Investigation of tumor motion influence on applied dose distribution in conventional proton therapy vs. IMPT; a 4D Monte Carlo simulation study

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ABSTRACT

Background: in radiation treatment of moving targets located in thorax region of patient body, the delivered dose does not match with the planned treatment, resulting in some over and under dosage in the tumor volume, as a function of motion magnitude and frequency. Several efforts have been done to investigate the target motion effects on dose distribution in the target and surrounding normal tissues. ***Materials and Methods:*** in this study a spherical object undergoing periodic motion was considered as target inside a water phantom and its motion magnitude and frequency were adjusted to mimic realistic respiratory patterns. We selected a proton beam for irradiation and considered two different strategies in the simulation procedure to provide 3D target dose coverage: 1- conventional proton therapy using passive dose delivery and 2- IMPT; both under respiratory gating technique. ***Results:*** in conventional proton therapy, the dose contribution within the normal tissues increases linearly at each gating window increment and in motion gated IMPT the delivered dose to the target and normal tissues strongly depends on the target and beam scanning motion interplay, that results an over and under dosage in target volume. ***Conclusions:*** In Conventional Proton Therapy, although the applied dose distribution on dynamic target volume is satisfactory at each gating window size, a significant dose is delivered to the surrounding normal tissues in comparison with same calculation in motion gated IMPT. In order to protect healthy tissues it is very important to use active spot scanning methods in dose delivery, minimized target and beam scanning motion interplay.

Keywords: *Moving targets, proton therapy, dose distribution, interplay effect.*

INTRODUCTION

In radiotherapy, the final purpose is to produce (three Dimensional) 3D homogeneous dose distribution onto the tumor volume while minimizing the dose to the surrounding healthy tissues around the tumor. Relating to moving targets, the delivered dose is not matched with the planned dose and some over and under dosage is resulted proportional to motion magnitude and frequency [1-4]. Various strategies have been developed which can be applied to compensate the effects of intra-fractional motion, including breath holding [5], respiratory gating [6-8] and tumor tracking [9]. In respiratory-gated radiotherapy the irradiated volume of normal tissues is minimized by irradiating the therapeutic beam only in a pre-defined phase of the breathing cycle [6-8]. In this approach the gating window can be set to turn on the therapeutic beam within a pre-defined window. Typically the gating window is selected near the

end of exhale to minimize the residual target motion. Gating window size is one of the most important parameters in respiratory gated radiotherapy, due to its impact on radiation exposure time and dose distribution within the target and surrounding healthy tissues [10, 11].

Our goal in this work is to obtain a quantitative assessment of 3D dose distribution on the moving targets and surrounding normal tissues affected by the breathing motion, in conventional proton therapy (PT) vs. Intensity Modulated Proton Therapy (IMPT). For this aim, a simulation study was performed using Monte Carlo FLUKA (FLU ktuierende KAskade) code [12,13] considering respiratory gated technique. Conventional proton therapy differs from IMPT due to its different procedure in 3D dose distribution generation [14,15]. Several efforts have been carried out in order to investigate the influence of target motion on prescribed dose distribution mainly in conventional radiotherapy and IMRT [11, 20-24]. Nevertheless, investigation of target motion effect on applied dose distribution is still required in conventional proton therapy versus IMPT while the clinical application of this latter is increasing.

A moving spherical target filled with water was built inside a water tank to simulate typical breathing motion. Three irradiation conditions were taken into account using one horizontal proton treatment field: 1- target as static case applying active spot scanning technique in dose delivery, 2- target as dynamic case using the same scanning technique, and 3- target as dynamic case with the use of conventional proton therapy approach in different gating windows. Dose contribution in target and normal surrounding tissues in the static case was chosen as reference for other calculations under motion-gated technique. In conventional proton therapy, calculating the fraction of dose contribution onto the healthy tissues was taken into account in different amplitude-based gating windows as different treatment plans, simulating all required passive devices [14, 15]. In contrast, in motion gated IMPT the same calculations were performed in one gating window considering interplay effect occurred between beam scanning and target motions. In IMPT method, the magnitude of interplay effect strongly depends on the speed and direction of beam scanning motion against target motion. A target motion in slow beam scanning causes an undesirable extended spot pattern, whereas in fast spot scanning the interplay pattern decreases significantly and is closer to the prescribed homogeneous dose [16-18]. In this work, in motion-gated IMPT the percentages of under and over dosage onto the target volume were calculated when the beam scanning (in Cartesian mode) interferes with the target motion from two different directions with a pre-defined speed.

Final analyzed results represent that in conventional proton therapy, although the dose contribution within the target volume is justified, but in comparison with stationary condition there is a significant delivered dose to the normal tissues which linearly increases at each gating window increment. In contrast, in motion gated-IMPT, the interplay effect arising from the relative speed of the target motion with respect to the scanning speed causes a distortion in prescribed dose distribution of the target volume in our case study. Furthermore, the dose received by surrounding normal tissues is variable depending on target and beam scanning motion directions. When the target and beam scanning directions are identical the moving target significantly avoids delivering dose to the normal tissues in its trajectory and therefore a maximum over-dosage is occurred on the target volume. Inversely, when the target and beam scanning directions are opposite, the contribution of total prescribed dose received by normal tissues is significant.

MATERIALS AND METHODS

The diameter of chosen spherical target is 12mm located inside a water tank with 50mm×50mm×100mm dimensions. The smaller side of the water tank was placed in front of the incidence beam, the distance between central

point of water tank and beam starting point is 680mm and the target origin (fixed as isocenter) is at 19mm far from the front side of the water tank. The chosen particle type is proton with energy in the range of 94.3 to 102.5 MeV in active beam delivery method. This range of energy was used to produce the 3D dose distribution onto the whole target volume in IMPT approach. The utilized Full-Width at Half Maximum (FWHM) for the proton beam was 3mm on X and Y axes whereas the beam direction is on Z.

Target motion characteristics and simulation procedure

The beam was assumed to irradiate in Z direction and scan the target slices in Cartesian mode in X and Y as horizontal and vertical directions, respectively. The target oscillates between 0 to 10 mm on Y axis and the motion parameters have been adapted to realistic parameters. The largest amplitude of target motion was set to 10 mm and each gating window sizes increases by 2 mm from 0 to 10mm in conventional proton therapy. In gated-IMPT condition, the beam scanning speed on Y direction was assumed to be 40mm/sec whereas the target speed on Y direction and its residual motion were set to 10mm/sec and 4 mm respectively. The interplay effect was taken into account in two modes. In the first mode the direction of target motion is same with the vertical direction of beam scanning motion, and in the second mode their motion are in opposite direction. A treatment plan program was developed under MATLAB (The MathWorks Inc., Natick, MA) in order to give a proper IMPT plan for our target as pre-irradiation step. This program also enables us to evaluate the 3D dose conformity onto the target volume before irradiation.

In the spot scanning method, the target volume was divided vertically into 8 slices with 1.5mm slice thickness, and the treatment planning program derived the number of required iso-energy spot beams at each slice, plus coordinate and weighting coefficient of each spot. In contrast, in the conventional proton therapy using passive beam delivery technique, the 3D dose conformity on each gating window is achieved using an iso-energy 102.5MeV extended proton beam. In this approach the required passive devices which taken into account, were ridge filter, collimator and compensator made by (Polymethyl methacrylate) PMMA. The designed ridge filter produces an acceptable Spread Out Bragg Peak (SOBP) 12mm onto the target volume in depth dose direction and the simulated collimator and compensator protect the normal tissues located in lateral and distal parts of the target, respectively.

Simulation procedure was performed using FLUKA code. FLUKA is a Multi-purpose multi-particles Monte Carlo transport code in particle physics [13]. The FLUKA code characteristics at intermediate energies make it particularly reliable in treating problems in the fields of radiotherapy and radiation protection [12, 19]. In this work the output of pre-irradiation treatment planning program including spot beam numbers, coordinates and weights were utilized in the extended version of FLUKA source.

RESULTS

In this work, the energy deposition (GeV/cm^3) was considered as output of the FLUKA simulation code and then converted into Gray (J/kg). The prescribed dose was 1Gy which was normalized in the illustrated results. The spatial resolution for simulation calculation was set as 0.4×0.4×0.4mm^3 and number of particles was chosen as 10^8 in order to keep the statistical uncertainty error less than 5%.

Figures 1 and 2, respectively, represent the normalized depth and transverse dose distributions in static target, using the spot scanning technique.

As shown in figure 1, 8 slices were considered as iso-energy slices for beam irradiation, from initial point of the target located at 68.0 mm of depth in the proximal part, toward end point of the target which is at 80.0 mm in depth in the distal part.

Figure 2 shows the transverse dose distributions in 7 selected circular slices of the target with 8.1, 10.6, 11.7 and 12.0 mm sizes in diameter. In this figure, each target slice is covered by a proper treatment region of each lateral dose profile which has been taken into account according to the flatness definition and recommendation (uniformity more than 95%). The data were fitted using least square polynomial curve fitting approach.

Figure 3 represents the percentage of 3D dose distribution received by normal tissues surrounding the target in different sizes of gating window in conventional proton therapy and motion gated IMPT in gating window 4mm vs. static case as reference. The assumed normal tissue geometry in this work consists of total irradiated region (in cm^3) received high dose, excluding spherical target volume with 12 mm diameter. In different gating window sizes the percentage of dose contribution in normal tissues is calculated by subtracting the delivered dose to the target volume in static case as reference from the dose delivered to the total region including residual motion.

As seen in this figure, the delivered dose to the healthy tissues increases linearly from 33.6% to 62.7%. In 4mm gated-IMPT, the dose contribution onto the normal tissue is 55.0% and 25.0% when the target and beam scanning motions on Y axis are in the opposite and identical directions, respectively. The illustrated results were strongly influenced by chosen

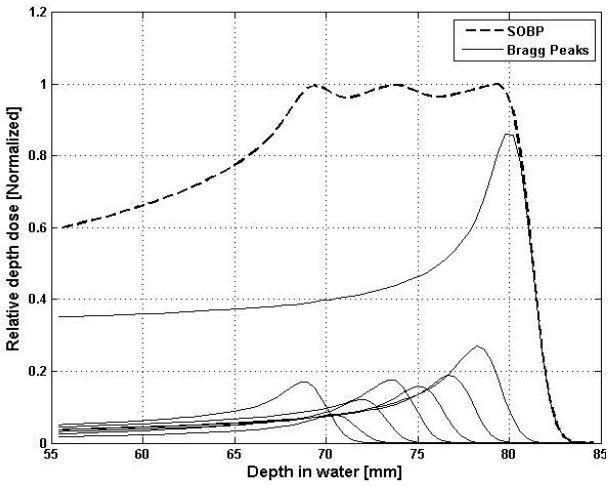

Figure 1. depth dose profiles of proton beam in 8 slices from distal toward proximal part of the target.

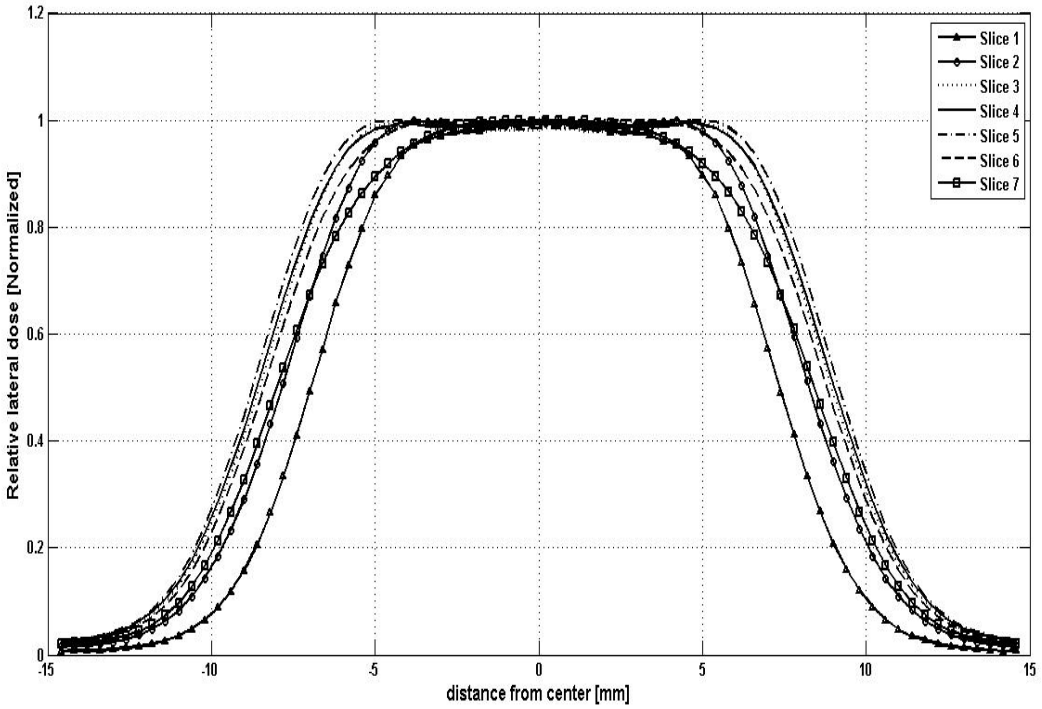

Figure 2. transverse dose profiles of proton beam in 7 selected circular slices of the target .

beam scanning speed as 40mm/sec vs. target motion speed that is 10 mm/sec in 4mm residual motion on Y axis. Higher scanning speed results lower interplay pattern that will be closer to the expected dose homogeneity, although in practical use, the scanning speed depends on deflection magnets capability.

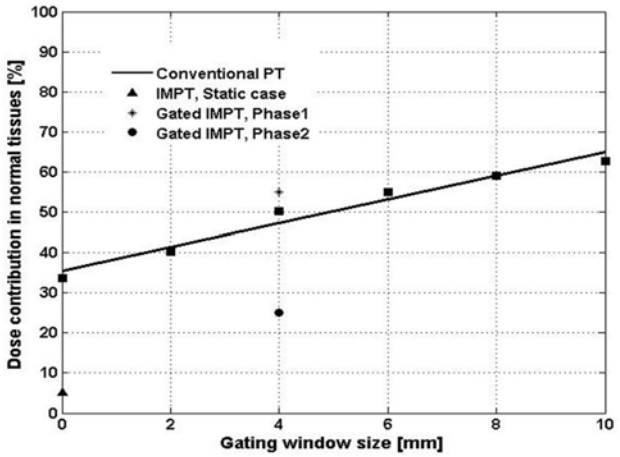

Figure 3. The percentage of dose distribution received by normal tissues in different size of gating window in conventional PT and in motion gated IMPT at gating window 4mm when beam scanning and target motion directions are opposite (phase 1, star point) and identical (phase 2, circle point) vs. stationary condition.

Figure 4 illustrates the over and under dosage occurred onto target volume duringtarget motion in 4mm gated-IMPT.

In the static case (figure 4-a), the middle slice is covered homogeneously with the prescribed dose, but in the dynamic case the under and over dosage inside the target volume occurs while the target moves in the opposite (figure 4-b) and similar direction (figure 4-c) with respect to the beam scanning direction. In this example the under and over dosages are 25.0% and 25.2% less and more than the prescribed dose to the target, respectively. Moreover, the dose uniformity of treatment region in middle slice was decreased from 95% in the static case to 74.1% (figure 4-b) and 65.0% (figure 4-c) in the dynamic case.

DISCUSSION

Studies were performed to assess the effect of tumor motion effect on the applied dose distribution in respiratory gated conventional proton therapy and IMPT. The residual tumor

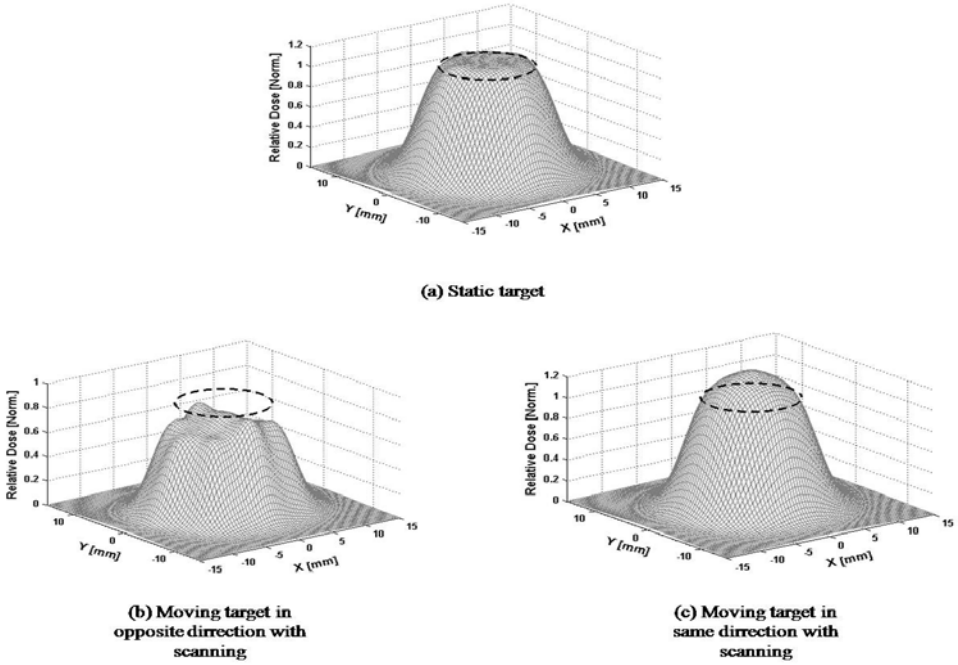

Figure 4. 3D dose homogeneity on middle slice of target volume is IMPT static case (a) and in 4mm gated-IMPT dynamic case while target motion is in opposite (b) and similar direction (c) with beam scanning. The dashed circle represents treatment region.

motions were analyzed using a moving spherical phantom and a gating window of up to 10 mm was considered to quantitatively assess the contributed dose in normal tissues. In gated conventional proton therapy, although the appropriate dose is delivered to the target, the dose contribution within the normal tissues ranges from 33.6% to 62.7% in different size of gating window in comparison with the stationary condition. In contrast, in gated IMPT, the dose received by surrounding normal tissues is variable depending on speed and direction of target and beam scanning motion. In our dynamic case, the interplay between target motion and beam scanning results an over and under dosage and the dose contribution on the target volume varies by approximately 1/4.

CONCLUSION

Final analyzed results represent that for conventional proton therapy there is a significant delivered dose to the normal tissues in comparison with same calculation in motion gated IMPT. In proton therapy, in order to protect healthy tissues it is very important to use active spot scanning methods in dose delivery, minimized target and beam scanning motion interplay. Further, Studies will investigate the motion effects on dose contribution using the (four Dimensional) 4D NCAT (Nurbs-based Cardiac Torso) phantom, considering also the effects of different spot scanning strategies on the delivered dose.

Declaration of interest

The author reports no declarations of interest.

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