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Effect of DIR uncertainty on prostate passive-scattering proton therapy dose accumulation

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ABSTRACT

Deformable image registration (DIR) is important in dose accumulation. Currently, the impact of DIR-algorithm-associated uncertainties in proton therapy is unclear. Here, we quantify the effect of DIR uncertainties on prostate passive-scattering proton therapy (PSPT) dose accumulation. Ten patients with an intermediate risk for prostate cancer formerly treated by PSPT (PTV D_{95} = 78 GyE) were studied. Dose distributions from all verification CT images (five images per patient) were warped and accumulated in the planning CT geometries with DIR. The dose-volume histogram parameters (D_{mean}, V_{40}, and V_{70}) for rectum and bladder were calculated. Two commercially available DIR software packages were employed: Velocity AI (Varian Medical Systems) and RayStation (RaySearch Laboratories). The dice similarity coefficient (DSC) and surface distance, which were calculated between planning CT contours and deformed contours, were used for DIR validation, with the relationship between the dose parameter and DIR uncertainty ultimately investigated. On average, when using RayStation, the DSC increased by 0.14 and surface distance decreased by 6.4 mm, as compared to Velocity. For D_{mean}, V_{40}, and V_{70} to the rectum, the average differences between the RayStation and Velocity were 3.9 GyE, 5.5%, and 3.2%, respectively. For the bladder, the differences were 5.2 GyE, 5.8%, and 5.4%, respectively. The maximum differences in V_{40} between RayStation and Velocity were 14.4% and 22.8% for the rectum and bladder, respectively, when the average DSC and surface distance differences were more than 0.14 and 6.4 mm, respectively. Such results suggest that DIR uncertainties might significantly affect prostate PSPT dose accumulations.

1. Introduction

External beam radiotherapy treatment for prostate cancer patients (for example, intensity modulated radiotherapy [IMRT] and proton therapy [PT]) has recently evolved into an important treatment option. A proton beam has a low entrance dose, followed by a region of uniform high dose at the tumor site, and then a steep falloff back to zero dose [1]. These characteristics enable a substantial dose reduction to normal tissues while maximizing the dose to the tumor that thus gives PT an inherent advantage over conventional photon therapies [2–4]. During prostate radiotherapy, changes in the volumes of the rectum and bladder often result in the displacement of the prostate's position with CT treatment plans, often leading to the risk of under-irradiation of the tumor and over-irradiation of the surrounding normal tissues [5,6]. To assess the accumulated dose actually received along the treatment area, deformable image registration (DIR) may be particularly useful for the purpose of guiding a replanning-based adaptive radiotherapy strategy [7–11]. Adaptive radiation therapy methods that use in-room imaging techniques, such as CT on-rails and cone beam CTs (CBCTs), are becoming increasingly popular within the domain of photon therapy [12]. Previous published reports have documented the advantages of DIR- based accumulated dose monitoring for considering anatomical variations of each treatment fraction during prostate PTs [13–17].

Recently, an increasing number of proton therapy system vendors have been equipping their gantries with CBCT imaging systems intended for patient positioning [18,19]; as such, the continued expansion of adaptive PT based on daily CBCT is expected well into the future [17,20]. However, accumulated dose results usually depend heavily on DIR quality [21]. In a previous study, effects of DIR uncertainty on lung stereotactic body

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radiation therapy (SBRT) dose accumulation [21] were evaluated. It was reported that a difference of target registration error (TRE) in DIR algorithms of only 1.6 mm may possibly cause a greater than 1.0 Gy difference in minimum Dose (D_{min}). However, the effects of DIR uncertainty within the pelvic region remain unclear at this time. Furthermore, these effects have likewise not been thoroughly evaluated to-date on PT as well. Hence, the overarching purpose of this study was to essentially quantify the effects of DIR uncertainties on prostate passive-scattering proton therapy (PSPT) dose accumulations.

2. Methods and materials

2.1. Patient data

Ten patients with an intermediate-risk for prostate cancer who received PSPT using a proton therapy system (Mitsubishi Electric, Kobe, Japan) at our institution were selected for this study. All patients underwent treatment-planning CT simulation with an Aquilion LB (Toshiba Medical Systems, Tokyo, Japan). Patients were instructed to have a full bladder (one hour of urine collection) as well as an empty rectum (by using a Fleets enema before simulation). If more stools or gas than expected were found, the planning CT simulation was resumed after evacuation or degassing via the use of a Nelaton catheter. The patients underwent treatment simulation in the supine position and were immobilized with a customized vacuum immobilization device. In this study, the patients did not use a rectal balloon. The settings for acquisition of planning CT images were 120 kV, 400 mA, 0.75 s, and a 2.0 mm slice thickness. To evaluate an anatomical organ volume change during treatment, ongoing verification CT scans were performed with a Discovery ST Elite system (GE Medical Systems, WI, USA). For each patient, five verification CT images were acquired over the course of radiotherapy within five minutes of treatment administration. Settings for the acquisition of verification CT images were 120 kV, 385 mA, 0.5 s, and a 2.5 mm slice thickness. The clinical target volume (CTV) included the prostate and the seminal vesicle(s) base. The CTV was expanded by 7 mm (6 mm posterior) to form the corresponding planning target volume (PTV). The prescribed dose was 78 GyE to 95% of the PTV, in 2 GyE fractions. The prostate, seminal vesicles, and CTV were contoured by a radiation oncologist, whereas the rectum and bladder were contoured by a medical physicist under the supervision of the radiation oncologist for both the planning CT and verification CT images.

2.2. Treatment planning

An Xio-M system (Elekta, Stockholm, Sweden) was used for PSPT treatment planning. The beams were centered on the CTV, with proton therapy plans designed using a standard Loma-Linda approach with two lateral opposite beams; the proton energy itself was at a level of 210 MeV [22,23]. Employed planning parameters included the following: 0.7 cm aperture expansion from the PTV; distal and proximal margins for CTV, which included 3.5% uncertainty for CT number accuracy and conversion to proton relative linear stopping power and a 0.3 cm beam range uncertainty for accelerator energy, variable scattering system thickness, and compensator density; and a 0.9–1.0 cm range compensator smearing [24]. These planning parameters were fundamentally selected using the methods described by Moyers [25,26]. The treatment planning was optimized to confirm our institutional treatment planning constraints as follows (V_X indicates the percentage of volume receiving more than x GyE): rectum, $V_{40} < 60\%$, $V_{60} < 25\%$, and $V_{70} < 20\%$; bladder, $V_{40} < 60\%$ and $V_{70} < 35\%$.

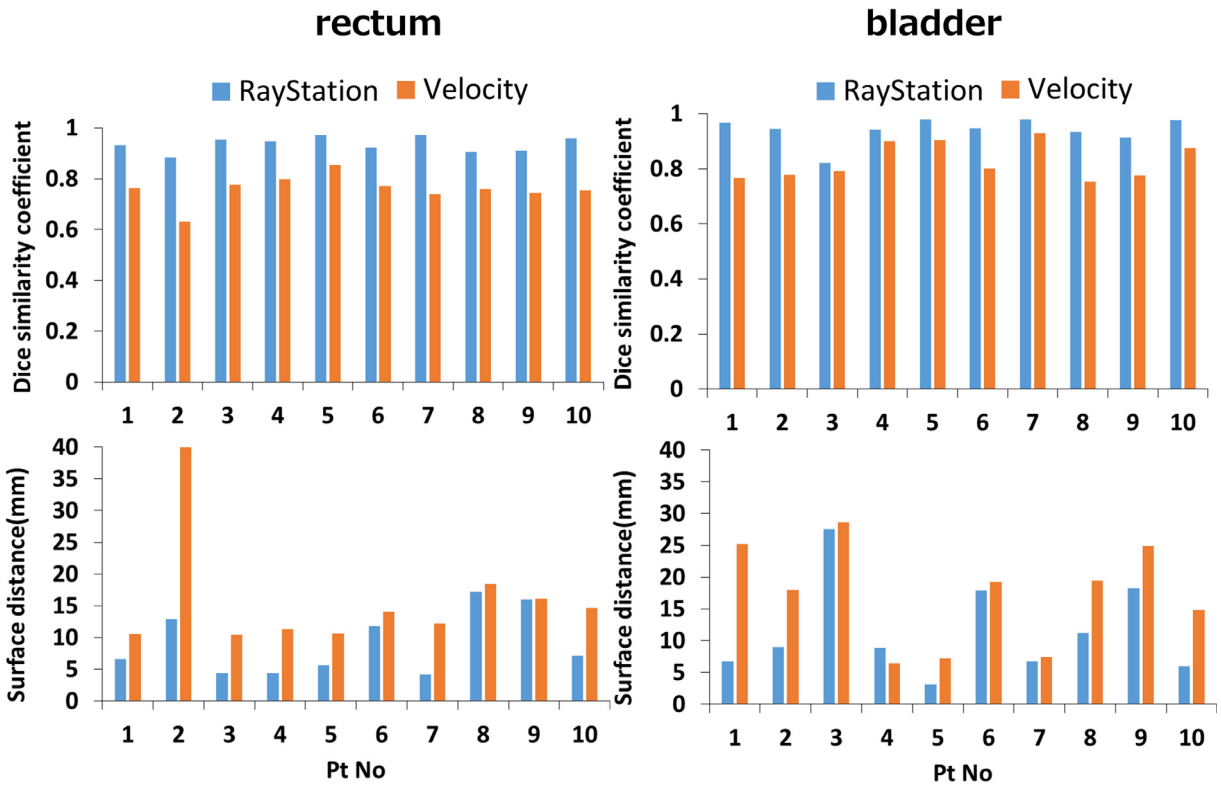

Fig. 1. The DIR accuracy result of the DSC and surface distance in ten patients for the rectum (left) and bladder (right) between Velocity and RayStation for each of ten patients.