding to the IMRT plan until the allowed beam number is reached. Two spinal cases were investigated in this study. The preliminary results show that dose quality of IMRT plans achieved by this approach is better than those achieved by the default approach with equally spaced beam setting. It is effective to find the optimal beam combination of IMRT plan with the intelligence-guided approach.

1. Introduction

Intensity-modulated radiation therapy (IMRT) was developed in order to deliver a highly conformal dose to tumor while bearing surrounding normal tissue, especially critical organs, under clinically acceptable dose level. For achieving this goal, multiple beams with modulated fluence maps from different angles were required. In current state-of-the-art treatment planning systems of IMRT, once beam angles are determined fluence maps can be automatically computed by inverse planning optimization algorithms. Usually, the optimal combination of beam angles is unknown aforehand and has to be "guessed" by trial-and-error approach. Several researchers attempt to resolve this issue with different way [1–5]. It was found that the optimal combination of beam angles for IMRT plan tends to be an even distribution over an angular range of 0–2π [1]. It was also demonstrated that with increasing number of beams the quality of plan dose could be improved [2]. However, for the cases with irregular spatial distribution of interested anatomical structures equally spaced beam configuration may be less effective. Moreover, an increased number of beams results in prolonged treatment time, which may increase delivery error caused by involuntary patient movement and intra-fractional organ motion. Therefore, the optimization of beam angles should have taken spatial distribution of interested anatomical structures into account for an improved dose quality of IMRT plan [6–9].

In general, the approaches of Beam angle optimization (BAO) can be divided into two categories. The first category treats BAO as an independent part in addition to fluence map optimization (FMO). An optimal beam set is selected based on scores of beam angles using prior knowledge, then forwarded to FMO for plan dose distribution. It is efficient to determine a suitable beam set for FMO but the optimality of resulting beam set is not guaranteed. The second category treats BAO as an integrated part of FMO, and jointly optimizes beam angles and fluence map. With the inclusion of beam angles, the solution space of FMO is expanded and could be non-convex [1]. To avoid trapping in local minima, it is ideal to thoroughly search the solution space in order to achieve global minima with exhaustive search strategy [10,11]. The stochastic approach, such as simulated annealing and genetic algorithm, which have been previously used in inverse planning optimization,

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are also effective for the problem of BAO [12–16]. It is also feasible to find a global minima by mixed integer linear programming [17,18]. It should note that as a general flaw of stochastic approaches it is usually time-consuming. Besides stochastic approaches, heuristic approaches are able to find an optimal combination of beam angles for an IMRT plan. In addition, several metrics in characterizing the effect of beam on those interested structures, such as the entropy and Fourier transform measures [19], the maximum beam separation and minimized non-target irradiation [20], and the score of beam angle based on pseudo beam's-eye-view technique [21,22] were proposed. These metrics could keep those "favorable" beams while remove those "unfavorable" beams.

It is believed the experience of human planner is critical in guiding the process of BAO for an IMRT plan. However, most of prior knowledge of human planners is vague and hardly quantified for computer applications. So far, there are few studies in applying intelligence technique in BAO of IMRT treatment planning. Novel approach was proposed to use a pattern search method framework in the optimization of BAO problem [23]. Beam's-eye-view dose (BEVD) metric furnishes a prior knowledge in guiding the searching of optimal beam ensembles. Although BEVD represents an intuitive consideration of the deliverable dose capability to the target of a single beam direction, the whole BAO procedure is virtually dominated by optimization algorithm and less controlled by human knowledge. Machine learning technique, such as artificial neural network (ANN), was used to map anatomical features to beam angle scores and learn the relationship using clinically approved plans [24]. As beam scores obtained by ANN the following optimization algorithm will use them to avoid the unnecessary search directions. Recently the relationship between beam angles and anatomical features was modeled by advanced machine learning technique – forest regression algorithm [25]. It is capable of mapping a multitude of anatomical features into an individual beam score. An optimization scheme is then built to select beam while considering the inter-beam dependencies. The results are promising and would be helpful in reducing the manual planning workload.

Among those prior knowledge guide BAO algorithms, the scores of beams are derived from the clinically approved plan or provided by empirical function, and then used by optimization algorithms. It is rare that the prior knowledge of human reasoning process in trial-and-error procedure of beam selection is learned and then applied to guide the searching of the best beam ensembles. It is expected that there is a way to bridge the gap between vague knowledge in trial-and-error procedure and precise quantities used by computer software. As fuzzy inference system is dedicated to simulate the human reasoning process based on the vague knowledge, it is ideal for this problem. In this study we proposed an intelligence guided approach in assisting the process of BAO. It incorporates both metric of beam geometry and prior knowledge of human planner into the optimization process of beam angles. Similar as our previous studies of applying fuzzy inference system into the parameter optimization of inverse planning [26–29], the beam angles are another set of planning parameters outside of FMO and with different characteristics. The remainder of this paper was organized as follow. In materials and methods section the concept of CRI and the principle of FIS were introduced. The implementation of inverse planning algorithm for FMO employed was described, and the process of intelligence guided approach was explained. For testing purpose the detail of clinical case study was introduced. In results section, dose volume histogram (DVH), dose distribution, and CRI values of plans resulted by the intelligence approach and default approach were presented and analyzed. Finally the benefit and limitation of this approach was discussed.

2. Materials and methods

2.1. Covered region of interest

Coverage region of interest is a metric in measuring the region of an interested structure (PTV, OAR, etc.) under radiation field of a beam at a specific angle while beam aperture is shaped to target volume. In this study, it is assumed that there are three types of anatomical structures: target volume (TV), critical organ (CO), and normal tissue (NT). As shown in Fig. 1 one beam passes through the CT volume of a patient and intersects with the regions of TV, CO, and NT along its path. The overlapping regions between radiation path and interested structures are labeled with different textures in Fig. 1. Since beam aperture is conformal only to TV, partial volume of CO and NT are outside of radiation field. As shown in Fig. 1 two third of CO is outside of radiation field. The whole volume of TV is covered by radiation filed but its distance from radiation source is varied. The fraction of CO (and NT) inside radiation filed is changed by beam angle, and its distance from radiation source is also varied.

For computation of CRI, both fraction of interested structures inside radiation field and its distance to radiation source are considered. At first, the voxels of interested anatomical structure inside radiation field are counted. Then the inverses of distances between the voxel and radiation source are summed. Finally, the value of sum is normalized by the total number of voxels inside radiation field. This final value is CRI for the interested anatomical structure at a given beam angle. Its value represents the effect of a beam on an interested structure. Note that the distance was calculated as the center of voxel to the source and the partial volume effect was not considered. As radiation source closer to an organ, the value of CRI is increased, otherwise decreased. As the number of voxels inside radiation field increased, the value of CRI is increased. For TV, the beam with larger value of CRI is preferred since higher dose to tumor could be achieved. However, for CO and NT, the beam with smaller value of CRI is preferred since low dose could be achieved. As there are several CRI for different interested anatomical structures, it is better to represent them

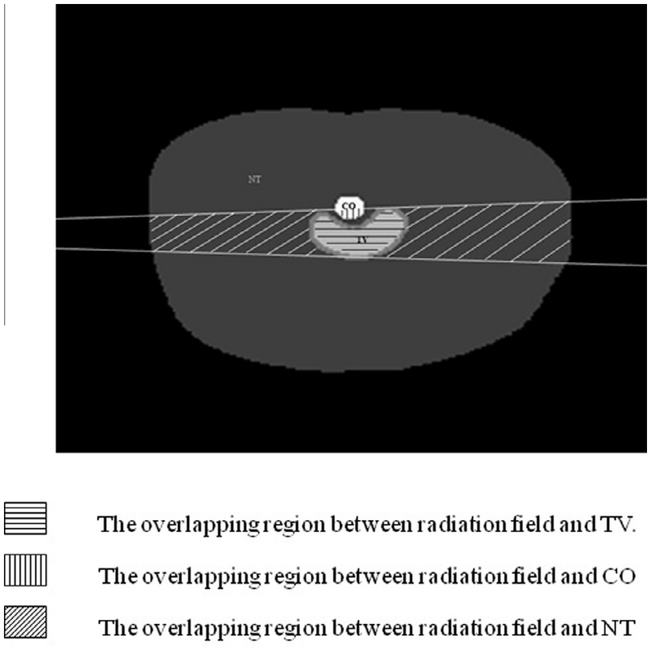

Fig. 1. Demonstration of single beam plan used for calculation of CRIs for TV, CO, and NT.

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