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Planning study: prone versus supine position for stereotactic body radiotherapy in prostate by CyberKnife

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ABSTRACT

This study aimed to clarify the differences in radiotherapy dose characteristics and delivery efficiency between the supine and prone positions in patients with prostate cancer using the CyberKnife. The planning computed tomography (CT) and delineations of the prone position were obtained by rotating the supine CT images with delineations of 180° using image processing software. The optimization parameters for planning target volume (PTV) and organs at risk (OARs) were based on the prone position. The optimization parameters determined for the prone position were applied to the supine position for optimization and dose calculation. The dosimetric characteristics of the PTV and OARs, and delivery efficiency were compared between the two different patient positions. The plans in the prone position resulted in better PTV conformity index (nCI), rectum $V_{90\%}$, $V_{80\%}$, $V_{75\%}$, $V_{50\%}$ and bladder $V_{50\%}$. A significant difference was observed in treatment time and depth along the central axis (d_{CAX}) between the two plans. The mean treatment time per fraction and d_{CAX} for the supine and prone positions were 20.9 ± 1.7 min versus 19.8 ± 1.3 min ($P = 0.019$) and 151.1 ± 33.6 mm versus 233.2 ± 8.8 mm ($P < 0.001$), respectively. In this study the prone position was found to improve dosimetric characteristics and delivery efficiency compared with the supine position during prostate cancer treatment with the CyberKnife.

Keywords: CyberKnife; SBRT; prostate cancer; supine position; prone position

INTRODUCTION

Radiotherapy for clinically localized prostate cancer typically entails conventional-dose fractions of 70–78 Gy administered in 35–39 fractions, and higher prescribed doses improve local control [1–4]. Recently, stereotactic body radiation therapy (SBRT) for prostate cancer using the conventional linac or CyberKnife (Accuray, Incorporated, Sunnyvale, CA) has been performed with 35–36.25 Gy administered in 5 fractions. SBRT for prostate cancer offers some distinct advantages, including greater radiosensitivity due to greater fractional dose and lower treatment cost [5–9].

The CyberKnife is used for stereotactic radiosurgery (SRS) as well as with stereotactic radiotherapy (SRT) system which is equipped with a lightweight compact linear accelerator mounted on a robotic manipulator. The SRT system can deliver high doses to tumor with sub-millimeter positional accuracy. Moreover, the CyberKnife is equipped with specific tracking systems for some treatment sites. Intracranial lesions can be treated using the Synchrony Skull Tracking® (Accuray, Incorporated, Sunnyvale, CA), while the tracking system for lung, liver and prostate lesions employs implanted fiducial markers using the Synchrony Fiducial Tracking® (Accuray, Incorporated, Sunnyvale, CA). The latest model of the CyberKnife system, which is equipped with a multi-leaf collimator and can deliver a high dose-rate [1000 monitor units (MU)/min] beam, has been shown to improve treatment efficiency and quality of treatment plans [10–13].

Radiotherapy for prostate and breast cancer using the conventional linac is typically administered to a patient in the supine position. Some studies have found that the prone position may reduce the dose to organs at risk (OARs) in some cases due to the changes in the anatomical configuration in different positions [14–16]. However, the prone position poses some problems, such as larger respiratory movements, difficult patient setup and discomfort [17, 18]. The effectiveness of radiotherapy administered using the CyberKnife in the prone position is not well characterized in the contemporary literature.

Geometric constraints inherent to the CyberKnife system prevent delivery of beams from underneath the treatment table. Martina *et al.* [19] and Christoph *et al.* [20] compared the dosimetric characteristics and delivery efficiency for spinal lesions between the supine and prone positions. They found that the prone position significantly reduced the ventral OARs dose, treatment time and total MU, compared with the supine position, because of the shorter effective path length and geometric constraints. We hypothesized that the use of the prone position reduces the bladder dose on the ventral side of the prostate. This study aimed to clarify the differences in dose characteristics and delivery efficiency between the supine and prone positions in prostate cancer patients using the CyberKnife.

MATERIALS AND METHODS

Patient characteristics

Seventeen patients with prostate cancer who underwent radiotherapy in the supine position using a CyberKnife at our hospital were included in this study. All patients had fiducial markers, visicoil® (RadioMed Corporation, USA), or gold anchor® (Naslund Medical AB, Sweden). The rectal spacer, SpaceOAR System® (Boston Scientific Corporation, USA) was used in 13 patients for reducing the rectal dose. This was a retrospective planning study. Therefore, the delineations including the target and the OARs, which were used for actual treatment, were used as such without any change. Bladder management was performed for the full bladder. The clinical target volume (CTV) was delineated from the prostate (plus seminal vesicle in one patient), and the PTV included a uniform margin of 3 mm, except a 2 mm margin in the posterior direction, for almost all patients. The OARs delineated were the bladder, rectum and urethra. The mean (± standard deviation [SD]) CTV and bladder volume were 45.25 ± 7.65 cc and 209.39 ± 63.75 cc, respectively. The prescribed dose was 36.25 Gy per 5 fractions with a $D_{95\%}$ prescription to the PTV. Two types of rings, the inner ring with a 4-mm distance from the PTV and the outer ring with a 20-mm distance from the PTV, were generated to improve dose conformity to the PTV (Fig. 1).

Planning study comparison for the supine versus prone position

The planning computed tomography (CT) patient position was different, but the optimization parameters and delineations were the same for a fair comparison of the treatment plans for the supine versus the prone position. For the treatment plans in the supine position, the

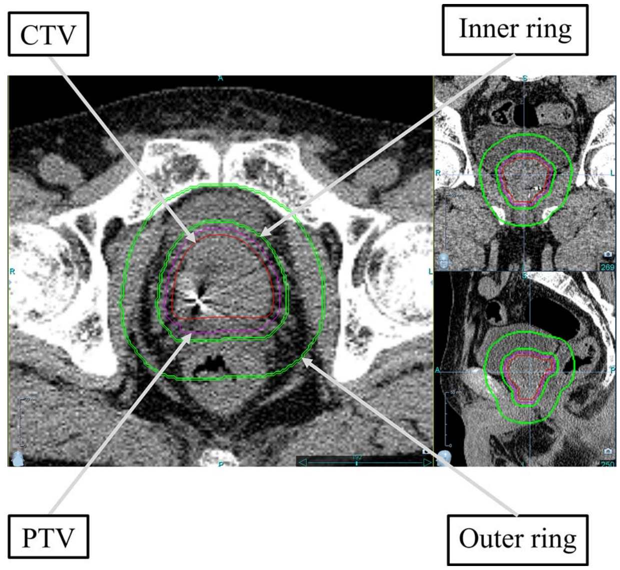

Fig. 1. PTV and the inner and outer rings.

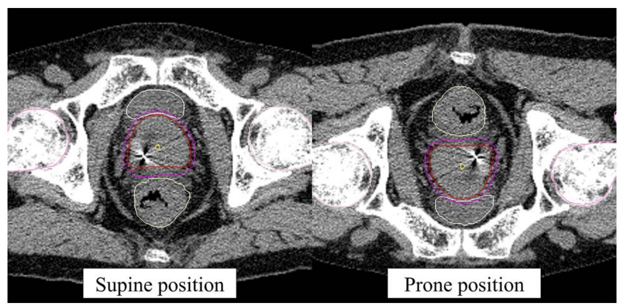

Fig. 2. The supine position and prone position planning CT.

planning CT and the delineations were used as is in this study. The prone position planning CT was obtained by image processing using a scientific programming code, python. Specifically, the supine position planning CT was rotated 180°. However, this programming code could not rotate the contours. Therefore, the contours of the supine position were rigidly propagated to the planning CT of the prone position using PreciseART® ver6.8.110 (Accuray, Incorporated, Sunnyvale, CA). The contours after deformation were identical to those after being rotated 180° because the same planning CT was used (Fig. 2).

The treatment device was CyberKnife M6® with MLC (Accuray, Incorporated, Sunnyvale, CA), and the treatment planning system (TPS) was Precision® ver3.1.0.1 (Accuray, Incorporated, Sunnyvale, CA). Optimization (Optimization Algorithm: VOLO) and dose calculation (Algorithm: FSPB, Resolution: High) were performed. The VOLO optimizer used in this study combines the dose-volume histogram (DVH) goals into a single cost function. The importance of the goal is specified as an objective weighting. For MLC collimation, plan optimization consists of two phases: (i) influence optimization, followed by (ii) segmentation and aperture adjustment before the final dose calculation [21]. The optimization parameters for PTV and the two rings were the same for all cases, with a lower limit of

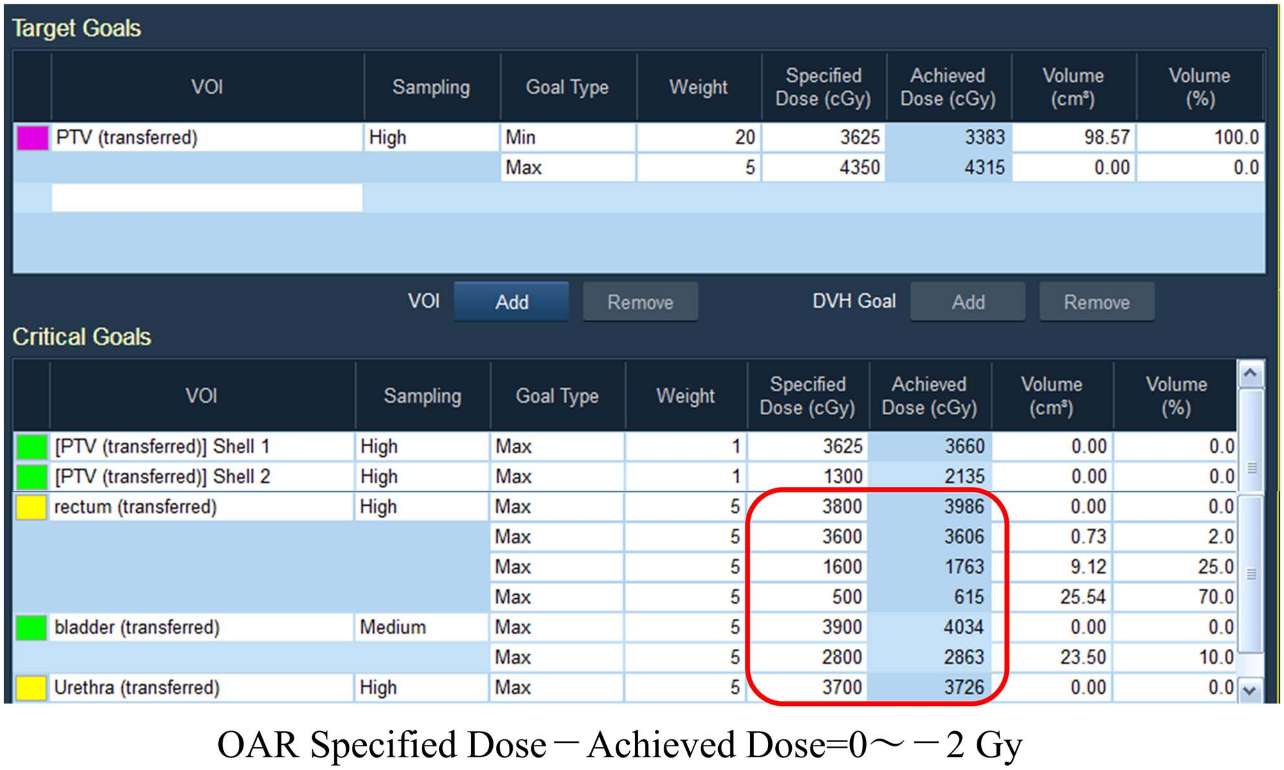

Fig. 3. Optimization parameters based on the prone position. These parameters were also used in the supine treatment planning.

36.25 Gy for 100% PTV volume, an upper limit of 43.50 Gy for 0% PTV volume, a lower limit of 36.25 Gy for 0% inner ring volume and a lower limit of 13 Gy for 0% outer ring volume. The optimization parameters for OARs were based on the prone position, and dose constraints were specified at 0%, 2%, 25% and 70% of the rectum volume, 0% and 10% of the bladder volume, and 0% of the urethra volume for optimization and dose calculation. Dose constraints were calibrated so that the difference between the specified doses and the achieved dose after optimization was within the range of 0 to −2 Gy. This was to ensure that the optimization parameters for each OAR were effectively functional, i.e. to maximize the plan quality (Fig. 3). A physician reviewed the final dose distributions and confirmed whether the treatment plans were acceptable or not. The same optimization parameters determined for the prone position were applied to the supine position for optimization and dose calculation.

Statistical analysis

The supine and prone position treatment plans were compared with respect to dosimetric characteristics (homogeneity, conformity index and DVH parameters), delivery efficiency (treatment time per a fraction [min], total MU, number of beams and segments), and depth along the central axis (d_{CAX}) (mm), as described later. In addition, to compare the DVH parameters of OARs, dose constraints were used to evaluate V_{36Gy}, $V_{100\%}$, $V_{90\%}$, $V_{80\%}$, $V_{75\%}$, $V_{50\%}$ of the rectum, V_{37Gy}, $V_{100\%}$, $V_{50\%}$ of the bladder and V_{37Gy} of the urethra [5]. Treatment time is evaluated based on that calculated in the TPS. This time includes beam-on time, robot movement time, wait time before or after beam-on, kV X-ray exposure time for tracking and 5-min patient setup time.

- Conformity index (nCI), $nCI = TV \times PIV/(TIV)^2$, where TIV is the target volume inside the prescription isodose volume (PIV).
- Homogeneity index (HI), HI = (maximum dose)/(prescription dose) for the PTV.

Supplementary Fig. 1 shows a conceptual diagram of d_{CAX}. The d_{CAX} was defined as the depth from the body surface along the beam central axis (CAX) perpendicular to the reference point direction, and the reference point is automatically generated in the TPS. Moreover, the reference point dose is equal to the global maximum dose. Statistical significance was calculated using the Wilcoxon signed-rank test. P values of <0.05 were deemed indicative of a statistically significant difference.

RESULTS

Dosimetric characteristics

There were no significant differences between the prone position and supine position plans with respect to PTV $D_{95\%}$ and PTV HI for all cases. The mean PTV $D_{95\%}$ and PTV HI in the supine and prone plans were 85.65% ± 1.88% vs 84.86% ± 2.17% ($P = 0.177$) and 1.17 ± 0.03 vs 1.18 ± 0.03 ($P = 0.194$), respectively. Plans in the prone position resulted in a better PTV nCI. The mean PTV nCI for the supine and prone positions were 1.18 ± 0.05 and 1.16 ± 0.04 ($P = 0.012$), respectively. The dosimetric characteristics of PTV are shown in Fig. 4 and Table 1. The dosimetric characteristics of the rectum, bladder and urethra are shown in Figs 5–7 and Table 2. No

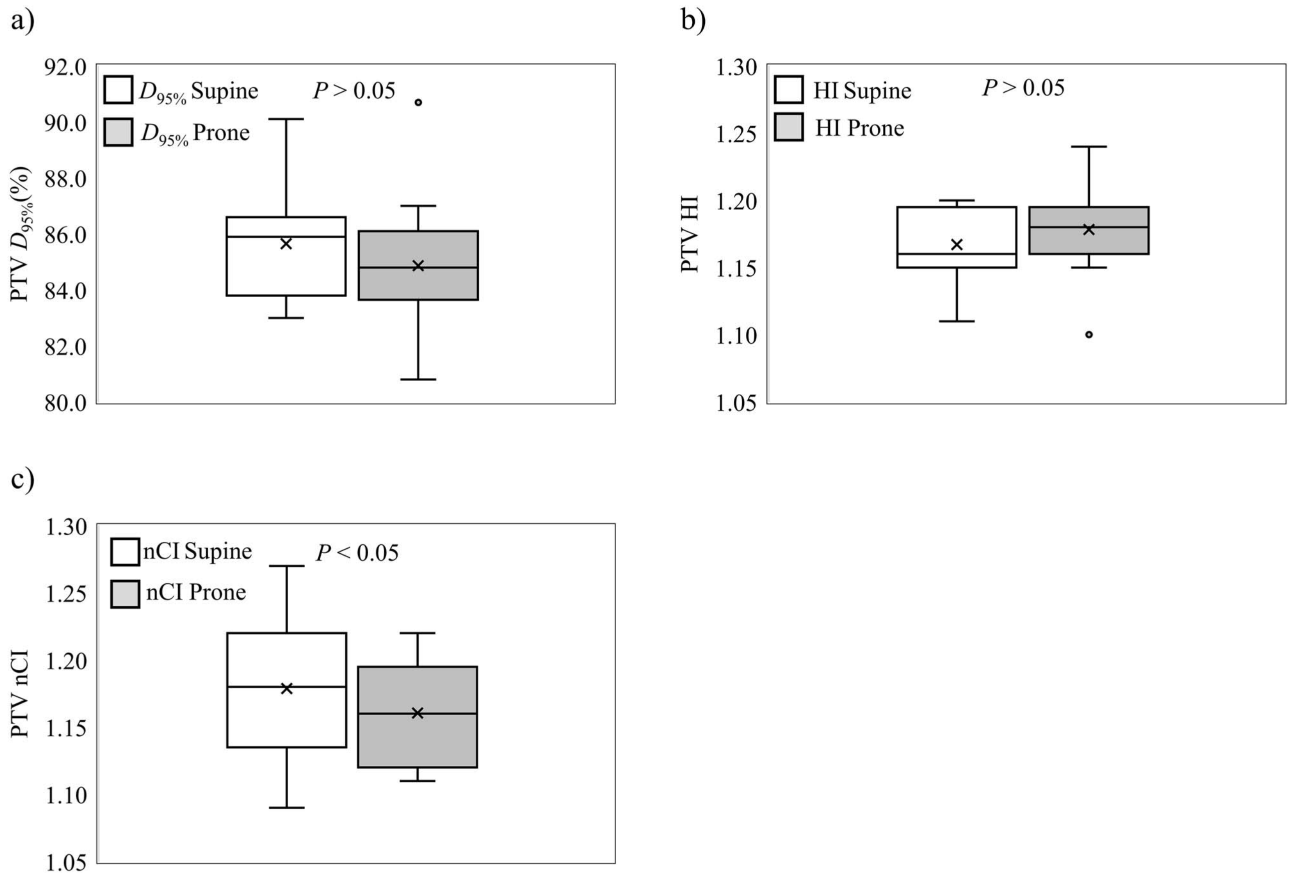

Fig. 4. a) PTV $D_{95\%}$ in the supine and prone positions, b) PTV HI in the supine and prone positions, c) PTV nCI in the supine and prone positions.

Table 1. PTV dosimetric parameters in the supine and prone positions

	PTV $D_{95\%}$ (%)		PTV HI		PTV nCI	
	Supine	Prone	Supine	Prone	Supine	Prone
mean	85.65	84.86	1.17	1.18	1.18	1.16
SD	1.88	2.17	0.03	0.03	0.05	0.04
P value	0.177		0.194		0.012	

significant differences were observed with respect to the dose to rectum V_{36Gy}, rectum $V_{100\%}$, bladder V_{37Gy}, bladder $V_{100\%}$ or urethra V_{37Gy} between plans obtained in the supine and prone positions. The plans in the prone position resulted in better rectum $V_{90\%}$, $V_{80\%}$, $V_{75\%}$, $V_{50\%}$ and bladder $V_{50\%}$. In the prone position, as the bladder and rectum are on the ventral and dorsal sides of the PTV, respectively, tangential irradiation to the PTV results in a dose concentration on the dorsal side. This beam arrangement also decreases the bladder dose on the ventral side owing to the attenuation of therapeutic photon beams.

Delivery efficiency

The results of the delivery efficiency are shown in Figs 8–9 and Table 3. There were no significant differences between the plans obtained in the supine and prone positions with respect to the total MU, the number of beams and segments. However, there were significant differences with respect to the treatment time per fraction and d_{cax}. The mean treatment time and d_{cax} for the supine and prone positions were 20.9 ± 1.7 min vs 19.8 ± 1.3 min ($P = 0.019$) and 151.1 ± 33.6 mm and 233.2 ± 8.8 mm ($P < 0.001$), respectively. Figure 9 shows the boxplot and the distribution of the d_{cax} for all beams in the supine and prone positions. The prone treatment plans exhibited a greater d_{cax} than the supine treatment plans. The prone position may have resulted in wider angle delivery, leading to the concentration of the dose on the dorsal PTV, efficiently avoiding the rectum and bladder. This may involve increase in d_{cax} and decrease in the number of beams and segments. In the prone and supine positions, there were no beams outside the CT scanned range.

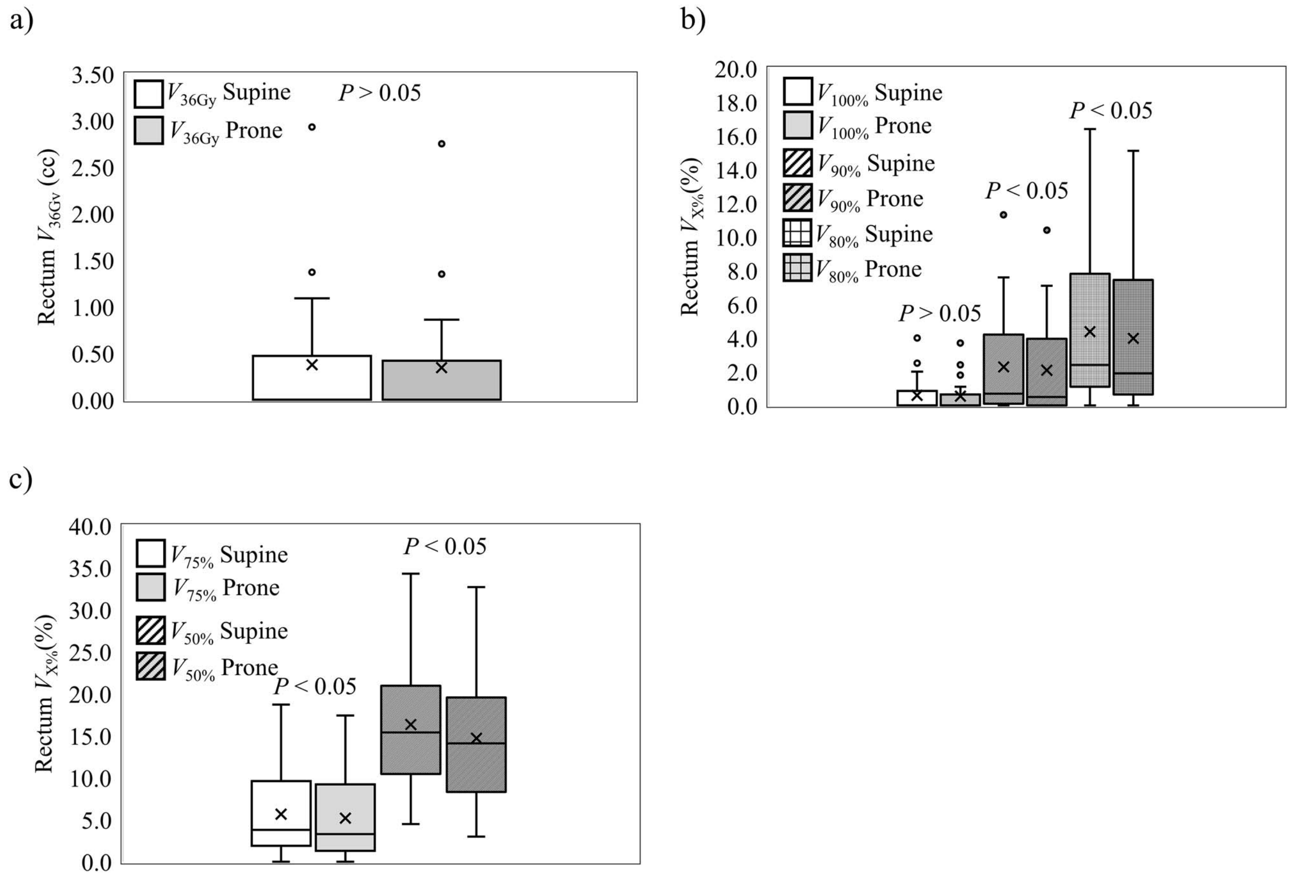

Fig. 5. **a) Rectum V_{36Gy} in the supine and prone positions, b) Rectum $V_{100\%}$, $V_{90\%}$, $V_{80\%}$ in the supine and prone positions, c) Rectum $V_{75\%}$, $V_{50\%}$ in the supine and prone positions.**

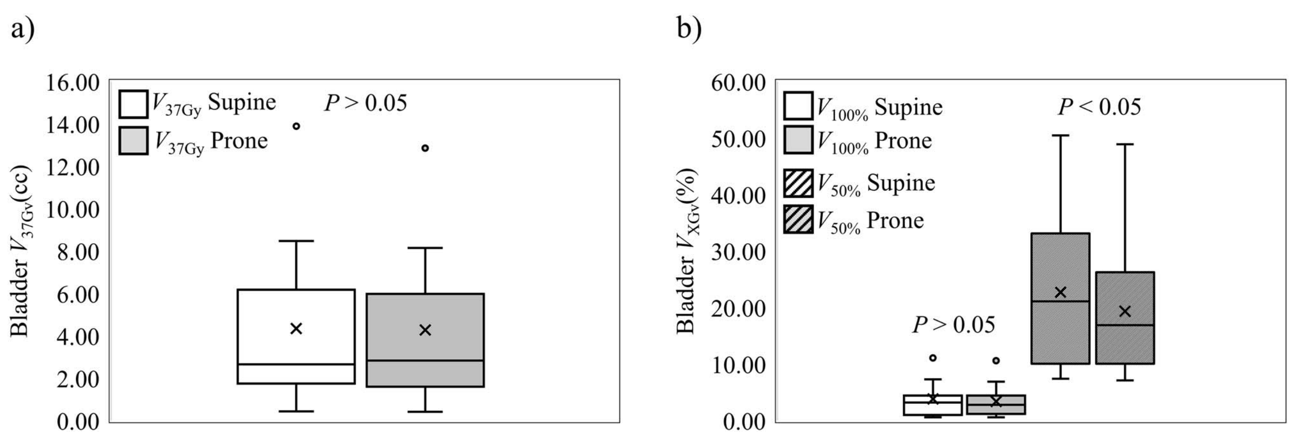

Fig. 6. **a) Bladder V_{37Gy} in the supine and prone positions, b) Bladder $V_{100\%}$, $V_{50\%}$ in the supine and prone positions.**

DISCUSSION

We investigated the dosimetric characteristics and delivery efficiency of the supine and the prone treatment plans for prostate cancer with the CyberKnife. The prone position significantly improved the nCI of the PTV compared to the supine position in terms of dose characteristics and reduced the $V_{90\%}$, $V_{80\%}$, $V_{75\%}$ and $V_{50\%}$ of rectum and $V_{50\%}$ of bladder. This may be due to the change in the anatomical positioning of the PTV and OARs. In the supine position, as the bladder is on the ventral side of the PTV and the rectum is on its dorsal side, tangential irradiation to the PTV entails dose concentration on the ventral side. This results in a higher dose to the bladder in the supine position. In contrast, in the prone position, tangential delivery to PTV

Table 2. OARs (the rectum, bladder and urethra) dosimetric parameters in the supine and prone positions

	Rectum V_{36Gy} (cc)		Rectum $V_{100\%}$ (%)		Rectum $V_{90\%}$ (%)	
	Supine	Prone	Supine	Prone	Supine	Prone
mean	0.38	0.35	0.60	0.54	2.29	2.08
SD	0.77	0.71	1.15	1.06	3.40	3.18
P value	0.151		0.106		0.011	
	Rectum $V_{80\%}$ (%)		Rectum $V_{75\%}$ (%)		Rectum $V_{50\%}$ (%)	
	Supine	Prone	Supine	Prone	Supine	Prone
mean	4.37	3.98	5.66	5.20	16.34	14.72
SD	4.86	4.63	5.42	5.21	7.47	7.73
P value	0.002		0.002		0.001	
	Bladder V_{37Gy} (cc)		Bladder $V_{100\%}$ (%)		Bladder $V_{50\%}$ (%)	
	Supine	Prone	Supine	Prone	Supine	Prone
mean	4.34	4.28	3.85	3.39	22.72	19.35
SD	3.29	3.09	3.25	2.51	12.75	10.77
P value	0.518		0.121		0.001	
			Urethra V_{37Gy} (%)			
			Supine	Prone		
		mean	6.78	5.21		
		SD	17.77	12.17		
		P value	0.859			

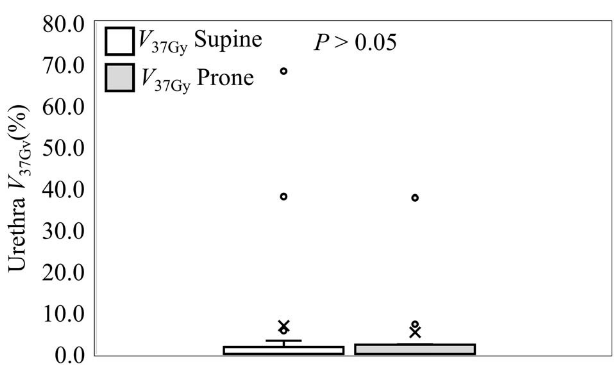

Fig. 7. Urethra V_{37Gy} in the supine and prone positions.

decreases the dose to the bladder due to attenuation of therapeutic photon beams. Moreover, we examined the difference of d_{cax} between the supine and prone positions. As shown in Fig. 9, the d_{cax} in the prone position was significantly longer than that in the supine position. This may have been attributable to the larger number of beams with wider delivery angle in the prone position compared to that in the supine position, which effectively reduces the rectum dose and achieves PTV dose coverage. Supplementary Fig. 2 shows a representative example of three-dimensional beam paths for the supine and prone positions. In contrast, the lesser number of wider delivery beam angles in the supine position was attributable to the fact that wider delivery angle is not needed owing to the presence of the rectum on the dorsal side of the PTV. As indicated by a circle in Supplementary Fig. 2, in contrast to the supine position, the dose can be concentrated on the dorsal side of the PTV, avoiding the rectum, and when delivered on the ventral side of the PTV, there is the advantage of wide-angle delivery because there are fewer OARs. The resultant distribution of the dose reduces the rectum dose. Regarding the delivery efficiency, the prone position was associated with a significantly shorter treatment time, because the direction of tangential incidence to the PTV can avoid the bladder and rectum, which may enable delivery with fewer beams and segments, thereby shortening the treatment time.

In this study population, the treatment plans were originally prepared in the supine position. The present study was a planning study in which the planned CT and contours in the supine position were rotated 180° in the TPS for the inherent geometric constraints of the CyberKnife. Other factors, such as those associated with anatomical changes, respiratory movements and difficulty in patient setup, were not considered. In general, changes in rectal gas or bladder volume affect prostate movement [22]. Moreover, respiratory movements may impact the prostate in the prone position compared with the supine

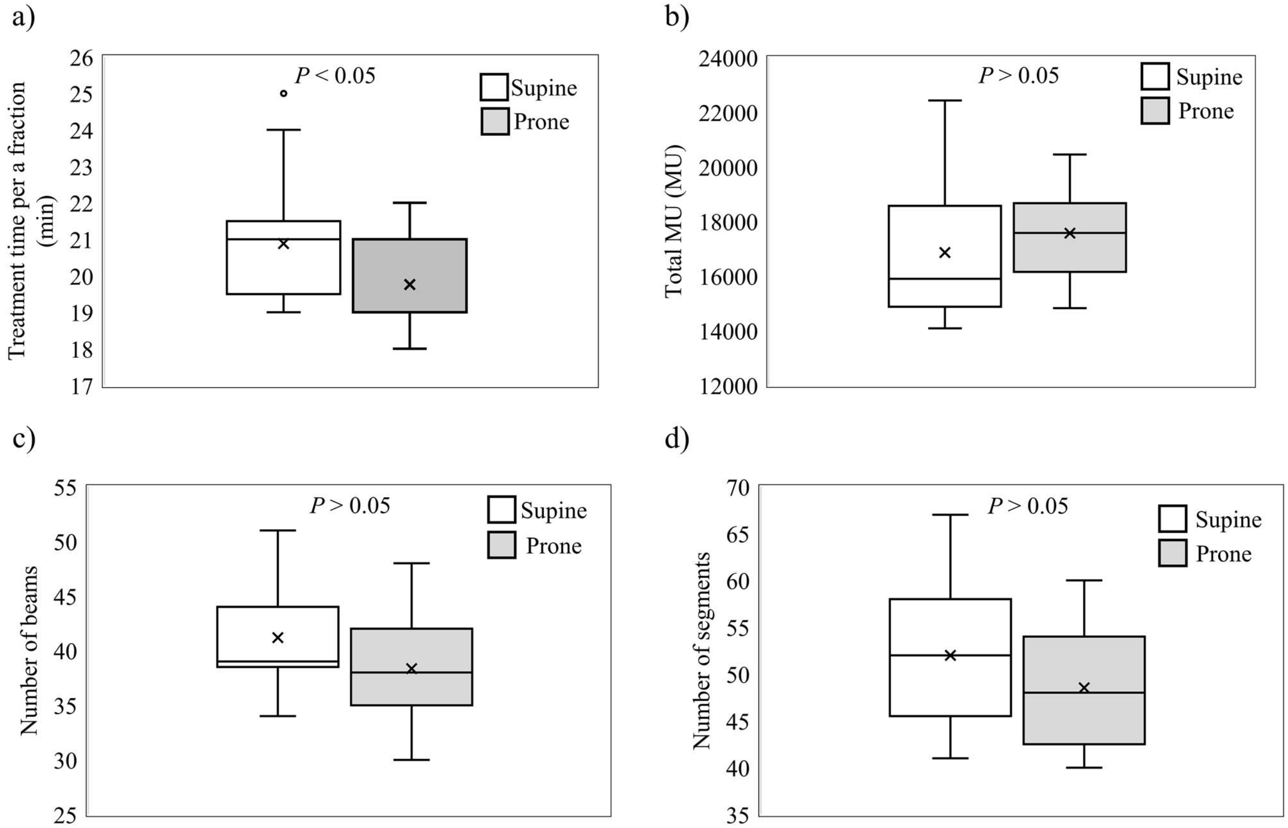

Fig. 8. a) Treatment time/Fr in the supine and prone positions, b) Total MU in the supine and prone positions, c) Beams in the supine and prone positions, d) Segments in the supine and prone positions.

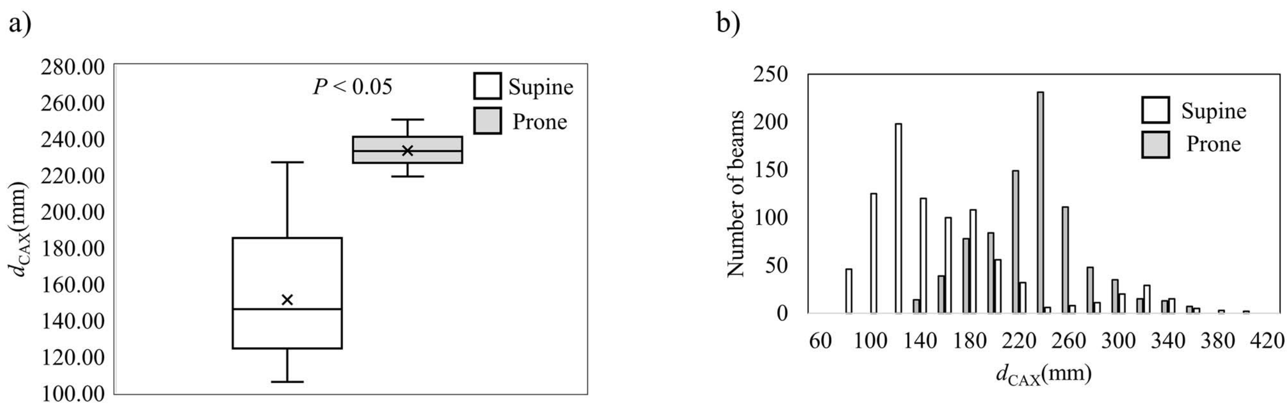

Fig. 9. a) The d_{cax} in the supine and prone positions, b) The distribution of d_{cax} of each beam in the supine and prone positions.

position, and frequent monitoring is necessary. To minimize this effect, the use of a belly board is recommended to control the respiratory movements in the prone position [23]. Fortunately, the CyberKnife offers a two-pair X-ray tracking system during treatment, and the position of the beam can be corrected according to changes in the tumor, although this may require an increasing number of two orthogonal X-rays and overall treatment time.

Moreover, we addressed the following issues occurring in the planning study using the 'true' prone position: Imaging dose was increased because planning CT scan is acquired twice, one CT scan each for the supine and prone positions; this leads to burden on the patient. In addition, delineation uncertainty at two different positions significantly influence plan evaluation. Notably, 'true' prone position potentially improved dose distribution according to the results of the present study. Similarly, Sawayanagi *et al.* demonstrated that dose distribution can be improved in the prone position using conventional linac as it decreases the overlapping volume of the PTV to the OARs, such as the bladder and small bowel [16]. In this study, we suggest avoiding

Table 3. Beam efficiency in the supine and prone positions

		Treatment time/Fr (min)		Total MU (MU)		
		Supine	Prone	Supine	Prone	
	mean	20.9	19.8	16860.9	17571.5	
	SD	1.7	1.3	2448.5	1569.4	
	P value	0.019		0.190		
	Beams		Segments		d_{CAX} (mm)	
	Supine	Prone	Supine	Prone	Supine	Prone
mean	41.2	38.4	52.0	48.5	151.1	233.2
SD	4.9	4.7	8.0	6.4	33.6	8.8
P value	0.083		0.147		<0.001	

imposing a change in patient position on patients to reduce their burden, and we decided to apply an image processing technique by rotating CT images by 180°. With this methodology, the geometric positioning can be precisely rotated by 180°, and we can directly evaluate the characteristics of the planning technique for the supine and prone positions without any uncertainties, such as the mentioned delineations and changes in anatomical geometry due to gravity. Our results indicated that, even for the same anatomical geometry, the OARs dose could be reduced in the prone position. Based on the previous papers [16, 17] and our results, the prone position in prostate radiotherapy can be expected to further reduce the OAR doses, and it can promote 'true' prone position in prostate cancer by the CyberKnife. As shown in Fig. 6, b, $V_{50\%}$ in the bladder was significantly decreased in the prone position. Because specific patients, who have difficulty in full bladder management, tend to have additional unnecessary doses in the bladder, we believe that prone treatment may be effective in reducing the bladder dose for such patients.

This study showed that during prostate cancer treatment with the CyberKnife, prone position may improve PTV nCI, significantly decrease the rectum dose, bladder dose and treatment time, and improve dosimetric characteristics and delivery efficiency compared with the supine position. Although the results of this study are not exhaustive, they suggest that the prone position is useful as an option for setup.

SUPPLEMENTARY DATA

Supplementary data is available at *RADRES Journal* online.

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ETHICS STATEMENT

This study was approved by the institutional ethics review board in National Cancer Center Hospital (approval number: 2017–091).

FUNDING

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CONFLICT OF INTEREST

The authors declare they have no conflicts of interest.

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