Beam Orientation Optimization Using Ant Colony Optimization in Intensity Modulated Radiation Therapy

Xi Pei, Ruifen Cao, Hui Liu, Chufeng Jin, Mengyun Cheng, Huaqing Zheng, Yican Wu, FDS Team

***Abstract*—**In intensity modulated radiation therapy (IMRT) treatment planning, beam angles are usually preselected on the basis of experience and intuition. Therefore, getting an appropriate beam configuration needs a very long time. Based on the present situation, the paper puts forward beam orientation optimization using ant colony optimization (ACO). We use ant colony optimization to select the beam configurations, after getting the beam configuration using Conjugate Gradient (CG) algorithm to optimize the intensity profiles. Combining with the information of the effect of pencil beam, we can get the global optimal solution accelerating. In order to verify the feasibility of the presented method, a simulated and clinical case was tested, compared with dose-volume histogram and isodose line between target area and organ at risk. The results showed that the effect was improved after optimizing beam configurations. The optimization approach could make treatment planning meet clinical requirements more efficiently, so it had extensive application perspective.

***Keywords*—**intensity modulated radiation therapy, ant colony optimization, Conjugate Gradient algorithm

I. Introduction

INTENSITY modulated radiation therapy (IMRT) means the radiation beam intensity can be adjusted [1]. With this technique, not only target can obtain a relatively uniform high dose distribution, but also organs at risk and normal tissues are protected. The traditional IMRT planning starts with the selection of suitable beam orientations then optimize the intensity map of beam or segments shape using inverse optimization methods. Finally, analyze whether the dose distribution meet clinical requirement. If plan is successful, we should to make the dose verification. Otherwise, beam orientation should be adjusted, then re-optimize the parameters until the dose distribution meet the clinical requirement. In IMRT, the selection of optimal beam orientation cannot rely on conventional conformal radiotherapy experience. For conventional conformal radiotherapy, beam orientation generally should avoid direct exposure to organs at risk. However, for IMRT, beam orientations do not have to be away from organs at risk [2-4]. Therefore, for more complicated cases, the selection of optimal beam angles needs several trial and error attempts. This research was a part of Advanced/Accurate Radiotherapy System (ARTS) [5~13], in precision radiation treatment planning and quality assurance system project, developed by FDS team in cooperation with several research institute.Ant colony optimization is a new general heuristics method, for solving combinatorial optimization problem. The method has the characteristics of positive feedback, distributed computation and constructive characteristics of the greedy heuristic search [14]. It was proposed by Marco Dorigo in 1991 in his doctoral thesis, and its inspiration was from finding food of real ants. Ant colony optimization in solving combinatorial optimization problems shows a superior performance, such as: routing problem, scheduling problem, a subset of the problem and so on.The purpose of this study is to find the optimal beam orientation using ant colony optimization, in the case of coplanar irradiation and fixed number of beam. The results showed that the approach could get the optimal beam orientation within the acceptable time, and it had extensive application perspective.

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II. Methods

Each set of beam orientation has different intensity map, and we must calculate to find which set was better. So beam orientation optimization has a high-level computational complexity, and cannot get the optimal solution in acceptable time using traditional optimization methods. In order to simplify the optimization process, we treated beam angles and intensity map as two independent variables. Beam angles were selected by stochastic methods, while the corresponding intensity maps were got using deterministic algorithms.

In this paper, we adopt the strategy above described that was the whole optimization process had two nested loops. In the outer loop, beam angles were selected by ant colony optimization. In the inner loop, the corresponding intensity maps were optimized using conjugate gradient method, after beam angles were fixed.

A simplified flowchart of the proposed optimization is shown in figure 1.

Here, we only studied coplanar irradiation, and the method could be easily applied to non-coplanar irradiation. The total 360° gantry angles were divided into equally fixed spaced, such as 5° or 10°. These discrete beam angles constituted a candidate constitute the search space. In order to improve the performance and reduce search space, the user could exclude the angles that cannot be implemented.

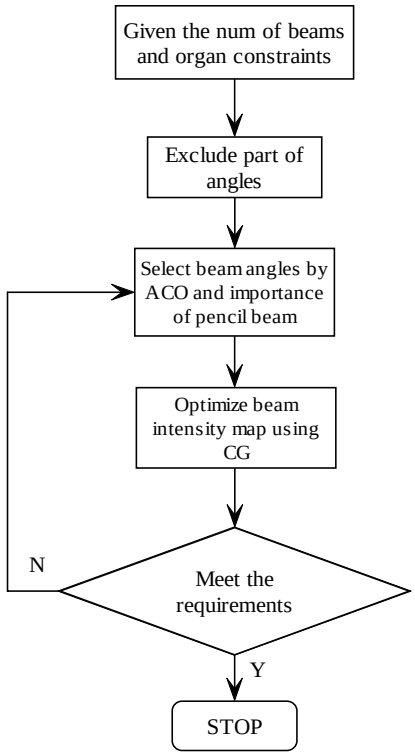

Fig. 1 Flow chart of ACO

A. Beam orientation optimization

Ant colony optimization is an intelligent optimization algorithm to find the optimal path in weighted graph. Using ACO to solve combinatorial optimization problems, the first task is to model the problem into a weight chart, and the rationality of the chart affect the efficiency and effectiveness of optimization [15].

Beam orientation optimization model was a multi-layers graph. Removing the top and bottom, the middle layers were equal to the number of beams, and nodes in each layer were the number of candidate beam. For example, figure 2 was a four beams case. In this model each layer had 36 nodes in the 10 ° dispersal coplanar illumination.

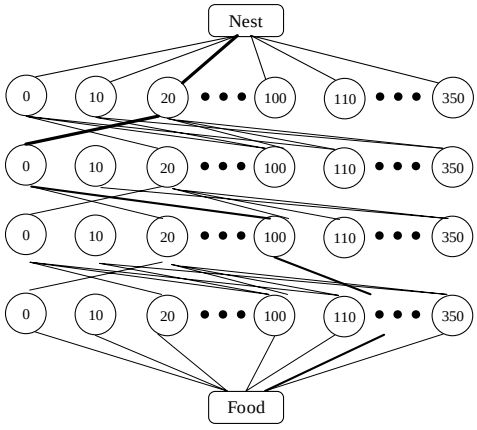

Fig. 2 Beam orientation optimization model

The process of ACO as follows: Firstly, initialized the N ants, and then made ants moving from the first layer to the last layer. Each ant chose node by p_k according to the side's pheromone, and only chose one node in each layer, at the same time, avoided the adjacent beam in the selection process. That was, if you selected 20 ° first, you could not choose 10 ° and 30 ° next. Each ant's path corresponded to a group of beam direction. For example, thick lines of the graph II represented a group of beam directions of an ant choice: 20 °, 0 °, 100 ° and 150 °. Then optimized the intensity map of this beam orientation by conjugate gradient method, and updated side's pheromone according to the objective function value.

Probability transfer formulas were as follows:

$$p_k(r,s)=\begin{cases}\dfrac{[\tau(r,s)]\cdot[\eta(r,s)]^{\beta}}{\sum_{u\in J_k(r)}[\tau(r,u)]\cdot[\eta(r,u)]^{\beta}} & if\ s\in J_k(r)\\ 0 & else\end{cases} \quad (1)$$

$$\eta=\sum_{j=0}^{N_{ray}}\left[\frac{1}{N_{PTV}}\sum_{i=0}^{N_{PTV}}a_{ij}-\sum_{k=0}^{m}\alpha_k\frac{1}{N_{OAR}}\sum_{i=0}^{N_{OARk}}a_{ij}\right] \quad (2)$$

In formula (1), τ was pheromone, η was the importance factor of each angle, $J_k(r)$ were candidate beam directions, in formula (2) , N_{PTV} and N_{OAR_k} represented the number of sampling points of the target and k-th organs at risk (OAR) respectively. m was the number of OAR. α_k was the importance factor of k-th OAR, and its value between 0 and 1.

Pheromone update formulas were as follows:

$$\tau(r,s)=(1-\rho)\cdot\tau(r,s)+\sum_{k=1}^{m}\tau_k(r,s) \quad (3)$$

$$\tau_k(r,s)=\begin{cases}\dfrac{1}{F_{obj}} & if\ the\ ant\ k\ through\ the\ path\ (r,s)\\ 0 & else\end{cases} \quad (4)$$

In formula (3), ρ was evaporation rate, generally taken to be 0.3. $\tau_k(r,s)$ was the additional pheromone. In formula (4), F_{obj} was the objective function value of k ant.

To overcome the possibility that ant colony optimization falling into the local optimum solution, we used two strategies.

1) Decreased the value of ρ in the iteration later.

$$\rho_j=\rho_{j-1}*0.95$$

j indicated the current number of iterations.

2) Defined the maximum and minimum pheromone value $\tau_{\max}$ and $\tau_{\min}$. If the updated pheromone value was greater than $\tau_{\max}$, then assigned to $\tau_{\max}$, on the contrary, if the updated pheromone value was less than $\tau_{\min}$, then assigned to $\tau_{\min}$.

B. Optimize the intensity profiles

After selecting beam angles, the intensity profiles and the fitness value of this set of beam orientation needed to be calculated. We were used to divide the beam into units, and use pencil beam algorithm to calculate dose contribution of the

sampling points of each unit, then used the reverse algorithm to calculate the intensity of units, so that dose distribution could be expected by adjusting the intensity map [16]. The goal of beam orientation optimization was a group beam selected from the candidate beams, which made the difference of dose obtained after optimization and the constraint dose given by doctors minimum, that was, the objective function value of the minimum.

The objective functions used in this article were as follows:

$$F_{obj}(\vec{x}) = \alpha \cdot F_{OAR}(\vec{x}) + \beta \cdot F_{PTV}(\vec{x}) \tag{5}$$

$$F_{OAR}(\vec{x}) = \sum_{i=1}^{N_{OAR}} \sum_{j=1}^{NT_i} \delta_j \cdot (d_j(\vec{x}) - p_j)^2 \tag{6}$$

$$F_{PTV}(\vec{x}) = \sum_{j=1}^{NT_{PTV}} \delta_j \cdot (d_j(\vec{x}) - p_j)^2 \tag{7}$$

$$d_j(\vec{x}) = \sum_{m=1}^{N_{ray}} a_{jm} \cdot \vec{x}_m \tag{8}$$

$\vec{x} = (x_1, x_2, ..., x_N)$ was pencil beam vector, and N was the number of units. $F_{obj}(\vec{x})$ was the objective function value of $\vec{x}$. $F_{OAR}(\vec{x})$ and $F_{PTV}(\vec{x})$ represented objective function value of OAR and target respectively. α and β were the weight of OAR and target. N_{OAR} was the number of OAR. NT_i was the number of sampling points of i OAR, and NT_{PTV} was the number of sampling points of the target. When the dose in the constrained range, δ_j was zero, otherwise was 1. a_{jm} was pencil beam dose deposition of j -point in the m -unit field under Unit intensity . $\vec{x}_m$ was m -element of $\vec{x}$. Conjugate gradient method was used in optimization of the intensity map.

III. RESULTS

This paper used two cases to test the algorithm. One was the simulation case, the other was the nasopharyngeal cancer case. (Compute: Lenovo M8000T, Intel (R) Core (IM) 2 Quad CPU Q9550@2.83GHz, 3.5GB.)

Cases were used in coplanar radiation, divided into 36 field directions. Beam was divided into 0.5cm * 0.5cm grid on the skin surface.

A. Simulation case

Simulation case was a 30cm * 30cm * 30cm water phantom. Target was a cuboids, whose height is 6cm, and its cross section is a square of side length 7cm. OAR surrounded target, whose height was 6cm, and its cross section was a square of side length 10cm. Dose constraints: prescription dose was 6000cGy; target dose was between 5500 and 6500cGy; volume of doses greater than 3000cGy of OAR not bigger than 50%.

After 28 minutes of optimization, we got the optimal solution at the 43-th generation, and the optimal beam orientation were 0 °, 90 °, 180 °, 270 °. Figure 3 was isodose distribution optimized, in which the red area was the target, and green area was organ at risk. It showed that target was in the high dose area, surrounded by 100% isodose line, and most of the OAR area was in outside of the 50% isodose line.

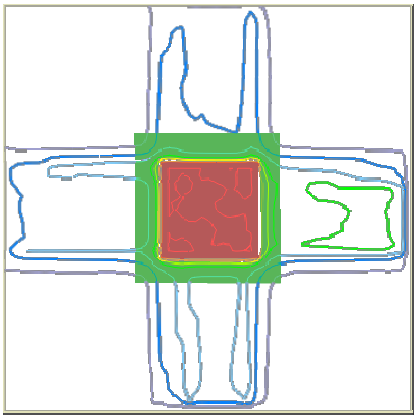

Fig. 3 Isodose distributions after optimized

To verify the effectiveness of the algorithm, we used exhaustive method to calculate all possible solutions. After 5.4 days of computing, the optimal solution were 0 °, 90 °, 180 °, 270 °, and this result was consistent with our results.

B. Nasopharyngeal cancer

Nasopharyngeal cancer was one of the most complex cases in clinical, because there were many organs at risk in the head (eye, parotid gland, optic nerve, etc.). Dose constraints: prescription dose was 6000cGy; the dose of GTV was between 5800 and 6200cGy; the dose of CTV was between 5500 and 6500cGy; the maximum dose of eyes and optic nerves was 1000cGy.Before optimization, we adopted the 5 beam angles usually used in clinic: 0 °, 45 °, 120 °, 240 ° and 315 °. After optimized, the optimal solution was: 30 °, 80 °, 270 °, 300 ° and 350 °. Figure 5 was dose volume histograms (DVH) before and after optimization, in which solid line was the optimized DVH graph, dashed line was DVH graph before optimization. Clearly, eyes and optic nerve were better protected after beam orientation optimization, at the same time the target dose was increased.

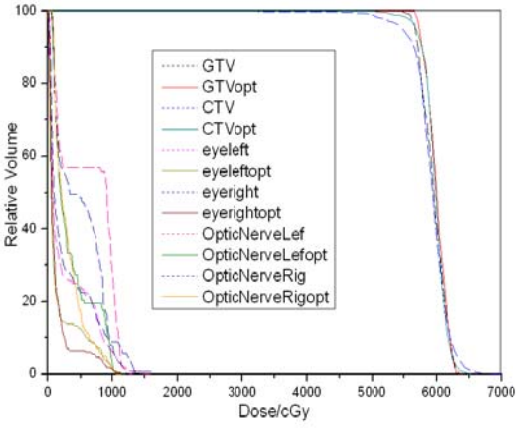

Fig. 4 DVH before and after optimized

Nasopharyngeal cancer case contains 13 organs, so optimization spent a relatively long time. The optimization process converged to the optimal solution in the 80th-generation and 40 minutes.

IV. Discussions

In simulation case, the method presented can get the optimal solution only in 28 minutes, compared with 5.4 days of exhaustive method. Figure 4 suggest the validity of treatment planning is improved after beam orientation optimization.

The time required of beam orientation relate to the number of organs and the complexity of cases. The more complex cases, the more the number of organs, the longer time needed to optimize.

V.CONCLUSIONS

Beam orientation optimization is an important issue in IMRT. A large number of studies have shown that the choice of angles plays a vital role for planning. Beam orientation optimization based on ant colony optimization in this paper can find the optimal beam orientation within an acceptable time in clinic.

By contrast with the exhaustion method in simulated case, the algorithm used in this article can find the optimal solution in clinically acceptable time, so this method is effective. Nasopharyngeal cancer case showed that the effect has been greatly improved after optimization by comparison of the organ DVH. Therefore, beam orientation optimization based on ant colony optimization meets clinical requirements, which can serve as an effective beam orientation optimization method applied to IMRT.

Acknowledgement

This article was supported by the Natural Science Foundation of Anhui Province (11040606Q55) and the National Natural Science Foundation of China (30900386).

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