5 - 71 Study on the Treatment Plan Optimization for Carbon Ion Arc Radiotherapy

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Nowadays, photon radiotherapy frequently makes use of arc delivery techniques for potential dosimetric advantages like improved dose conformity and reductions in treatment time compared to static delivery approaches like intensity modulated radiotherapy (IMRT)[1]. The combination of carbon ion therapy and arc technology is also likely to be potential[2]. To apply carbon ion arc technology in clinic, two problems should be solved firstly: treatment plan optimization and estimates of deliverability.

Based on the open source treatment planning platform matRad, the optimization objective function was implemented as follows,

$$argmin\,\|Ax-d_0\|_2^2+\sum_{b=1}^{B}\sum_{e=1}^{E}\alpha_{be}\,\|x_{be}\|_2^{\frac{1}{2}}-\beta\sum_{b=1}^{B}\log\left(\sum_{e=1}^{E}y_{be}\right). \tag{1}$$

The first term is the dose fidelity term, penalizing the actual dose, calculated by Ax, from the prescription dose d_0. The second term is an L2, 1/2 norm group sparsity term. In the third term, a log barrier regularization function is used to distribute the selected layers to the whole gantry rotating range. To minimize this objective, a FISTA solver was coded for investigating the feasibility of carbon ion arc radiotherapy

The treatment plan design process is as follows:

Step 1: obtain a set of “optimal energy” (72 angles, one angle and one energy) through the FISTA optimizer.

Step 2: reoptimize the dose distribution for the first term only with the selected “optimal energy” in Step 1.

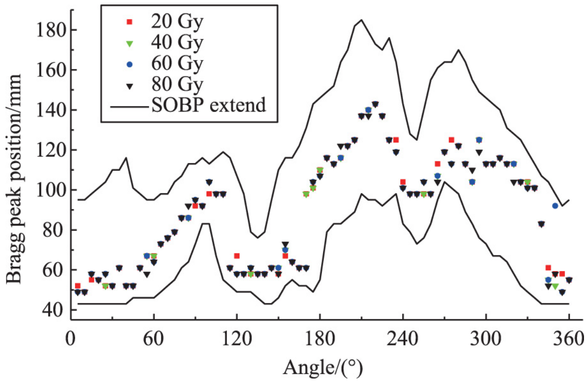

Fig. 1 (color online) The Bragg peak positions of each angle under different prescription doses.

Through the setting of different prescription doses (20, 40, 60, 80 Gy), the planning design of 15 cases was carried out, and some preliminary results were obtained. The Bragg peak positions of each angle under different prescription doses is shown in Fig. 1. As shown in Fig. 1, the dose prescription has little effect on energy selection.

Originally, the energy candidate (availabenergy) set for the FISTA algorithm was the entire SOBP energy extent of each angle (from minenergy to maxenergy). In order to reduce the optimization time and the memory pressure of the computer, candidate energies was limited in partial of the entire SOBP energy extent. The limiting strategies is shown in Table 1.

Table 1 The limiting strategies of candidate energies.

Energy candidate extent, k	D_{mean}/Gy	D_{95}/Gy	CI	HI	Time/s
The entire SOBP (0~1)	59.79	58.20	0.84	0.07	18826s
0.2~0.8	59.79	58.23	0.84	0.07	16690
0.15~0.45,0.55~0.85	59.77	58.04	0.86	0.08	15803
0.35~0.65	59.81	58.15	0.84	0.08	13185
0.25~0.4,0.6~0.75	59.81	58.20	0.83	0.07	12155
0.2~0.3,0.45~0.55,0.7~0.8	59.84	58.28	0.81	0.07	12107

Note: $d_0 = 60$ Gy, $k = (availabenergy - minenergy)/(maxenergyminenergy)$

After limiting the energy candidate extent, there is no significant effect to the quality of the plan, but the plan optimization time is obviously shortened.

To apply the treatment plan to clinic, beam delivery efficiency should also be considered. In the future, the plan delivery time will be evaluated with the features of carbon ion synchrotron beam extraction time structure. Further, it will be explored to improve the delivery efficiency of carbon ion arc radiotherapy in the treatment plan optimization.

References

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[2] S. Mein, T. Tessonnier, B. Kopp, et al., Int. J. Radiat. Oncol. Biol. Phys., 114, 2(2022)334.

5 - 72 Sensitivity Study of the Logistic Nanodosimetry Model for Carbon Ion Radiotherapy

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With the development of ion beam radiotherapy, nanodosimetry is considered a more suitable tool for track structure description. In logistic nanodosimetry model, the coefficient parameters in the linear-quadratic(LQ) relation of cell survival curve are derived as follows [1]:

$$\alpha = \frac{\rho V}{w M_1} F_2 P\left(M_1^{C2}\right) - \frac{\rho V P_{S-l}}{w M_1}\left[1 - F_2 P\left(M_1^{C2}\right)\right] + \frac{\rho V P_{S-l}}{w M_1}\left[1 - F_2 P\left(M_1^{C2}\right)\right]^2, \tag{1}$$

$$\beta = \frac{\rho^2 V^2 P_{S-l}}{w^2 {M_1}^2}\left[1 - F_2 P\left(M_1^{C2}\right)\right]^2, \tag{2}$$

where,

$$P\left(M_1^{C2}\right) = \frac{k}{1 + \exp\left(-r\left(\left(M_1^{C2} - m_0\right)\right)\right.} \tag{3}$$

Therefore, this model introduces four free parameters: P_{s-1}, r, m_0, k.

Sensitivity analysis of model parameters is a necessary work for a model to move from proposal to clinical practice. To study the parameter sensitivity of the model, $\alpha\beta$ values were recalculated by varying the parameters separately by $\pm\{5, 25, 50\}\%$ of the nominal values[2]. This work is based on the parameters of HSG cells in normoxic state, which are 2.0×10^{-11}, 3.602, 3.296 and 9.3×10^{-5} for P_{S-1}, r, m_0, k, respectively. Nanodosimetric quantities were obtained with condensed-history Monte Carlo simulation (Gate) and the pre-calculated nanodosimetric database[3] at the depth of 0, 24, 52, 83, 86, 87, 92, 100 mm of a carbon-ion pencil beam with initial energy of 200 MeV/u.

Figure 1 shows the variation of $\alpha\beta$ values at different depths. As shown in Fig. 1, β is proportional to P_{S-l}, but the changes of other parameters have no effect on β or can be negligible (not shown). As for α, it is proportional to k, the effect ofP_{S-l} can be negligible. The effect of variations in r m_0 on α exhibits different behavior at different depths. The reason for this is P_{S-l} and k are very small. So, equation 1 and 2 can be simplified as the following equations.

$$\alpha = \frac{\rho V}{w M_1} F_2 P\left(M_1^{C2}\right), \tag{4}$$

$$\beta = \frac{\rho^2 V^2 P_{S-l}}{w^2 {M_1}^2}. \tag{5}$$