Investigating the relationship between Anatomical changes and organ at risk dose in magnetic resonance imaging (MRI)-guided carbon-ion radiotherapy (MRgCT) of prostate cancer

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Abstract
In the present study, first, the anatomical changes impact on dose variations in prostate and bladder organs (as an organ at risk) was assessed. Second, variation in prostate and bladder dose due to a set-up error for a potential method of magnetic resonance imaging-guided carbon-ion radiotherapy (MRgCT) of prostate cancer was investigated. For this purpose, carbon-ion beams perpendicular to a pelvis phantom in which 1.5 T transverse magnetic field was applied were simulated using the FLUKA code. To assess the effect of anatomical changes, changes in dose of the bladder, prostate, and rectum, as well as set-up error were investigated. The results show that anatomical changes lead to important change of the dose in MRgCT prostate cancer.
Keywords: Absorbed dose, Anatomical change, Carbon-ion radiotherapy, Magnetic field, Prostate cancer

Introduction
The special properties of carbon ions relative to photons lead to greater sensitivity of carbon ion radiotherapy (CIRT) to the patient's anatomical changes. . It is also more effective in image-guided particle therapy (IGPT) due to the naturally higher geometry sensitivity of the ion than the photon [1]. A magnetic resonance imaging (MRI) system is an appropriate tool for IGRT. Due to applying a magnetic field during MRI-guided ion therapy, this field influences both the primary ions and the secondary charged particles produced as well, hence, particle therapy is more effective than photon beam therapy-based MRI guidance[2], Which leads to a higher dose perturbation in the patient's body.
During RT, intra- and inter-fractional variation may notably influence the robustness of particle therapy [3]. Therefore, the dosimetry impact of anatomical changes in the presence of a magnetic field might need to be assessed. The main purpose of this study is the assessment of the radiation absorbed dose variation in the whole volume target due to anatomical changes when the Gaussian 250 MeV/n C-ion beams with characteristics of full width at half maximum (FWHM) = 0.6 MeV/n, $\Delta\varphi$ =1 mrad, and $\Delta X=\Delta Y=7.065$ mm traverse in a media affected by a 1.5T transverse magnetic field.

Monte Carlo simulation
In this paper, the FLUKA Monte Carlo (MC) code was utilized for all the simulation calculations. This code has a fast algorithm for traversing charged particles in a magnetic field. In all the simulations performed in this work, the recommended settings suited to ion-beam therapy applications and dosimetry [4], were selected in the code. A maximum number of 10^5 C-ion histories are required to have statistical accuracy of less than 1% . A validation with the available experimental data for C-ion depth-ionization curve were done in the absence of a magnetic field (Figure 1). In this validation, the ionization-depth profile of carbon has less than 1mm different with the experimental curve.
To simulate a patient-specific scenario with a tumor located in the pelvic region (prostate in this study), a rectangular inhomogeneous phantom (Figure 2) includes water, soft tissue, air materials was considered.
Anatomical change during treatment (intra-fraction) and between treatment sessions (inter-fraction) in the pelvic region using a change in bladder displacement and diameter that may occur depending on the volume of fluid in the bladder, diameter change of tumor and its displacement, and diameter change of rectum cylinder air-filled were studied. In addition, the effect of set-up dose received by the bladder and the prostate was calculated. To assess the risk of secondary bladder cancer as an OAR, in this study, change in the bladder dose equivalent of protons, and secondary particle in the volume of air inside the rectum were calculated.

Results and discussion
In this study, the c-ion particles were irradiated in the +Z direction to the pelvis phantom while the direction of 1.5T transverse magnetic field is in the +X direction.

The size and location of tumor and bladder were changed to assess the anatomical change in the prostate cancer treatment.

Changing the prostate tumor size from 6 to 1 cm leads to 88% reduction of absorbed dose. About the effect of the location prostate tumor change, a 1 cm shift in lateral direction leads to 17% increase of absorbed dose. In addition, by moving the tumor location 1 cm in the direction of parallel beam, a maximum of 24 % increase of the tumor dose occurs.

If the bladder size changing does not change the tumor location, changing the size of the bladder does not affect the tumor absorbed dose. In this case, by reducing the bladder size from 10 to 5 cm, the bladder dose reduce by 92%. The bladder motion upstream of the beam direction ranging from 5 to 0.1 cm leads to a reduction of 0.84% in the tumor dose.

In addition, the impact of set-up error perpendicular to the beam and towards the bladder surface on the prostate and bladder dose was investigated. While set-up error increases from 1 mm to 5 mm, the prostate dose reduces from 0.0% to 5.0%, and the bladder dose increases from 4.5% to 32%.

Finally, the effect of change in the volume air inside the empty rectum was assessed.in this case, by reducing the diameter of the rectum from 5 to 3 cm, the amount of prostate dose increases by about 20% and the bladder dose increases by 26%. In this condition, the dose equivalent of the bladder due to secondary particles of protons, neutrons, and alpha particles increases.

Conclusions

The average flux of the primary incident C-ion particles in the patient body is 2.0×10^7 particles/s (a maximum of 5.3×10^7) that results the dose range of about 3.2–4.3 Gy in each fraction. The results showed that although anatomical changes as an important factor must be considered in prostate cancer. In the case of prostate, anatomical changes leads to change of the prostate dose notably, but it does not change the dose of the bladder significantly. About the impact of anatomical changes on the bladder but the prostate dose Change in prostate and bladder dose due to a set-up error is important and depends on the amount of the set-up error.

By increasing the set-up error perpendicular to the beam and towards the bladder surface in the range of millimeters, the prostate and the bladder dose increase. If the volume of air inside the rectum changes, it has a significant effect on the absorbed dose of the bladder and prostate, as well as the dose equivalent of the bladder.

The results of this study highly supports making a decision to change the contouring of the target volume or organs at risk and the strategy of the C-ion treatment plan by guiding the MRI image, as a potential treatment option in the future.

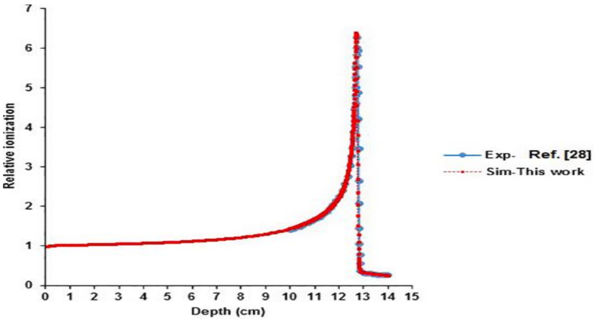

Figure 1Comparison of the relative ionization – depth curve of a C-ion beamwith an energy of 250 MeV/n in the absence of a magnetic field with the experimental data

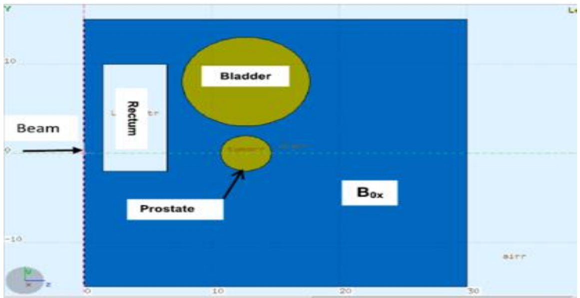

Figure 2. The simulated pelvis phantom affected by a 1.5 T magnetic field (B0x).

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