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Predicting patient-specific prostate motion using pelvic fat and pelvic cavity volume for prostate radiotherapy

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► ***Original article***

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ABSTRACT

Background*:** The prediction of prostate motion is important for matching planned and delivered dose distributions in prostate radiotherapy. This study aimed to assess the relationship between anatomical characteristics and inter- and intra-fraction prostate motion. ***Materials and Methods: Sixty-six patients who underwent fiducial marker implantation were retrospectively evaluated. The anatomical characteristics (subcutaneous adipose tissue thickness, pelvic cavity volume, and fat volume of the lesser pelvis around the prostate), inter- and intra-fraction prostate motion, and standard deviations (SDs) in the anterior-posterior (AP), superior-inferior (SI), and left-right (LR) directions were determined, and their correlations were analyzed. Additionally, the three-dimensional (3D) distance between the coordinates of the center of gravity of the prostate and inferior margin of the symphysis pubis was calculated. ***Results:*** The pelvic cavity volume around the prostate exhibited a moderate correlation with the SD for inter-fraction prostate motion in the LR direction (r=0.47) and that for intra-fraction prostate motion in the AP and LR directions (r = 0.41, 0.52). The 3D distance between the coordinates of the center of gravity of the prostate and inferior margin of the symphysis pubis showed a moderate correlation with the average inter-fraction prostate motion in the AP direction (r=0.46). ***Conclusion:*** Prostate motion in the AP and LR directions may be related to the fat and pelvic cavity volumes around the prostate. The evaluation of anatomical characteristics can help predict patient-specific prostate motion during treatment planning.

INTRODUCTION

Prostate cancer, a common solid tumor in men, is frequently treated with high-accuracy irradiation techniques, such as volumetric modulated arc therapy (VMAT) and stereotactic body radiotherapy [1, 2]. The management of prostate motion adjacent to at-risk organs is crucial to ensure high treatment accuracy [3, 4]. Motion management can predict the direction of prostate motion, thereby enabling optimal margin setting. This helps prevent dose discrepancies between planned and actual radiotherapy [3, 5].

During radiotherapy planning, comprehensive statistical analysis of prostate motion depicted on computed tomography (CT) images can facilitate information dissemination among medical personnel [4]. Risk analysis for individual patients during prostate radiotherapy involves determining the changes in the positional relationship of the prostate and pelvic bones, rectal volume, bladder volume, and body shape during planned and actual treatment [6]. Large prostate motions in the anterior-posterior (AP) and superior-inferior (SI) directions can be predicted using multiple planning CT scans [7, 8]. However, evaluating small prostate motions in the left-right (LR) direction can be difficult.

Prostate motion varies among individuals with cancer, involving changes in rectal volume, muscle contraction due to strain, and body mass index (BMI) [8, 9]. A previous study described the BMI and prostate motion in patients with obesity, suggesting a positive correlation between anatomical factors and LR motion [10]. Another study reported a correlation between subcutaneous adipose tissue (SAT) thickness and LR-directed prostate motion in patients with a BMI >25 kg/m² [11].

Regarding treatment of prostate cancer, various radiation-based treatment methods, such as hypofractionated irradiation, stereotactic radiation therapy, and VMAT, are available. Information on patient-specific prostate motion is important to determine the optimal treatment method and individualized planning target volume margin [1, 2, 12]. Moreover, information on anatomical characteristics is useful for understanding patient-specific prostate motion.

To the best of our knowledge, no study has evaluated the utility of predicting patient-specific prostate motion using anatomical characteristics for optimal treatment planning. Moreover, considering that many patients without obesity undergo prostate radiotherapy, assessing prostate motion in this patient group can provide valuable insights for margin setting. Therefore, we aimed to evaluate the correlation of prostate motion with pelvic bone size and fat volume around the prostate during the treatment period using treatment-planning CT images. This study evaluated a novel method for patient-specific prostate motion management.

MATERIALS AND METHODS

Patients and materials

We retrospectively analyzed the data of 66 patients (median age, 72 [57-82] years; median height, 165.8 [150.0-180.0] cm; median weight, 64.0 [41.5-115] kg; BMI, 23.2 [16.3-35.5] kg/m²) who underwent VMAT (total dose 78 Gy, 39 fractions) and had 2.0-mm-diameter fiducial markers (iGold, Medikit, Tokyo, Japan) implanted in the prostate. No patients were excluded from the study as there were no established exclusion criteria. This study was approved by the Ethics Committee of the Institutional Review Board (IRB) of Tokuyama Central Hospital (IRB K456-20230201, date of registration: February 2, 2023) and conducted following the ethical guidelines of the Declaration of Helsinki.

Planning CT was performed using an Aquilion LB scanner (Toshiba, Tokyo, Japan), and treatment planning was performed using a radiotherapy treatment planning system (RTPS), Eclipse version 11 (Varian Medical Systems, Palo Alto, CA, USA). VMAT was performed using a Novalis STX linear accelerator (Varian Medical Systems, Palo Alto, CA, USA) attached to an ExacTrac X-ray system (BrainLAB AG, Feldkirchen, Germany). The patients were immobilized using a knee fix and foot-lock cushion. All patients were required to empty their rectum and maintain a full bladder during treatment planning. The correlation between measured anatomical characteristics at planning CT, set-up errors, and prostate motion during the treatment period was analyzed (figure 1).

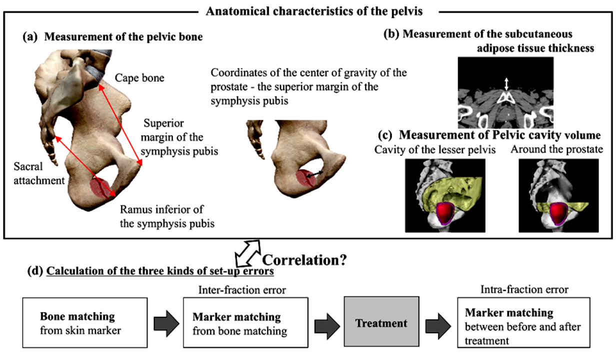

Figure 1. Measurement of anatomical characteristics using planning CT scans. **(a)** The method used for measuring the length of the pelvic bone, **(b)** method used for measuring the subcutaneous adipose tissue thickness, **(c)** method used for measuring the fat volume, and **(d)** calculation of patient set-up errors and prostate motion.

Measurement of pelvic bone size around the prostate

The anatomical characteristics of the pelvis were measured using treatment-planning CT. The sizes of the cape bone (inferior margin of the symphysis pubis [CS]) and sacral attachment (inferior ramus of the symphysis pubis [SR]) were measured (figure 1a). Next, the three-dimensional (3D) distance between the coordinates of the center of gravity of the prostate (AP_p, LR_p, and SI_p) and CS (AP_b, LR_b, and SI_b) was calculated using the following equation (1):

$$\text{3D distance} = \sqrt{(AP_b - AP_p)^2 + (RL_b - RL_p)^2 + (SI_b - SI_p)^2} \quad (1)$$

Assessment of anatomical characteristics of region around the prostate

SAT thickness was measured using axial CT images of the CS based on a previous study (figure 1b) [11]. The pelvic cavity volume in the lesser pelvic cavity and that around the prostate were measured using the RTPS. Next, the lesser pelvic cavity volume and fat volume surrounding the prostate were calculated by determining the range of CT values (CT value, −50–−500 HU) within the pelvic cavity on the CT images using the RTPS (figure 1c). Then, the bladder, rectal, and prostate volumes on the treatment-planning CT images were contoured by an oncologist using the RTPS.

Calculation of patient set-up errors and prostate motion

Figure 1d shows the process of calculating the patient set-up errors and prostate motion. The bone matching set-up errors were calculated as the difference in spatial coordinates (AP, SI, and LR) between skin markers using a laser coordination system and bone matching with six degrees of freedom using the ExacTrac X-ray system. The inter-fraction prostate motion of the fiducial marker was calculated as the difference in spatial coordinates between the bone and fiducial marker matching with three-axis translation using the ExacTrac X-ray system. Moreover, the intra-fraction motion of fiducial markers was calculated as the difference in spatial coordinates of fiducial marker matching before and after treatment with three-axis translation using the ExacTrac X-ray system.

The median treatment time of VMAT was 83.8 s. All set-up errors and prostate motions were calculated using the average and standard deviation (SD) of the translational directions (AP, SI, and LR).

Evaluation of relationship between the anatomical characteristics of region around the prostate and set-up errors, prostate motion

To estimate the risk of prostate motion during treatment planning, the correlation between the anatomical characteristics of the region around the prostate and set-up errors and prostate motion was analyzed. The anatomical characteristics used were BMI; fat, bladder, rectal, and prostate volumes; and SAT thickness (average, SD).

Statistical analysis

The correlation between the anatomical characteristics of the region around the prostate, set-up errors, and prostate motion was determined using Pearson's correlation coefficient (r) in JMP Pro 15 (SAS, Cary, NC, USA).

RESULTS

Patients' anatomical characteristics, set-up errors, and prostate motion

Table 1 shows the median, maximum, and minimum BMI and pelvic measurements. Of 66 patients, 17 had a BMI >25 (median, 23.2) kg/m^2. Table 2 shows the average, maximum, and minimum values for bone matching set-up errors and fiducial markers matching prostate motion during the treatment period. The average set-up errors for bone matching were −3.0, 1.1, and 0.1 mm in the AP, SI, and LR directions, respectively. The inter-fraction average prostate motion was >10.0 mm in the AP and SI directions; however, it was <3.0 mm in the LR direction. Both inter- and intra-fraction prostate motions were lower in the LR direction than in the AP and SI directions.

Table 1. Anatomical characteristics.

	BMI	Fat volume (cm^3)		Pelvic cavity volume (cm^3)		Pelvic bone measurement		SAT thickness (cm)	Prostate – ISP (cm)	Treatment time (s)
		Cavity of the lesser pelvis	Around the prostate	Lesser pelvis	Around the prostate	CS (cm)	SR (cm)			
Mean	23.2	763.7	85.7	1443.4	227.6	11.3	10.6	3.4	3.67	83.8
Min.	16.3	82.6	10.1	2453.0	654.2	8.9	8.4	1.2	3.1	71.5
Max.	35.5	1776.3	277.8	927.4	95.5	13.7	12.4	6.1	4.89	107.5

BMI: body mass index; SAT: subcutaneous adipose tissue thickness; Min: minimum; Max: maximum; Prostate-ISP: The 3D distance between the coordinates of the center of gravity of the prostate and the inferior margin of the symphysis pubis.

Table 2. Set-up errors and prostate motions using each image matching.

		Bone matching (mm)			Inter-fraction motion (mm)			Intra-fraction motion (mm)		
		AP	SI	LR	AP	SI	LR	AP	SI	LR
Ave.	**Mean**	−3.0	1.1	0.1	0.9	0.5	0.4	-0.1	0.0	0
	Min.	−10.0	−3.2	−5.6	−4.1	−7.1	−1.5	-1.0	-1.0	-0.9
	Max.	7.0	5.8	6.7	8.9	6.9	1.2	2.3	1.7	0.7
SD	**Mean**	2.3	1.3	1.6	1.6	1.4	0.5	0.8	0.7	0.4
	Min.	1.3	0.9	0.7	0.6	0.7	0.3	0.4	0.3	0.1
	Max.	3.9	4.5	3.6	5.5	5.2	1.2	4.8	3.9	1.3

AP: anterior-posterior; SI: superior-inferior; LR: left-right; Ave: average; SD: standard deviation; Min: minimum; Max: maximum.

Correlation of anatomical characteristics with set-up errors and prostate motion

Table 3 and figures 2 and 3 show the correlations of set-up errors and prostate motion with the anatomical characteristics. Bone matching revealed the absence of a correlation between set-up errors and any of the anatomical characteristics. The fat volume around the prostate in the LR direction was weak/moderately correlated with the SD for the inter - and intra-fraction prostate motions (r=0.35 and 0.46, respectively).

Pelvic cavity volume around the prostate showed a moderate correlation with the SD for inter-fraction prostate motion in the LR direction (0.47) and that for intra-fraction prostate motion in the AP and LR directions (r=0.41, 0.52).

The BMI, fat volume of the lesser pelvic cavity, size of the CS and SR, SAT thickness, bladder capacity, and rectal volume were not correlated with inter- and intra-fraction prostate motions. The 3D distance between the coordinates of the center of gravity of the prostate and the inferior margin of the symphysis pubis showed a moderate correlation with the average inter-fraction prostate motion in the AP direction (r=0.46) and the SD for intra-fraction motion in the AP and SI directions (r=0.46, 0.43).

Table 3. Pearson's correlation coefficient (r) between anatomical characteristics and set-up errors.

r			BMI	Fat volume		Pelvic cavity volume		Prostate – ISP	SAT thickness	Bladder capacity	Rectal volume
				Lesser pelvis	Around the prostate	Lesser pelvis	Around the prostate				
Inter-fraction motion	AP	Ave.	-0.17	-0.25	0.17	-0.24	0.33	0.46	-0.15	-0.07	-0.06
		SD	-0.30	-0.15	0.14	-0.12	0.36	0.26	-0.24	0.00	0.14
	SI	Ave.	-0.11	-0.19	0.06	-0.14	0.16	0.23	-0.12	-0.07	-0.06
		SD	-0.27	-0.10	0.05	-0.06	0.21	0.24	-0.19	0.05	0.04
	LR	Ave.	-0.13	-0.05	-0.28	-0.05	-0.29	-0.25	-0.02	-0.09	0.07
		SD	-0.11	-0.08	0.35	-0.08	0.47	0.28	-0.05	-0.09	0.17
Intra-fraction motion	AP	Ave.	-0.09	0.25	0.33	0.11	0.34	0.29	0.09	-0.17	0.01
		SD	-0.18	-0.04	0.23	-0.09	0.41	0.46	-0.13	-0.14	0.11
	SI	Ave.	-0.15	0.13	0.20	0.02	0.21	0.21	0.03	-0.07	0.01
		SD	-0.29	-0.07	0.14	-0.12	0.30	0.43	-0.23	-0.13	0.16
	LR	Ave.	0.05	-0.03	0.13	-0.11	0.06	-0.04	0.12	0.06	0.06
		SD	0.00	-0.07	0.46	-0.07	0.52	0.23	0.05	-0.03	0.15

AP: anterior-posterior; SI: superior-inferior; LR: left-right; Ave: average; SD: standard deviation; BMI: body mass index; SAT: subcutaneous adipose tissue, Prostate-ISP; The 3D distance between the coordinates of the center of gravity of the prostate and the inferior margin of the symphysis pubis

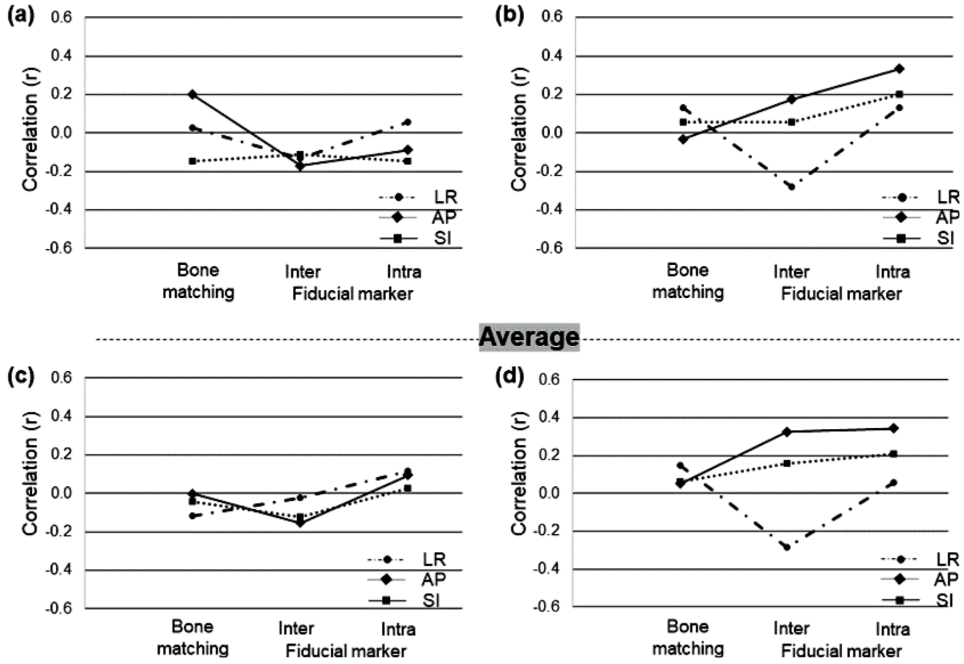

Figure 2. Correlation between anatomical characteristics of region around the prostate, average prostate set-up errors, and average prostate motion. **(a)** Body mass index, **(b)** fat volume around the prostate, **(c)** subcutaneous adipose tissue thickness, and **(d)** pelvic cavity volume around the prostate.

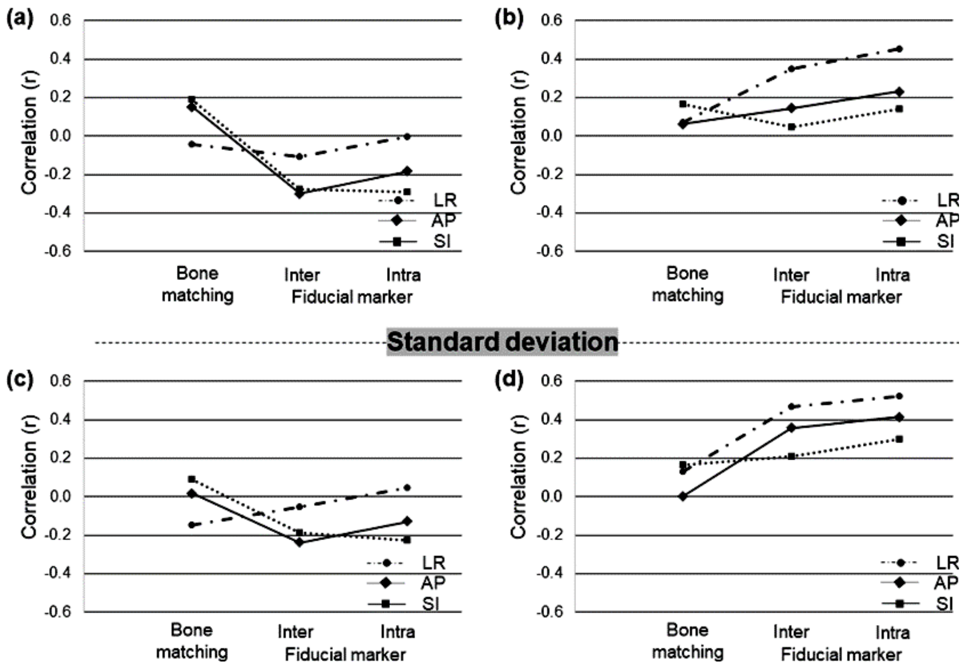

Figure 3. Correlations between anatomical characteristics of region around the prostate, standard deviation of set-up errors, and standard deviation of prostate motion. **(a)** Body mass index, **(b)** fat volume around the prostate, **(c)** subcutaneous adipose tissue thickness, and **(d)** pelvic cavity volume around the prostate.

DISCUSSION

This study evaluated the relationship between anatomical characteristics and bone matching and fiducial marker matching for each direction during treatment in the context of prostate motion. The data of patients with a median BMI of 23.2 kg/m^2 were evaluated. Unlike that observed in previous studies, BMI and SAT thickness showed almost no correlation with prostate motion [9, 11]. The inter- and intra-fraction prostate motions were not correlated with the fat volume of the lesser pelvic cavity and prostate motion in each direction. The fat volume around the prostate was moderately correlated with the SD for the inter- and intra-fraction prostate motions in the LR direction. The LR direction of prostate motion during treatment has been previously associated with fat volume [9], and the underlying factors contributing to the relationship between fat volume and prostate motion in the LR direction were elucidated here. Previous studies have suggested a margin in the LR direction of approximately 0.7 mm, which was significantly larger than the set-up margins in other directions [3, 13]. Our results suggest that examining the margin by assessing fat volume is helpful.

The pelvic bone sizes in the CS and SR showed no correlation with prostate motion. The SD for inter-fraction prostate motion in the AP direction was moderately correlated with the 3D distance between the coordinates of the center of gravity of the prostate and the inferior margin of the symphysis pubis. The pelvic cavity volume around the prostate showed a moderate correlation with the SD for intra-fraction motion in the LR direction. The movable area of the prostate may increase with an increase in the pelvic cavity volume around the prostate. In addition, since a large prostate motion is associated with random errors in the tension of the muscle layer, we believe that there was a correlation with SD for prostate motion [7, 14]. Similarly, a previous study reported that a hydrogel spacer was not affected by intra-fraction motion [15], and prostate motion in the LR direction was reduced using a double-balloon rectal catheter [16, 17]. The pelvic bone size around the prostate can be used to estimate the movement of the prostate gland and determine whether this movement needs to be suppressed.

A limitation of this study was that prostate motion was not evaluated using information on anatomical characteristics during the treatment period. Therefore, one potential factor contributing to the prostate motion was changes in the bladder, rectum, and fat volume between planned and actual radiotherapy [18-21]. However, we believe that using anatomical characteristics to evaluate intra-fraction prostate motion will be helpful in treatment planning.

The method for measuring the pelvic bone around the prostate and fat volume used in this study is a straightforward evaluation method that can be performed in any facility. The inter-fraction prostate motion observed in this study was attributed to the treatment time of VMAT being less than 5 min. Additionally, determining the correlation between small prostate motion in the LR direction over short periods and patient-specific information can significantly contribute to a safer treatment approach. The movement of individual patients during treatment planning should be evaluated, and the movement of the prostate in the AP and LR directions should be predicted [22, 23]. Patients whose prostates have a low α/β ratio undergo extreme hypofractionated stereotactic body and adaptive radiotherapies, and determining the individual risk of prostate motion can facilitate appropriate selection of treatment methods [15, 24, 25].

CONCLUSION

We evaluated the correlation of pelvic bone size and fat volume with prostate motion during the treatment period using CT images obtained at the time of treatment planning in patients with a normal BMI. The SD for prostate motion in the AP and LR directions during the treatment period and treatment time were moderately correlated with the fat volume around the prostate. The method described in this study can be used to assess the risk of AP and LR motion during treatment planning and to determine treatment methods and individualized margins for each patient because it is possible to understand each patient's prostate motion simply by pre-evaluating their anatomical characteristics.

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Author contributions statement: Y.T. wrote the main manuscript text. Y.T. and A.N. prepared the figures. Y.T., A.N., and K.N. analyzed the data. A.N. and Y.T. prepared the tables. All authors reviewed and approved the manuscript.

Ethics approval: This study was approved by the Ethics Committee of the Institutional Review Board (IRB) of Tokuyama Central Hospital and conformed to the ethical guidelines of the Declaration of Helsinki (IRB K456-20230201; date of registration: February 2, 2023). The IRB waived the need to obtain informed consent from the patient owing to the retrospective nature of the study.

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