MODEL ANALYSIS OF RESPIRATION-RELATED DOSIMETRIC CHANGE DURING RADIOTHERAPY

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ABSTRACT

To estimate the respiration-induced dosimetric change at beam edge during a beam-on interval of radiotherapy, by the integration of a mathematical model for organ motion and a modeled beam profile. A method is proposed which incorporated the effects of intra-treatment organ motion due to breathing on the dosimetric change for the treatment of liver cancer. The basic algorithm was to assume the motion of intra-abdominal organs was predominantly in the superior-inferior (S-I) direction. The starting phase was defined as the mid-phase at exhale, to reproduce the same situation of computed tomography simulation for liver cancer. The S-I extent of motion was defined as 1.5cm. The period of a breathing cycle was defined as 4.2 seconds. The shape parameter of the respiratory model was defined as 3. The radiation dose of 100 cGy given with the rate of 300 MU/minute was designed for the model analysis. The position at the beam edge as a function of time could be parameterized for a 10cm × 10cm field with a setup of SAD 100cm. The dose profiles of both 6MV and 18MV photons were applied for the dosimetric calculation of the beam-edge point during the dynamic movement in a beam-on time interval of radiotherapy. The point doses at the superior beam edge for 6MV photons and 18MV photons during a beam-one interval of 22.8 seconds were 73.5% and 77.2% of the isocenter dose, respectively. The point doses at the inferior beam edge for the two energies were 31.2% and 32.4%, respectively. There were 147-154% dose increase for superior beam edge and 62.4-64.8% dose decrease for inferior beam edge, as compared to the 50% isocenter dose with the static dose distribution. It is simple and feasible to use the mathematical model to estimate the dosimetric change of the intra-abdominal organ motion from respiration. The impact of respiration on the dosimetric difference deserves more attention in the prescription of radiation treatment. Further measurement of the exact organ motion during the real treatment is warranted to optimize the model.

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Key words: Respiration, Dosimetry, Beam edge, Radiotherapy

1. INTRODUCTION

The goals of radiation therapy are to give as much dose as possible to the target volume, and to minimize dose to normal tissues. With the advanced techniques and equipments, we can now design the delicate radiation treatment plans and operate the delivery systems

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more accurately [1, 2]. However, some uncertainties from the intra-treatment organ movement and the daily setup error still deserve attention to overcome [3, 4]. In the ICRU Report 50, planning target volume (PTV) is defined to take both components into consideration [5]. The intra-treatment organ movement is especially prominent and important in the treatment of pulmonary and intra-abdominal malignancies, such as lung cancer and liver cancer [6]. Respiration-induced movements of the visceral organs, including diaphragm, liver, stomach, and kidney, may result in significant difference in dosimetric distribution and sufficient safe margin designed to adequately cover the target volume [7]. Several efforts have been devoted to solve the respiration-related movement during radiotherapy, such as the designs of the gating system and immobilization device [8]. In this study we tried to estimate the respiration-induced dosimetric change at beam edge during a beam-on interval of radiotherapy, by the integration of a mathematical model for organ motion and a modeled beam profile.

2. MATERIALS AND METHODS

A method was proposed to incorporate the effects of intra-treatment organ motion due to breathing on the dosimetric change for the treatment of liver cancer. The basic algorithm was that primarily transitional motion of intra-abdominal organs related to respiration during radiation therapy was predominantly along the longitudinal, superior-inferior (S-I) direction. Therefore, we focused on the motion of the S-I direction in this study.

The starting phase of treatment was defined as the mid-phase of exhale, to reproduce the same situation during computed tomography (CT) simulation for liver cancer. The applied respiratory parameters included: the S-I extent of motion of 1.5cm; the period of a breathing cycle of 4.2 seconds; the shape parameter of

the respiratory model of 3. The mathematical equation of respiration-related movement was listed as below [9]:

$$\text{Movement} = z_0 - b \sin^{2n}(\pi t / \tau - \phi)$$

$$\phi = 0 \text{ at exhale}$$

Where z_0 is the position at exhale, b is the extent (amplitude) of the motion, $z_0 - b$ is the position at inhale, τ is the period of breathing cycle, n is a parameter that determines general shape (steepness and flatness) of the model, and ϕ is the starting phase of the breathing cycle. The model to be measured was the dosimetry at the beam edges in the S-I directions during the dynamic movement in a beam-on time interval of radiotherapy. The position at the beam edge as a function of time was parameterized for a 10cm x 10cm field with a source-axis distance (SAD) setup of 100cm. Radiation dose of 100 cGy was given with the rate of 300 MU/minute. The dose profiles of both VARIAN CL-1800 6MV and 18MV photons were applied for the dosimetric calculation of the beam-edge points.

3. RESULTS

Based on the mathematical equation for respiration-induced movement and the starting phase in the mid-phase of exhale, the movement profile at superior and inferior beam edges were shown in Fig 1 and Fig 2, respectively.

The dose profiles for VARIAN CL-1800 6MV and 18MV photons, with field size of 10cm x 10cm and depth of 10cm, were listed in Table 1. With the combination of movement profiles and dose profiles, the calculated dose profiles of 6MV and 18MV photons, for different positions from field center to superior and inferior beam edges were shown in Fig 3 and Fig 4, respectively.

Given a radiotherapy beam-on time of 22.8 seconds and the starting phase in the mid-phase of exhale,

Fig 1. The movement profile at superior beam edge during the respiration cycles

Fig 2. The movement profile at inferior beam edge during the respiration cycles

Fig. 3 The calculated dose profile (distance from isocenter) of 6MV photons with (static) and without (superior/inferior) integration of the respiration model

the doses were 77.2% at the superior beam edge and 32.4% at the inferior beam edge, as compared to 50% of the isocenter dose at either beam edge without the impact of respiration. The dose ratios were 154% for superior edge and 65% for inferior edge of the condition without the respiration-induced movement.

4. DISCUSSION

Upon the integration of the advanced techniques into radiation treatment, it becomes more practical to deliver higher doses for intra-thoracic and intra-abdominal malignancies [10]. With the three-dimensional conformal design and the application of dose-volume model for normal tissue tolerance, it is now more effective and safer to escalate doses of radiation, to obtain the therapeutic gain, and to restore the organ function [11]. The University of Michigan series have indicated the effectiveness of high-dose three-dimensional conformal radiotherapy for unresectable intrahepatic malignancy [12]. They also established the dose-volume model with the normal tissue complication probability method as the basis of dose escalation plan [13].

Respiration-induced organ movement has been of much clinical significance for radiation therapy. The most prominent motion during respiration is usually present in lower lobes of lung, diaphragms, and liver. Several efforts have been made to quantify the respiration-related movement during the treatment. The Japanese series demonstrated the serial CT images during radiotherapy at the level with the maximal diameter of intra-thoracic tumor [4]. They found that tumors in lower lobes sustained more respiration-related diameter changes than those in middle or upper lobes. They concluded that the effect of respiration on the intra-

Fig. 4 The calculated dose profile (distance from isocenter) of 18MV photons with (static) and without (superior/inferior) integration of the respiration model

thoracic organ movement should be cautiously studied for radiotherapy of lung cancer. The University of Michigan series conducted the study with three CT sets for the full inhale, full exhale, and free breathing phases [6]. The respiration-induced maximal movements of liver and kidneys were quantified and shown. They provided an important reference of the respiration-related intra-abdominal organ movement during radiotherapy. Other series also documented the largest difference in respiration-related movement was in the superior-inferior (S-I) direction [7]. The estimated movements in different directions were 6:1 for S-I versus right-left directions, and 5:1 for S-I versus anterior-posterior directions. Based on these findings, we estimated the movement in S-I direction as the only indicator in this study.

It is a simple and feasible way to use the mathematical model to estimate the dosimetric change of the intra-abdominal or intra-thoracic organ motion from respiration. The other treatment conditions, such as different beam-on time, starting phase of breathing, and respiratory motion extent can be calculated with the integrated model accordingly. Respiration-induced organ movement results in a significant dose variation at the beam edge, with as high as 77% at superior and as low as 32% at inferior beam edges of radiation ports, as compared to 50% of the isocenter dose without the impact of respiration. The respiration-induced dosimetric changes deserve further attention for radiation oncologists, medical physicists, and medical dosimetrists to prescribe and design the treatments carefully. The difference in dosimetry between superior and inferior beam edges is mainly from the pre-defined starting phase in mid-phase of exhale. The dosimetric results will vary with the different setting of the starting phase, beam-on time, motion extent, and specific dose profile

Table I. The dose profiles for VARIAN CL-1800 6MV and 18MV photons (field size: 10cm x 10cm; depth: 10cm)

Distance away from center (mm)	VARIAN 6MV ratio	VARIAN 18MV ratio
0	1.000	1.000
2	0.999	0.999
4	1.001	1.001
6	1.002	1.001
8	1.003	1.003
10	1.004	1.003
12	1.006	1.005
14	1.005	1.004
16	1.006	1.006
18	1.007	1.008
20	1.006	1.005
22	1.004	1.007
24	1.003	1.006
26	1.002	1.009
28	1.001	1.008
30	0.999	1.005
32	0.992	1.003
34	0.991	0.998
36	0.987	0.993
38	0.979	0.984
40	0.973	0.969
42	0.961	0.952
44	0.943	0.918
46	0.911	0.874
48	0.795	0.761
50	0.562	0.559
52	0.310	0.345
54	0.179	0.200
56	0.136	0.144
58	0.110	0.106
60	0.099	0.086
62	0.089	0.072
64	0.080	0.057
66	0.076	0.047
68	0.069	0.042
70	0.064	0.035
72	0.059	0.032
74	0.056	0.028
76	0.053	0.024
78	0.048	0.021
80	0.047	0.019
82	0.044	0.017
84	0.040	0.016
86	0.039	0.014
88	0.036	0.012
90	0.028	0.010

of linear accelerator for the radiation treatment [3]. The University of Michigan group have been using the end-phase of exhale for their patients to be the static phase of CT simulation and the starting phase of daily treatment [11]. With the integration of the mathematical description of respiration for the individual patient and the dose profiles of treatment machine, we are able to graphically estimate the exact dosimetric change at either beam edge. It is helpful either in designing the

adequate margins around target volumes or in sparing the critical organs from excess radiation damage.

According to ICRU Report 50, PTV is defined as the adequate margin around clinical target volume (CTV). The design of PTV includes the setup error and the intra-treatment organ movement [5]. The appropriate PTV by selection of adequate margins around CTV can be derived from the information of the respiration-related dosimetric model analysis. Further measurement of the exact respiration-induced organ motion during the real-time treatment and the mathematical description of movement are warranted to optimize the model for the individual patient.

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