Optimization of ripple filter for pencil beam scanning (Postprint)

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Abstract

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Full Text

Preamble

Optimization of Ripple Filter for Pencil Beam Scanning

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Abstract

This paper presents a novel approach to seek the bar width for ripple filter used in pencil beam scanning proton therapy. A weight decay quadratic programming method is employed for the new optimization strategy. Compared to the commonly used iterative-least-square technique, the ripple filter derived by the proposed method not only has better depth dose uniformity, i.e., the dose uniformity is within 0.5%, but also has triangle-like vertical cross-sectional shape which is suitable for manufacture. Moreover, the new method has such good

robust characteristics that it is also applicable to the real application with unavoidable measurement errors and noises. The simulation results of this study may be helpful in improving the design of the ripple filter.

Key words: Dose uniformity, Proton therapy, Ripple filter, Weight decay quadratic programming

Introduction

One of the main advantages of proton therapy is the depth dose profile, which has been named Bragg peak. The few-mm-wide pristine Bragg peak allows irradiation of a well-localized region within the body, keeping dose release low in the proximal (entrance plateau) and distal (tail) regions. If the tumor cells are larger than the width of the Bragg peak, superposition of several Bragg peaks from different beam energies is introduced to create uniform radiation dose over the tumor.

For pencil beam scanning, the target is irradiated layer by layer with different beam energies. However, switching time between energy layers is a major contribution to the overall treatment time. Few energy layers may result in large ripple produced on the flat-top depth-dose curve, which becomes serious for low energy. The ripple filter, which has been of great interest in recent years[1 5], is used to address this problem. Fig. 1 [Figure 1: see original paper] shows the vertical cross-section of a commonly used ripple filter. After inserting the ripple filter perpendicular to the beam, the Bragg peak of the proton beam will become smooth[1,3].

Although Weber and Kraft[1] have presented a least square (LS) objective function to seek the width of the ripple bar, they have not mentioned the method to solve it. In Ref.[2], iterative-least-square technique (ILST) is introduced to optimize the weights. In this paper, a new quadratic objective function is proposed for designing the width of the ripple filter bar. Additionally, the ILST is also used to optimize the LS function for comparison.

2 Optimization Methods

The goal of treatment planning is to deliver a desired biological dose, which is calculated by multiplying the physical dose by the relative biological effectiveness (RBE). As recommended by the ICRU[6], the RBE is set to 1.1 in this paper.

The principle of the analytical computation for ripple filter design used in Ref.[1] is adopted in this study. When the proton beam passes through the ripple filter with thickness tr, the dose distribution will be shifted to a certain water-equivalent value that corresponds to tr along the beam direction. Therefore, when the proton beam passes through the ripple filter perpendicular to the beam direction, the pristine dose Bragg peak will be transformed by the ripple-bars into a superposition of displaced Bragg curves. Gaussian Bragg peaks were chosen to generate homogeneous depth dose profiles with low ripple for the smoothing effect after superposition[1,3,5]. To form a dose profile close to Gaussian shape in the peak region, the weight of the proton component must be calculated. Since the weight of the proton component passing through the ripple-bar step is proportional to the width of the ripple-bar step, the weight determines the shape of the ripple bar.

Additionally, the difference in proton fluence caused by nuclear interaction in the ripple filter and water is taken into account for the computation. After the proton beam passes through the ripple filter, the biological dose is modulated as follows:

$$d_{\mathrm{mod}}(z_i) = \sum_{j=j_{\min}}^{j_{\max}} w_j \cdot d_{\mathrm{phy}}(z_{i+j}) \cdot f_j \cdot \frac{2\Delta z}{\lambda}$$

where $d_{\mathrm{mod}}(z_i)$ represents the modulated biological dose at depth z_i; Δz is the step size of the dose points; λ is the period of the groove structure; $j_{\min}$ and $j_{\max}$ are defined as the minimum and maximum water-equivalent thicknesses of the ripple bar divided by Δz, respectively; $d_{\mathrm{phy}}(z_{i+j})$ is the pristine physical dose at depth z_{i+j}; w_j is the weight of the j-th segment of the proton beam; f_j is the fluence difference introduced by the j-th step of the ripple bar, as described in Eq.(2)[7]:

$$f_j = \exp\left(-\frac{t_j}{\lambda_{\mathrm{rf}}}\right) \cdot \exp\left(-m_p \cdot \frac{R}{t_j}\right)$$

where $t_j = t(z_j) = 1.19 t_r(z_j)$ is the water-equivalent thickness of the ripple filter in the z-direction; $\lambda_{\mathrm{rf}} = 69.54$ cm is the nuclear interaction length of plexiglass; $m_p = 0.012\ \mathrm{cm}^{-1}$; R is the proton range in water.

To simplify the analysis, Eq.(1) can be further written in the following matrix form:

$$D_{\mathrm{mod}} = A \cdot W$$

where D_{mod} is the modulated biological dose; $a_{ij} = 2\Delta z \cdot d_{\mathrm{phy}}(z_{i+j}) \cdot f_j/\lambda$; m is the dimension of D_{mod}; $n = j_{\max} - j_{\min} + 1$, which is the dimension of weight W; A is an $m \times n$ matrix; W is an $n \times 1$ vector with $w_j \geq 0$. Since it is often the case that $m > n$, Eq.(3) is an over-determined equation and thus might have no unique solution. Furthermore, the coefficient matrix A is usually ill-conditioned, so the solution of Eq.(3) must be derived by solving an optimization problem. In this paper, two optimization methods with different objective functions are used and compared for ripple filter bar design.

2.1 Iterative Least-Squares Technique

ILST is a commonly used method for solving the least square objective function[8 10] with relatively fast convergence rate and good performance in averaging out noisy data. In the hadron therapy range modulation field, Schaffner et al.[2] utilized the ILST to produce the large, biologically uniform spread-out Bragg peak (SOBP) depth dose from small SOBPs. The weight updating between two consecutive iterations (k-th iteration and $(k-1)$-th iteration) can be calculated by:

$$w_j^{(k)} = w_j^{(k-1)} \cdot \frac{\sum_{i=1}^{m} g_i \cdot a_{ij} \cdot P(z_i)}{\sum_{i=1}^{m} g_i \cdot a_{ij} \cdot d_{\text{mod}}^{(k-1)}(z_i)}$$

where g is set to 1 inside the SOBP and 0 outside; $P(z_i)$ is the prescribed biological dose at depth z_i.

2.2 Quadratic Programming Method

A large condition number of matrix A, i.e., larger than 100, may result in derived weight values w_j of different orders of magnitude. This leads to manufacturing difficulties for the ripple filter because the normalized value of w_j is proportional to the width of the j-th ripple bar segment. For example, if w_{j+1} is 100 times smaller than w_j and the width of the j-th segment is 10 m, then the required width of the $(j+1)$-th segment would be 0.1 m, which might exceed manufacturing precision (1 m). To prevent the weights from growing too large, a new objective function is proposed in this study, consisting of a least-squares term and an additional weight decay term[11]:

$$\min \quad 0.5\|P - AW\|^2 + 0.5\gamma\|W\|^2$$

where $\|\cdot\|$ represents the Frobenius norm operation; P $(m \times 1)$ is the prescribed biological dose; γ $(\gamma \geq 0)$ is a parameter that determines how strongly large weights are penalized. The larger γ is, the more uniform the weights become. Particularly, when $\gamma = 0$, Eq.(5) becomes:

$$\min \quad 0.5\|P - AW\|^2$$

Problem (6) is a special case of (5). Problem (6) is a least-squares optimization problem with nonnegative constraints. Problem (5) can be written in the standard quadratic form as follows:

$$\min \quad 0.5W^T(A^{TA} + \gamma I)W - (P^{TA})W$$

where I is an $n \times n$ identity matrix. Problem (7) can be solved by a quadratic programming method (QPM)[12]. Adding the weight decay term in ripple bar design can improve generalization[11].

2.3 Performance Evaluation

The optimized results using ILST[2] and QPM are compared in this paper. Moreover, the robustness (anti-noise ability) of the two methods, specified as the dose difference, was also examined:

$$r = \frac{\|d_n - d_0\|}{\|d_0\|}$$

where d_n and d_0 represent the dose derived from the noisy data and original data, respectively; r is the relative dose variation, which represents the robustness of the filter. The smaller r is, the stronger the robustness.

3 Results and Discussion

In this study, a typical beam delivery system for proton therapy is simulated with Geant4. Bragg peaks obtained from the simulation are used to evaluate the methods. Since the Bragg peaks of proton beams become narrower with decreasing energy, the relatively low energy of 70 MeV is chosen in the simulation.

3.1 Simulated Model

As shown in Fig. 2 [Figure 2: see original paper], the schematic of the simulated model consists of a kapton window located at the end of the beam transport line, a nozzle, and a water tank phantom. The components of the nozzle include scanning magnets, a vacuum chamber, beam monitors, a ripple filter, etc. The scanning magnets are used to steer the beam. The vacuum chamber is designed to reduce beam scattering. The beam monitors are ionization chambers with an equivalent water thickness of 1.1 mm. The ripple filter is used to smooth the flat-top region of the SOBP. The distance between the isocenter and the ripple filter is 50 cm. The momentum spread for protons is set as $\Delta p/p = 0.05\%$.

3.2 SOBP Dose Uniformity with Ripple Filter Designed by QPM

Fig. 3 shows the dose uniformity with and without ripple filters for 70 MeV proton beams. As illustrated in Fig. 3(a), for the same scanning step (3.2 mm), the dose uniformity is as high as 24.7% without a ripple filter and sharply decreases to less than 2.5% when a 3 mm ripple filter is added to the system. In Fig. 3(b), the dose uniformity is more than 20.7% without a ripple filter, while with the ripple filter the maximum dose scanning error decreases to less than 2.5% at the same step (3 mm). As described in Ref.[3], the widths of the distal fall-off (80%–20% distal falloff) are both moderate (less than 3 mm).

3.3 Comparison Between ILST and QPM

Fig. 4 illustrates the simulation results with ILST and QPM when the pencil beam scanning step is 2.14 mm (a random value). As shown in Fig. 4(a), the depth dose distribution with QPM (solid line) is more uniform and closer to the ideal value (1.00 in the figure) than that with ILST (dashed line). Particularly, the maximum dose uniformity with QPM is 0.5%, which is less than the 0.7% achieved with ILST. In addition, the shape of the ripple filter with QPM is closer to triangular than that with ILST, as shown in Fig. 4(b). The reason is that the extra weight decay term prevents the value of individual weights, which correspond to the width of the ripple filter bar, from growing too large. Therefore, the width of the ripple filter bar tends to have the same order of magnitude. Consequently, its corresponding ripple filter bar is close to a triangular shape, which is convenient for manufacturing. The results for a scanning step of 3.2 mm with the use of a 3 mm ripple filter are similar.

In real applications, the dose is measured experimentally rather than derived from simulation. Therefore, unavoidable measurement errors in dose should be considered. In this study, noise with a Gaussian distribution was added to the simulated dose. Fig. 5 shows the relative dose variation and the ripple filter shape curve difference when 5% noise is added in the simulation. The dose difference values with QPM and ILST are shown in Fig. 5(a). The calculated standard deviation of the relative dose uniformity with QPM (0.0039) is smaller than that with ILST (0.0042). Fig. 5(b) further compares the filter shape difference, where the horizontal axis represents the shape difference with and without noisy data. The smaller values derived by QPM indicate its stronger robustness. In other words, the proposed QPM is capable of obtaining a similar ripple filter even when using data with noise, which is preferred in real applications. The good robustness is due to good generalization ability.

Fig. 6 compares the individual proton beam Bragg curves and the corresponding lateral dose distributions at different positions with and without a 2 mm ripple filter. As illustrated in Fig. 6(a), the relative dose of the modulated curves is higher than that of the pristine Bragg curve at the depth of the modulated Bragg peak. This phenomenon is also reflected in Fig. 6(b), where the lateral dose distributions of the proton beam without ripple filters are both lower than those with ripple filters. Besides, the curves for A and B are close to each other in Fig. 6(b), which indicates there is slight difference in lateral dose distribution at the Bragg peak between the two different ripple filters. This is due to the proton beam being scattered by different ripple filters mainly according to Moliere theory[13,14].

4 Conclusion

A new design approach for ripple filter bar was proposed in this paper. The new approach uses the objective function with QPM. It has been successfully applied to calculate the weights, which were further converted to the ripple filter dimension. Compared to the ILST, the proposed method not only achieves better performance, i.e., better depth dose uniformity and ripple filter shape for manufacturing, but also has better robustness characteristics. This ripple filter can be manufactured more accurately and achieve good flatness of the SOBP simultaneously.

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Note: Figure translations are in progress. See original paper for figures.