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Original paper

Computational analysis of interfractional anisotropic shape variations of the rectum in prostate cancer radiation therapy

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ABSTRACT

Purpose: To analyze the uncertainties of the rectum due to anisotropic shape variations by using a statistical point distribution model (PDM).

Materials and methods: The PDM was applied to the rectum contours that were delineated on planning computed tomography (CT) and cone-beam CT (CBCT) at 80 fractions of 11 patients. The standard deviations (SDs) of systematic and random errors of the shape variations of the whole rectum and the region in which the rectum overlapped with the PTV (ROP regions) were derived from the PDMs at all fractions of each patient. The systematic error was derived by using the PDMs of planning and average rectum surface determined from rectum surfaces at all fractions, while the random error was derived by using a PDM-based covariance matrix at all fractions of each patient.

Results: Regarding whole rectum, the population SDs were larger than 1.0 mm along all directions for random error, and along the anterior, superior, and inferior directions for systematic error. The deviation is largest along the superior and inferior directions for systematic and random errors, respectively. For ROP regions, the population SDs of systematic error were larger than 1.0 mm along the superior and inferior directions. The population SDs of random error for the ROP regions were larger than 1.0 mm except along the right and posterior directions.

Conclusions: The anisotropic shape variations of the rectum, especially in the ROP regions, should be considered when determining a planning risk volume (PRV) margins for the rectum associated with the acute toxicities.

1. Introduction

Prostate cancer was ranked as the fifth leading cause of death from cancer for men worldwide in 2012 [1]. Incidence rates are increasing every year in the developed countries such as United Kingdom and Japan [2]. Several options are available to treat the prostate cancer including radiation therapy which allowed the prostate to be treated with high dose of radiation while sparring surrounding normal tissues [3].

The quality of radiation therapy in prostate cancer treatment is affected by high dose regions which could be induced by patient movement, internal motion of the organ, and patient set-up errors [4,5]. Fig. 1 illustrates the anatomical regions of a rectum, bladder, and planning target volume (PTV) determined by radiation oncologists. Anterior parts of the rectum may overlap with the PTV due to large internal margins and/or rectal displacements as shown in Fig. 1. The rectal position uncertainties, which could cause toxicities (e.g., rectal bleeding, fecal incontinence), mainly comes from the rectal motion due to the changes in rectal filling [6–10]. The two common methods used to study the rectal motion were tracking the changes in rectal volume and evaluating the translation and rotation errors of the rectum [5,11–13]. Fontenla et al. [14], however, noted that the more complex problem of internal organ motion involve changes in the shape (shape variations) of the organ especially along the anterior direction of the rectum [5,15]. Therefore, the shape variations of the rectum, especially along the anterior direction, need to be investigated.

In order to dealt with the position uncertainties of the organs at risks (OARs), the International Commission on Radiation Units and Measurements (ICRU) reports no. 62 [16] and 83 [17] introduced the concept of planning risk volume (PRV) margins. In the case of prostate

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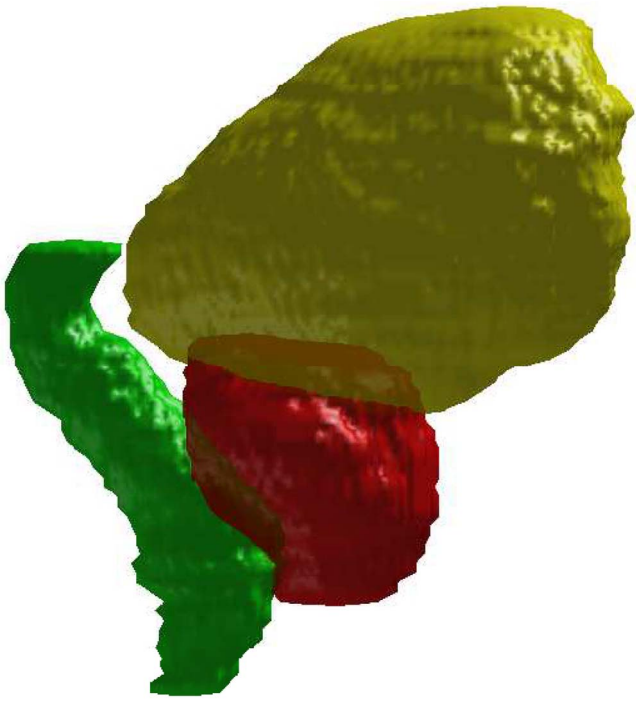

Fig. 1. An illustration of the anatomical regions of a rectum (green), bladder (yellow), and PTV (red) determined by radiation oncologists. Note that parts of the rectum and the bladder were overlapped with the PTV which could cause high-dose exposure to both OARs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cancer radiation therapy, the use of PRV dose-volume histograms (DVHs) is recommended to predict acute rectal toxicity [15,18,19]. "Recipes" to determine the uniform PRV margins have been developed by McKenzie et al. and Stroom and Heijmen [20,21]. However, the uniform PRV margins are inadequate to represent the actual rectal variations during treatment, as noted by McKenzie et al. [20] and Prabhakar et al. [22]. Therefore, an application of anisotropic PRV margins of the rectum should be considered.

There have been three studies that dealt with the shape variations of the rectum. Hoogeman et al. [23] analyzed the quantification of local rectal wall displacements by calculating local systematic and random errors of the rectum along three directions where they unfolded the outer surface of the delineated rectal wall and projected the 3-space coordinates of each surface element to a 2D map. Sohn et al. [24] investigated the correlated motion of adjacent organ structures between prostate, bladder and rectum which were parametrized by using sets of corresponding surface points and calculated the displacements between surface points at each fraction. They did not calculate the systematic and random errors that could be used in determining anisotropic PRV margins. Brierley et al. [25] investigated the determination of the PTV based on the rectal shape variations by using finite element modeling. They did not investigate the geometric errors related to the determination of PRV margins.

None of the previously mentioned studies, including ICRU, investigated directly the shape variations of the rectum along each anatomical direction separately (anterior, posterior, superior, inferior, left and right). The investigation along separate anatomical directions is indispensable for determining the anisotropic PRV margins. There have been also no studies on the systematic and random errors of the region in which the rectum overlapped with the PTV along the anterior wall (ROP regions), even though the shape variations of the ROP regions may cause the regions to be included in high dose distributions which can lead to rectum toxicities. Therefore, this study aims to investigate the anisotropic shape variations of the rectum and the ROP regions for prostate cancer radiation therapy along separate anatomical direction (anterior, posterior, superior, inferior, left and right).

2. Material and methods

2.1. Clinical study

This study was performed with the approval of the Institutional Review Board of our university hospital. The clinical data used in this study were obtained from 11 patients (range: 60–75 years; median age: 64 years; stage: T1-T3a, N0, M0), who had undergone intensity modulated radiation therapy (IMRT) for prostate cancer. The planning CT images were acquired from a CT scanner (Mx 8000, Philips, Amsterdam, Netherlands) with 512 × 512-pixel dimensions, 0.98 mm in-plane pixel size, and 2.0 mm slice thickness. Each patient received a dose of 76 Gy at 38 fractions using an accelerating voltage of 10 MV on a linear accelerator (Varian Medical Systems Inc., Palo Alto, USA).

The analyses of systematic and random errors of interfractional anisotropic shape variations of the rectum were derived from contours delineated on the planning CT and cone-beam CT (CBCT) images at 80 fractions of 11 patients. CBCT scans were performed just before irradiation at 5–9 fractions (mean: 7.3) of each patient. The CBCT data were used for correcting target localization at each fraction and only acquired at the beginning of the week to reduce the dose received by the patients. A kilovoltage CBCT scanner (On-Board-Imager, Varian Medical Image Systems Inc., Palo Alto, USA) was used to perform the scans which produced images with 384 × 384 pixel dimensions, 1.17 mm in-plane pixel size, and 2.5 mm slice thickness. The delineations of the rectum contours were based on a consensus between a radiation oncologist (S.O.) and a medical physicist (T.H.) using a commercially available radiation treatment planning (RTP) system (Eclipse version 6.5 and 8.1; Varian Medical Systems Inc., Palo Alto, USA).

2.2. Pre-processing

The original planning CT and CBCT images were converted into isotropic images with an isovoxel size of 1.17 mm using a cubic interpolation method. The rectum structures delineated on both planning CT and CBCT images were also extracted and converted using a shape-based interpolation method [26].

In this study, we focused on the errors introduced by the interfractional organ motions of the rectum. To reduce the effect of intraobserver variation and delineation artifacts in the calculation [24], uniform-length rectums were used for all cases. The reference length was equal to the shortest length (7 cm) of a rectum between starting and ending slices (around anus to sigmoid positions) delineated on the CBCT images among all cases [27].

2.3. Calculation of errors due to shape variations

This study evaluated the local errors of the shape variations by dealing with them separately along each axis, as illustrated in Fig. 2. The x, y, and z axes are each separated along their positive and negative directions corresponding to the anterior, posterior, superior, inferior, left and right directions. The local errors were calculated as the displacements of position vectors at points on 3D surfaces of the rectum (Fig. 3). The rotation errors of the rectum were included as shape variations since the errors also introduced the displacements of the surface points [28].

The flowchart to calculate errors due to shape variations from planning CT and CBCT images were described in Fig. 3. First, all rectums were registered using a centroid matching technique. Then, the surfaces of the registered rectums were triangulated using a marching cubes algorithm to obtain 3D surfaces of the rectum [29]. The produced surfaces consisted of many vertices, which were reduced to a similar number of vertices (~ 1000) using a quadric error metric method [30].