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Original paper

Monte Carlo study of out-of-field exposure in carbon-ion radiotherapy with a passive beam: Organ doses in prostate cancer treatment

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ABSTRACT

Purpose: The aim of this work was to estimate typical dose equivalents to out-of-field organs during carbon-ion radiotherapy (CIRT) with a passive beam for prostate cancer treatment. Additionally, sensitivity analyses of organ doses for various beam parameters and phantom sizes were performed.

Methods: Because the CIRT out-of-field dose depends on the beam parameters, the typical values of those parameters were determined from statistical data on the target properties of patients who received CIRT at the Heavy-Ion Medical Accelerator in Chiba (HIMAC). Using these typical beam-parameter values, out-of-field organ dose equivalents during CIRT for typical prostate treatment were estimated by Monte Carlo simulations using the Particle and Heavy-Ion Transport Code System (PHITS) and the ICRP reference phantom.

Results: The results showed that the dose decreased with distance from the target, ranging from 116 mSv in the testes to 7 mSv in the brain. The organ dose equivalents per treatment dose were lower than those either in 6-MV intensity-modulated radiotherapy or in brachytherapy with an Ir-192 source for organs within 40 cm of the target. Sensitivity analyses established that the differences from typical values were within ~30% for all organs, except the sigmoid colon.

Conclusions: The typical out-of-field organ dose equivalents during passive-beam CIRT were shown. The low sensitivity of the dose equivalent in organs farther than 20 cm from the target indicated that individual dose assessments required for retrospective epidemiological studies may be limited to organs around the target in cases of passive-beam CIRT for prostate cancer.

1. Introduction

Prostate cancer is the second most common cancer (after lung cancer) among men globally and the most common cancer in developed countries [1]. There are many treatment modalities for prostate cancer, including radiotherapies such as three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT), and ion-beam radiotherapy such as proton radiotherapy and carbon-ion radiotherapy (CIRT), the last one being one of successful treatment modalities for prostate cancer [2,3]. Since 1995, the National Institute of Radiological Sciences (NIRS) of Japan has performed CIRT at the Heavy-Ion Medical Accelerator in Chiba (HIMAC) in both clinical trials and clinical practice for prostate cancer treatment. Ion-beam radiotherapy can greatly reduce the entrance dose because of their physical characteristics called the Bragg peak. In addition, CIRT offers physical and biological advantages over proton beams, namely, a lower scattering power and a higher biological effect. These physical and biological advantages in CIRT lead to high-dose localization in the target volume with minimal damage to the surrounding normal tissue, thereby indicating favorable outcomes and a treatment duration that is less than half that of photon radiotherapy [4,5].

Meanwhile, the radiation-induced second cancer risk of patients receiving radiotherapy is a major concern, as is increasing the effectiveness of the radiotherapy and extending life expectancy [6–9]. The second cancer risk depends on the volumes of both the high-dose region in the irradiation field and the low-dose region outside the field. It has been shown that more modern radiotherapy techniques can achieve the reduction of the volume receiving high dose by the sparing of the organs at risk (OARs) compared to conventional radiotherapy, but the volume receiving low doses would increase because of the presence of stray protons and secondary neutrons in proton radiotherapy and the increased use of monitor units and irradiation fields in IMRT. [10] In photon radiotherapy, when the beam energy is higher than the threshold energy of photo-nuclear reaction, photo-neutrons are emitted, which then contribute significantly to the whole-body dose when the beam energy exceeds 15 MV [11,12]. In CIRT, carbon beam

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can produce secondary neutrons and charged particles during irradiation because of interactions with matter, which results in whole-body exposure. However, the contribution of the dose due to these secondary neutrons is lower at positions closer to the treatment target because of the presence of scattered primary carbon ions and secondary charged particles [13,14].

To predict the second cancer risk for modern treatment modalities, several dose-risk models were suggested [15–18]. Many findings were reported by combining the models and doses obtained from the treatment planning system (TPS), measurements, and Monte Carlo simulations [19–22]. Mavroidis et al. evaluated the clinical efficacy and the second cancer risks in bladder and rectum in prostate cancer treatment with step-and-shoot IMRT and 3D-CRT. The results indicated that the treatment modalities that were more effective regarding the treatment effects such as tumor control probability and normal tissue complication probability did not show similar results regarding second cancer risk [22].

In contrast, the epidemiological data are essential for establishing, enhancing and verifying the risk models, but such data are scarce for modern radiotherapy techniques. Previous investigations indicated that the prediction of the second cancer risk depends on the model with large uncertainties [5,7]. Murray et al. reviewed the study related to second primary cancer following prostate cancer treatment with radiotherapy and evaluated the risks and impacts of treatment modalities [23]. They concluded that the risk of radiation-induced second primary cancer appears small in older treatment modalities and appears to increase over time. However, the follow-up data were limited and insufficient to draw firm conclusions about modern treatment modalities, including IMRT and proton radiotherapy with passive beam.

In this regard, the follow-up data that are available on more than 10,000 patients who received CIRT at NIRS are of particular value and are collectively a possible candidate for an epidemiological study. Because the general information required for epidemiological studies is well recorded in clinical practice, accurate estimations of organ doses are also desired. In the beam path, the TPS can calculate organ doses near the target volume. However, a different method is required outside the beam path because the current TPS (XiO-N (Mitsubishi Electric Corporation, Tokyo, Japan)) cannot calculate the dose outside the beam path including the dose due to secondary neutrons. Thus, Monte Carlo simulation plays an important role in such calculations. We have already established a calculation method using Monte Carlo simulation to estimate the absorbed dose, the quality factor, and the dose equivalent simulating CIRT with passive beam at NIRS [24].

The aim of the present study is to use Monte Carlo simulations with an anthropomorphic phantom to estimate the doses to out-of-field organs during CIRT with the beam parameters of a typical prostate treatment plan with passive beam. We determined the typical beam-parameter values from statistical data on the target properties of patients who received CIRT at HIMAC. In addition, we performed sensitivity analyses of organ doses for various beam parameters and phantom sizes, thereby elucidating the expected dose range. This study provides the typical values of organ doses during passive-beam CIRT (PB-CIRT) for prostate cancer, and it also allows comparison with those in other modalities. At present, numerous new treatment facilities with carbon beam introduce an active scanning technique rather than a passive technique because of their high irradiation accuracy, flexible treatment planning, and less unwanted dose [25,26]. Treatments at NIRS are also shifting to those with an active-scanning beam [27], and it is no doubt that PB-CIRT is becoming an older radiotherapy technique. However, since about 9000 patients were treated with PB-CIRT at NIRS, it is still of value to analyze their clinical implications and to investigate the dose reconstruction in light of a potential epidemiological study.

2. Materials and methods

2.1. Estimation of typical beam parameters for prostate cancer treatment at HIMAC

We determined the typical values of the beam parameters from statistical data that summarized the parameters used in clinical practice at HIMAC in fiscal year 2011 (FY2011: April 2011 to May 2012), that being the final year in which clinical irradiations for prostate cancer were performed with only the passive beam line at HIMAC; since then, prostate treatment has been relocated to the active-scanning beam line at the new treatment facility [28]. There were 184 patients in the period in question, from whom we selected 165 to provide patient data for protocols 9904-3 and 0507G, in which the total prescribed dose was 57.6 GyE and the fractionation number was 16 for four weeks, namely, 3.6 GyE per fraction [2]. We did not consider a patient-specific collimator in this study because it was not used in any of the cases of prostate cancer treatment with CIRT at HIMAC. The number of irradiation directions varied according to the individual patient, but we assumed 13 fractions from two opposite horizontal beams and three fractions from one vertical beam (the anterior–posterior (AP) direction) based on the median value of the aforementioned statistical data.

We began by determining the properties of a typical target from the statistical data. We then determined the typical beam parameters to cover this target as follows:

1) The size of the laterally uniform field formed by the single-wobbling method [29] was determined from the irradiation field of the typical target assuming a circular irradiation field.
2) The spread-out Bragg peak (SOBP) width was determined from the maximum target thickness of the typical target.
3) The beam energy was determined from the maximum target depth of the typical target so that the beam range was long enough to cover the target. In theory, the beam range should depend on the species and energy of the beam and material in the beam path. In practice, however, it is also affected by the scatterer thickness when using the single-wobbling method.
4) The thickness of the range shifter was determined from the residual range of a carbon beam with the energy determined in step 3 above, the maximum target depth, and a minimum machinable patient-compensator thickness of 2.9 mm, which corresponds to 3.0 mm in water-equivalent length (WEL), which is defined as the length traversed by the beam in water until it loses the same energy that it loses in a given material. Here, the WEL of a patient compensator made of polyethylene (as used routinely in clinical practice) is 1.029 mm.

At the HIMAC passive beam line, there are clinically used beam-parameter sets of around 250 vertical lines and 360 horizontal lines according to the beam energy, the size of laterally uniform field, the SOBP width, and the thickness of the range shifter. Three typical beam-parameter sets could be specified with parameters determined in steps 1–3 above for the AP, right lateral (RLAT), and left lateral (LLAT) directions, respectively. However, we determined the typical beam parameters for the RLAT and LLAT directions without distinction in this study because the prostate is located laterally almost at the center. Finally, we determined two typical beam-parameter sets for the vertical and horizontal directions.

Because it has been shown that neutrons produced within a patient compensator are a minor source of the out-of-field dose [30], we determined the engraved depression of the patient compensator roughly so that we could adjust the beam range to cover the prostate volume of the anthropomorphic phantom used in this study. We determined the outer thickness of the patient compensator from the median value of the aforementioned statistical data.