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EXPERIMENTAL SIMULATION OF VOLUME REPAINTING TECHNIQUE AT PROTON SYNCHROTRON IN CONTEXT OF SPOT SCANNING PROTON THERAPY

M. A. Belikhin†[1], A.A. Pryanichnikov[1], A. E. Shemyakov,
Lebedev Physical Institute RAS, Physical-Technical Center, Protvino, Russian Federation
A.P. Chernyaev, Lomonosov Moscow State University, Accelerator Physics and Radiation Medicine Department, Moscow, Russian Federation
[1]also at Lomonosov Moscow State University, Accelerator Physics and Radiation Medicine Department, Moscow, Russian Federation

Abstract

Reduction the influence of respiration-induced intrafractional motion is one of the main tasks of modern Spot Scanning Proton Therapy (SSPT). Repainting is one of the techniques of motion compensation. It consists in multiple repeated irradiations of the entire volume or individual iso-energy layers with the dose that is a multiple of the prescribed dose. As a result, the dose is averaged which leads to an increase in the homogeneity of the dose field.

The purpose of this study is experimental simulation of volume repainting and dosimetric estimation of its capabilities in the context of SSPT.

Simulation of respiration-like translational motion is performed using a non-anthropomorphic water dynamic phantom. Target of this phantom is compatible with EBT3 films and ion chamber. Estimation of repainting technique is based on the analysis of dose field shape, average dose and dose homogeneity in the Region of Interest (ROI) located within Planning Target Volume (PTV), and dose gradients along the direction of motion. Repainting technique was used for motion with amplitudes of 2, 5, 10 mm with 2, 4, 6, 8 and 10 iterations at the prescribed dose of 6 Gy. For each case values of the average dose, dose homogeneity and dose gradient were calculated and compared with corresponding values in case of no motion.

Repainting removes hot and cold spots and increases the homogeneity in the ROI from 85.9% to 96.0% at amplitude of 10 mm and 10 iterations. The dose gradient is inversely proportional to the motion amplitude and was not improved by repainting. Optimization of the irradiation time, PTV dose and dose field margins is necessary for clinical using of repainting.

INTRODUCTION

Today proton therapy is the most precision and effective method of modern radiation oncology. These advantages are based on the presence of sharp Bragg peak at the end of the path, low lateral scattering and dependence of the beam penetration depth on its energy [1, 2].

However, these advantages can be fully realized only in case of complete immobility of the tumor, for example, in case of head and neck tumors. Respiration-induced intrafractional motion [3] leads to significant distortions of dose distribution and conformity degradation in case of other localizations such as lungs, liver, prostate, breast and etc. Interplay effect between tumor motion and beam delivery dynamic causes hot and cold spots in the target volume, and irradiation of healthy tissues and organs at risk. These factors significantly decrease efficiency of SSPT [4].

Conventional photon radiation therapy has a lot of solution [5] for monitoring, compensation and mitigation of intrafractional motion. However, direct transfer of these techniques to SSPT is difficult and requires additional research [4, 5]. In the main, the difficulties are caused by differences in the interaction principles of proton and photon beams with matter.

Repainting [3] is a specific method of tumor motion compensation used in SSPT. This one increases homogeneity of dose field and eliminates hot and cold spots. Repainting consists in multiple repeated irradiations of the entire volume or individual iso-energy layers with a dose that is a multiple of the prescribed dose. Intensity of the beam for repainting can be calculated as:

$$I = {}^{I_0}/_{N}$$

where I – intensity of the repainting beam, I_0 – total intensity, N – number of scanning iterations. Prescribed dose in the target volume are delivered as a result of the summation of doses from individual rescans. There are several repainting strategies: uniform, random, level, time delay and breath sampling repainting [3]. These methods differ from each other in the sequence of scanning the target volume and optimization of the irradiation time.

MATERIALS AND METHODS

Proton Therapy Complex

The current experiment was carried out on proton therapy complex «Prometheus» [6, 7]. This one is a specialized serial medical installation for particle therapy manufactured by Protom Ltd. This complex consists of proton synchrotron, patient immobilization system in sitting position and X-ray system. Irradiation of tumor is performed by a thin scanning proton beam with energy in the range of 30-330 MeV and with intensity about 10^9 particles per second in spot scanning mode. Also the complex

† mikhailbelikhin@yandex.ru

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is equipped with a planning system for treatment plans calculation with Monte-Carlo method.

Dynamic Phantom

Target motion simulation is carried out by the non-anthropomorphic water dynamic phantom (Fig. 1) designed and manufactured by Protom Ltd. This one is optimized for working with «Prometheus». The dynamic phantom consists of a container with water in which a mobile target is placed. Size of the container is 30×20×20 cm^3, and volume of the targets is 6x6x6 cm^3. The targets are made of PLA using 3D-printing with 10%-filling that improves its visibility on CT. The target is moved by a servo along one axis with precision of ±0.1 mm and high repeatability. A specialized controller drives position of the target and sets motion patterns via PC software. The motion patterns (Fig. 2) are based on respiration which consists of phases: inhale, exhale and pause. Standard dosimetry equipment such as dosimetric films and ion chambers is compatible with the targets.

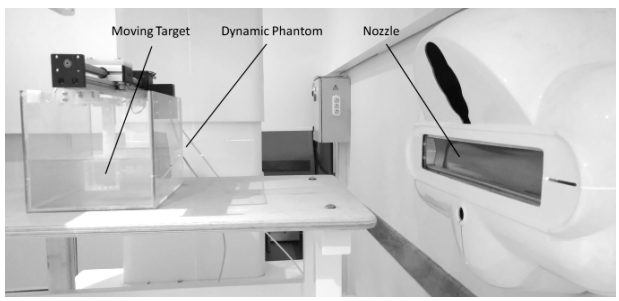

Figure 1: Photo of experimental setup.

Planning

Today used proton therapy complex is not equipped with specialized hardware and software for repainting therefore repainting simulation was carried out manually. For this six irradiation plans with doses: 0.60, 0.75, 1.00, 1.50, 3.00 and 6.00 Gy were calculated in Protom planning system. This set of plans allows to deliver the prescribed dose of 6.00 Gy in 10, 8, 6, 4, 2 and 1 iterations of repainting, respectively. One execution of the plan is equivalent to iteration of repainting. PTV has a cube shape with size of 2×2×2 cm^3 and is located in the target center. The time of 6 Gy plan execution is 1 min 46 sec.

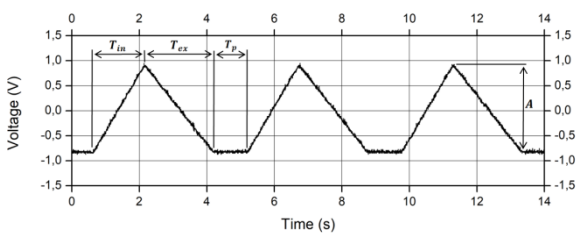

Figure 2: Graph of free breathing motion pattern of the phantom target. Motion was monitored by Protom optical respiration sensor with voltage output.

Irradiation

The dynamic phantom is placed in the immobilization system (Fig. 1) by laser pointers. Verification of phantom position is performed by two orthogonal X-ray snapshots. Free breathing pattern (Fig. 2) is used for target motion simulation. Target moves across the direction of beam propagation. Irradiation is executed in combinations: 1×6.00 Gy, 2×3.00 Gy, 4×1.50 Gy, 6×1.00 Gy, 8×0.75 Gy and 10×0.60 Gy with motion parameters: Inhale=1,5 sec, Exhale=2,0 sec, Pause=1,0 sec, Amplitude=2, 5, 10 mm.

Dosimetry

Dosimetry is carried out by dosimetric films Gafchromic EBT3 and ion chamber PTW PinPoint 3D Chamber 31022. The films and the ion chamber are installed into targets of the phantom. Two-dimensional dose distributions of target cross central layer are measured by the films. Irradiation plans verification in the central point of target is performed by the ion chamber. Irradiated films are processed according to the method described in [8, 9].

Data Analysis

Analysis of dose distributions is performed qualitatively and quantitatively. Qualitative analysis consists in visual inspection of the dose distribution for the presence of distortions such as hot and cold spots, dose field blur. Quantitative analysis consists in evaluation of average dose (Eq. (1)), standard dose deviation (Eq. (2)) and dose homogeneity (Eq. (3)) in the ROI, and dose gradients (Eq. (4)).

$$\langle D_{ROI} \rangle = \frac{\sum_{i=i_1,j=j_1}^{i_2,j_2} D_{ij}}{(i_2-i_1)(j_2-j_1)} \quad (1)$$

$$\sigma_{ROI} = \sqrt{\frac{\sum_{i=i_1,j=j_1}^{i_2,j_2} (D_{ij}-\langle D_{ROI} \rangle)^2}{(i_2-i_1)(j_2-j_1)}} \quad (2)$$

$$H_{ROI} = 100\% - \frac{\sigma_{ROI}}{\langle D_{ROI} \rangle} \cdot 100\% \quad (3)$$

$$\frac{dD}{dx} = \frac{|D_2-D_1|}{|x_2-x_1|} \quad (4)$$

Dose distribution is described by a two-dimensional dose matrix where i_1, j_1, i_2, j_2 – coordinates of the ROI, D_{ij} – element of dose matrix. The dose gradients calculated along the direction of motion on the linear section of dose fall where D_1 and D_2 – dose values at the ends of the linear section, x_1 and x_2 – coordinates of the ends of the linear section. The ROI is selected so that it is less than the PTV therefore size of the ROI is 1.8×1.8 cm. This makes it possible to exclude from the calculations the dose drops at the PTV angles.

RESULTS

The dose distribution images were built in the dose range from 0.00 to 6.50 Gy and in the millimeter coordinate system with resolution of 72 dots per inch (dpi). The calculated quantitative characteristics of dose distributions are presented in Table 1.

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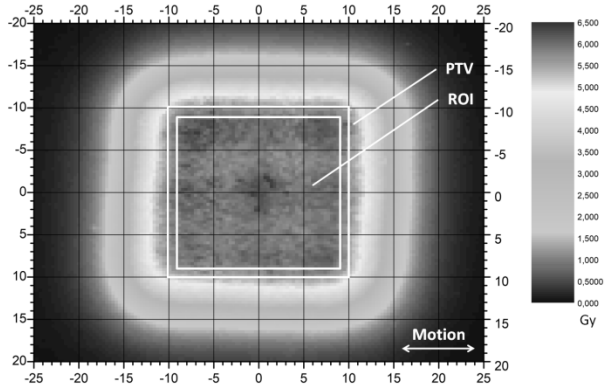

Figure 3: The dose distribution of 6.00 Gy plan without motion and with delineation of PTV, ROI and motion direction (view from nozzle).

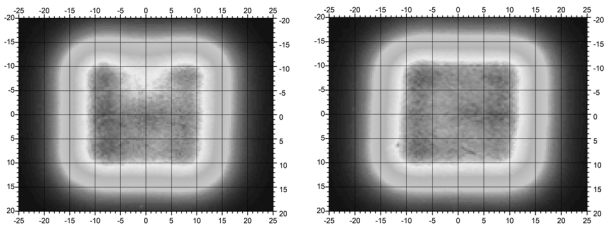

Figure 4: Motion with amplitude of 2 mm: left image – without repainting (4.6 Gy cold spot and no hot spots), right image– 6-iterative repainting.

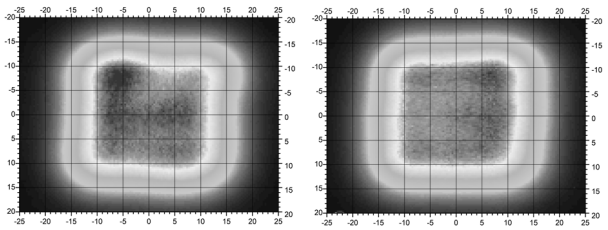

Figure 5: Motion with amplitude of 5 mm: left image – without repainting (6.6 Gy hot and 5.1 Gy cold spots), right image – 8-iterative repainting.

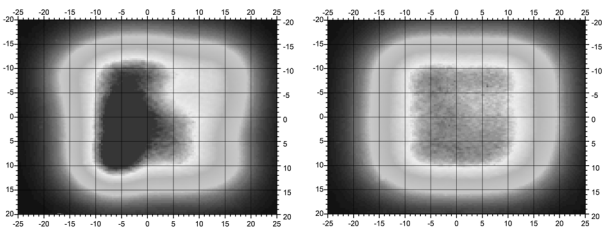

Figure 6: Motion with amplitude of 10 mm: left image – without repainting (7.8 Gy hot and 4.5 Gy cold spots), right image – 10-iterative repainting.

The dose distribution of non-moving target is shown in Fig. 3. This one is characterized by high homogeneity about 97.9% and dose gradient about 0.60 Gy/mm, and no hot and cold spots. The dose distributions of moving target without and with repainting for 2 mm (Fig. 4), 5 mm (Fig. 5) and 10 mm amplitude (Fig. 6) are shown. There are significant distortions of dose distribution without repainting: presence of hot and cold spots with doses of 7.8 Gy and 4.5 Gy (Fig. 6), shape distortion and dose blur along the direction of motion. Dose homogeneity and dose gradient decrease from 97.9% to 85.9% and from 0.60 Gy/mm to 0.44 Gy/mm, respectively, in case of 10 mm motion amplitude.

The images with repainting show that repainting removes hot and cold spots and improves homogeneity from 85.9% to 96.0% in case of 10 mm motion amplitude and 10 iterations. However, the dose gradient is inversely proportional to motion amplitude and is not improved by repainting. This one remains at the same level with ±0.02 Gy/mm fluctuations at a different number of iterations. The average dose in the ROI is lower than the prescribed dose on average 0.3 Gy that may be caused by dose blur along motion direction and film quenching effect [9].

Here the best dose distributions with the least number of repainting iteration are shown. Using more iteration did not improve the dose distribution (Fig. 4,5). The larger the amplitude of motion, the more iteration is needed to achieve acceptable homogeneity.

Table 1: Result of Quantitative Analysis of Dose Distributions

A, mm	N	H, %	Dose, Gy	Gradient, Gy/mm
-	1	97.9	6.0	0.60±0.01
2	1	94.7	5.6	0.59±0.02
	4	97.3	5.8	
	6	97.4	5.7	
5	1	92.1	5.5	0.56±0.02
	6	97.1	5.7	
	8	97.1	5.8	
10	1	85.9	6.2	0.44±0.02
	6	92.5	5.7	
	10	96.0	5.6	

CONCLUSION

Repainting greatly increases the dose homogeneity and removes hot and cold spots when irradiating a moving target. However, the dose gradient along motion direction is inversely proportional to motion amplitude and does not improve by repainting. Average dose in the ROI may decrease due to dose field blur. Thereby, optimization of the irradiation time, PTV dose and dose field margins is necessary for clinical using of repainting.

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