

TO EVALUATE THE SETUP DISCREPANCY OF CARCINOMA OF PROSTATE PATIENTS AND CALCULATE THE PLANNING TARGET VOLUME (PTV) MARGIN BY USING DIFFERENT IMAGING MODALITIES

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DOI: <https://doi.org/10.5281/zenodo.21884561>

Keywords

Prostatectomy, Radiotherapy,
Cone Beam computed
radiography, Linear Accelerator,
Systematic error

Article History

Received: 11 March 2026

Accepted: 15 April 2026

Published: 30 April 2026

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Abstract

Introduction: Radical prostatectomy remains a primary treatment option for men with clinically localized prostate cancer. However, radiotherapy has demonstrated comparable outcomes in disease control. The prostate is a mobile organ located anterior to the rectum and inferior to the bladder. Therefore, managing both inter-fraction and intra-fraction prostate motion during radiotherapy is crucial for achieving optimal treatment outcomes. In addition, variations in bladder and rectal volumes can influence dose delivery and may increase the risk of treatment-related toxicity.

Materials and Methods: A total of 25 patients with prostate cancer were enrolled in this study. Data were collected prospectively using the cone-beam computed tomography (CBCT), megavoltage (MV), and kilovoltage (kV) imaging systems integrated with the Varian TrueBeam linear accelerator. In total, 250 CBCT images and 500 MV and kV portal images were acquired. For each patient, kV-CBCT, planar kV, and MV portal images were obtained in accordance with the institutional imaging protocol. Data were entered and analyzed using SPSS software (Version 21). Setup margins (SM) were calculated according to the van Herk formula

Results: The systematic setup errors measured using CBCT were 0.165 cm, 0.140 cm, and 0.150 cm in the dorsoventral (DV), mediolateral (ML), and craniocaudal (CC) directions, respectively. These values were lower than those obtained using kV and MV portal imaging. Similarly, CBCT demonstrated the lowest random setup errors, with values of 0.23 cm (DV), 0.17 cm (ML), and 0.22 cm (CC). Random setup errors measured using kV imaging were 0.39 cm, 0.27 cm, and 0.32 cm in the DV, ML, and CC directions, respectively. The highest random setup errors were observed with MV portal imaging, measuring 0.37 cm (DV), 0.30 cm (ML), and 0.35 cm (CC). Consequently, the smallest setup margins were achieved with CBCT-based

image guidance, with calculated margins of 0.53 cm, 0.44 cm, and 0.49 cm in the DV, ML, and CC directions, respectively.

Conclusion: CBCT is a valuable imaging modality for patient setup verification prior to the delivery of radiotherapy fractions. Compared with kV and MV imaging, CBCT resulted in smaller setup margins in all three directions. This reduction in treatment margins can help minimize radiation exposure to surrounding organs at risk, particularly the bladder and rectum, while maintaining adequate target coverage. The findings suggest that institutions without access to CBCT and relying on MV portal imaging for setup verification should establish and apply site-specific MV-based setup margins to ensure accurate treatment delivery.

Introduction:

Prostate cancer is the second most commonly diagnosed malignancy among men and remains a leading cause of cancer-related mortality worldwide [1]. In 2022, approximately 1.46 million new cases were diagnosed, and nearly 400,000 deaths were attributed to the disease globally [2]. The burden of prostate cancer is not uniformly distributed across low-, middle-, and high-income countries. Variations in incidence and mortality are influenced by factors such as public awareness, availability of screening programs, access to healthcare services, and population aging [3]. Mortality rates tend to be higher in low-income countries due to delayed diagnosis and limited access to advanced treatment modalities [4].

Prostate-specific antigen (PSA) testing is widely used as a screening and diagnostic tool for the early detection of prostate cancer [5]. Elevated PSA levels may indicate the presence of malignancy; however, histopathological confirmation through tissue biopsy remains the gold standard for diagnosis.

Treatment options for prostate cancer include hormonal therapy, radical prostatectomy, and radiotherapy [6]. The choice of treatment is determined based on disease stage, patient characteristics, and comprehensive clinical evaluation. Radiotherapy plays a pivotal role in the management of prostate cancer and has demonstrated outcomes comparable to radical prostatectomy in terms of disease control and overall survival [7]. Traditionally, definitive radiotherapy courses were delivered over 5–7 weeks, depending on the prescribed dose and

treatment technique. However, advances in radiotherapy technology and treatment planning have enabled the delivery of radical treatment in as little as 1–2 weeks through hypofractionated treatment regimens [8].

One of the major challenges in radiotherapy is the accurate delivery of radiation to the target volume while minimizing exposure to surrounding healthy tissues. The prostate is located inferior to the bladder and anterior to the rectum, making precise targeting particularly important to reduce treatment-related toxicity. Treatment outcomes and toxicity profiles are highly dependent on the accuracy and precision of radiation delivery. In addition, toxicity may be influenced by the Planning Target Volume (PTV), which is generated by expanding the Clinical Target Volume (CTV) to account for organ motion and setup uncertainties. The magnitude of the PTV margin is influenced by the imaging and verification technologies available at a treatment facility and is generally larger when two-dimensional imaging techniques are used for patient setup verification.

Several image-guided radiotherapy (IGRT) technologies are currently available, with Cone Beam Computed Tomography (CBCT) and Electronic Portal Imaging Devices (EPID) being among the most widely used. CBCT is an advanced IGRT modality that provides high-resolution three-dimensional (3D) visualization of the target and surrounding organs at risk (OARs) [9]. Integrated with a kilovoltage (kV) imaging source, CBCT systems can also acquire two-dimensional planar kV images for patient positioning and verification.

The aim of this study was to evaluate patient positioning accuracy and compare setup errors among planar kilovoltage imaging (kV-PI), Electronic Portal Imaging Devices (EPID), and Cone Beam Computed Tomography (CBCT). Additionally, the study sought to calculate and compare the Planning Target Volume (PTV) margins derived from each imaging modality.

Materials and Methods:

A total of 25 patients with prostate cancer staged as T3-T4N₀M₀ were enrolled in this study between April 2023 and September 2025. All patients underwent computed tomography (CT) simulation using a Toshiba 16-slice CT scanner.

To ensure reproducible bladder filling during simulation and subsequent treatment sessions, patients were instructed to drink 300–500 mL of water approximately 20 minutes before the simulation procedure. They were asked to notify the radiation therapist when they experienced the urge to urinate and to maintain bladder filling until the completion of the simulation. No routine bowel preparation protocol was implemented. However, patients with severe constipation were advised to use laxatives before simulation and treatment, as rectal distension was carefully evaluated during both procedures. Patients who were unable to maintain adequate bladder filling for the required duration were excluded from the study.

During CT simulation, patients were positioned supine using the in-room laser positioning system (LAP Isomark), with sagittal and lateral laser alignment serving as reference points. No immobilization devices were used. Head support was selected according to patient comfort using one of the available headrests (A-F; IV-T black cushion). Following patient positioning, scout images were acquired from the T12 vertebral level to the mid-thigh region to verify alignment.

CT images were acquired with a slice thickness of 3 mm and subsequently transferred to the Eclipse Treatment Planning System (Version 16) for contouring and treatment planning. The radiation oncologist delineated the Gross Tumor Volume (GTV), Clinical Target Volume (CTV), Planning Target Volume (PTV), and organs at risk (OARs),

including the bladder, rectum, colon, and femoral heads. Treatment plans were generated by a medical physicist and transferred to the treatment delivery system.

All patients were treated using a Varian TrueBeam linear accelerator equipped with Cone Beam Computed Tomography (CBCT), kilovoltage (kV), and megavoltage (MV) portal imaging systems. Prior to each treatment session, patient setup verification was performed using CBCT. The acquired CBCT images were registered with the planning CT images, and the required couch shift parameters were recorded. Subsequently, orthogonal kV and MV portal images were acquired, independently matched, and their corresponding setup correction parameters were documented for comparison.

Data were entered and analyzed using SPSS software (Version 21). Setup margins (SM) were calculated according to the van Herk formula:

$$SM = 2.5\Sigma + 0.7\sigma [10]$$

where Σ represents the standard deviation of the mean setup error for each patient (systematic error), and σ represents the root mean square of the standard deviations of day-to-day setup variations across all patients (random error).

Results:

A total of 250 cone-beam computed tomography (CBCT) images, 500 megavoltage (MV) portal images, and 500 kilovoltage (kV) planar images were collected from 25 patients undergoing radiotherapy for prostate cancer. All patients received conventionally fractionated intensity-modulated radiotherapy (IMRT) to a total dose of 79 Gy delivered in 39 fractions. Patients with advanced-stage or metastatic disease were excluded from the study. The age of the participants ranged from 53 to 75 years.

Systematic Setup Errors (Σ):

The calculated systematic setup errors (Σ), defined as the standard deviation of the mean setup shifts for each patient within the study population, are presented in Table 1. Among all evaluated imaging modalities, CBCT demonstrated the lowest systematic setup errors in all three directions. The systematic errors measured with CBCT were 0.165

cm in the dorsoventral (DV) direction, 0.140 cm in the mediolateral (ML) direction, and 0.150 cm in the craniocaudal (CC) direction.

For kV planar imaging, the corresponding systematic setup errors were 0.24 cm (DV), 0.22 cm (ML), and 0.23 cm (CC). The largest systematic setup errors were observed with MV portal imaging, measuring 0.31 cm, 0.275 cm, and 0.295 cm in the DV, ML, and CC directions, respectively.

Random Setup Errors (σ):

The random setup errors (σ), defined as the root mean square of the standard deviations of daily setup variations across all patients, are presented in Table 2. Similar to the systematic error analysis, CBCT demonstrated the lowest random setup errors, with values of 0.23 cm in the DV direction, 0.17 cm in the ML direction, and 0.22 cm in the CC direction.

The random setup errors obtained using kV planar imaging were 0.39 cm, 0.27 cm, and 0.32 cm in the DV, ML, and CC directions, respectively. The highest random setup errors were observed with MV portal imaging, with values of 0.37 cm (DV), 0.30 cm (ML), and 0.35 cm (CC).

Setup Margins:

Table 1 shows the systematic setup error of prostate cancer in all three directions for CBCT, kV and MV port. (which is defined as the S.D over group mean error.)

SYSTEMATIC SETUP ERROR (Σ)			
	DORSOVENTRAL (cm)	MEDIO LATERAL (cm)	CRANIOCAUDAL (cm)
CBCT	0.165	0.14	0.15
kV PORT	0.24	0.22	0.23
MV PORT	0.31	0.275	0.295

Table 2 shows the random setup error in all three directions for CBCT, kV and MV port (which is defined as the root mean square of the patients S.D)

RANDOM SETUP ERROR (σ)			
	DORSOVENTRAL (cm)	MEDIOLATERAL (cm)	CRANIOCAUDAL (cm)

Planning target volume (PTV) setup margins were calculated using the van Herk formula:

Setup Margin = $2.5\Sigma + 0.7\sigma$. The calculated setup margins for each image-guidance modality are summarized in Table 3.

CBCT-based image guidance resulted in the smallest setup margins, measuring 0.53 cm, 0.44 cm, and 0.49 cm in the DV, ML, and CC directions, respectively. In comparison, the setup margins derived from kV planar imaging were larger, with values of 0.80 cm (DV), 0.69 cm (ML), and 0.74 cm (CC).

The largest setup margins were observed with MV portal imaging, measuring 0.96 cm, 0.84 cm, and 0.91 cm in the DV, ML, and CC directions, respectively.

Overall, the findings demonstrate that CBCT-based image guidance provides superior setup accuracy compared with both kV planar imaging and MV portal imaging. The reduced systematic and random errors achieved with CBCT translated into smaller setup margins, potentially enabling improved target localization while minimizing radiation exposure to surrounding organs at risk. The detailed results for systematic and random setup errors are presented in Tables 1 and 2, respectively.

CBCT	0.23	0.17	0.22
kV PORT	0.39	0.27	0.32
MV PORT	0.37	0.3	0.35

Table 3 represents the setup margins for prostate cancer. The setup margins were computed using the Van Herk's formula $SM = 2.5\sigma + 0.7\sigma$

PROSTATE CANCER			
SETUP MARGINS			
	DORSOVENTRAL (cm)	MEDIOLATERAL (cm)	CRANIOCAUDAL (cm)
CBCT	0.53	0.44	0.49
kV PORT	0.80	0.69	0.74
MV PORT	0.96	0.84	0.91

Discussion:

The planning target volume (PTV) margin applied around the clinical target volume (CTV) plays a crucial role in achieving a high tumor control probability (TCP) while minimizing radiation exposure to surrounding organs at risk (OARs) [11]. Prostate cancer presents a unique challenge in radiotherapy because of the anatomical location of the prostate, which lies immediately inferior to the bladder and anterior to the rectum. Consequently, careful consideration is required during PTV delineation. Even a small increase in the PTV margin may result in excessive radiation dose to the bladder and rectum, potentially increasing treatment-related toxicity. Conversely, inadequate margins may compromise target coverage, leading to reduced TCP. Therefore, understanding the limitations and accuracy of the image-guidance systems used for patient setup verification is essential for determining appropriate PTV margins.

In the present study, setup uncertainties associated with three image-guidance modalities CBCT, kV planar imaging, and MV portal imaging were evaluated, and modality-specific setup margins were calculated using the van Herk formula. The

analysis of systematic setup errors demonstrated that CBCT produced the lowest deviations, measuring approximately 0.17 cm, 0.15 cm, and 0.15 cm in the dorsoventral (DV), mediolateral (ML), and craniocaudal (CC) directions, respectively. These findings are consistent with previously published studies that have reported superior setup accuracy with CBCT-based image guidance [12]. Slightly larger deviations were observed in the DV direction, likely due to variations in bladder filling and rectal distension, which can influence prostate position during treatment.

The superior performance of CBCT can be attributed to its ability to provide high-resolution three-dimensional visualization of patient anatomy. CBCT allows more accurate image registration with the planning CT dataset and provides detailed information regarding the position, shape, and volume of both the target and surrounding organs at risk. As a result, prostate localization can be performed with greater accuracy compared with two-dimensional imaging techniques [13].

Kilovoltage (kV) planar imaging also demonstrated relatively good agreement with

CBCT, with a maximum deviation of approximately 6 mm in the DV direction. Although kV imaging provides only two-dimensional anatomical information, its image quality is superior to MV imaging due to the predominance of the photoelectric effect, which enhances contrast resolution. Consequently, bony anatomy can be visualized more clearly, facilitating image matching with digitally reconstructed radiographs (DRRs). However, kV imaging remains limited in its ability to accurately visualize the prostate gland, particularly the apex, and does not adequately account for daily variations in bladder and rectal filling.

Megavoltage (MV) portal imaging exhibited the largest setup deviations among the three evaluated modalities, with systematic errors of approximately 0.31 cm, 0.28 cm, and 0.30 cm in the DV, ML, and CC directions, respectively. The primary reason for this reduced accuracy is the limited anatomical information available from two-dimensional MV images. Since the Compton effect dominates image formation at megavoltage energies, image contrast is inherently lower, resulting in poorer image quality and less precise registration. Consequently, setup verification relies almost exclusively on bony anatomy, which may not accurately represent the position of the prostate.

The findings of this study are consistent with previously published literature demonstrating the superiority of CBCT over conventional kV and MV imaging techniques for prostate radiotherapy setup verification [14–16]. The improved localization accuracy provided by CBCT enables the use of smaller PTV margins, thereby reducing radiation exposure to the bladder and rectum while maintaining adequate target coverage. Furthermore, CBCT facilitates assessment of daily variations in bladder and rectal filling and eliminates the need for invasive procedures, such as fiducial marker implantation, for routine patient setup verification. Although fiducial markers have been shown to improve localization accuracy, particularly when using two-dimensional imaging techniques, their placement requires an invasive procedure and may not be feasible for all patients.

Despite its strengths, this study has several limitations. The analysis was restricted to translational setup errors in three dimensions and did not account for rotational uncertainties, including roll, pitch, and yaw. These rotational variations may contribute to residual setup errors and influence target coverage, particularly in highly conformal treatment techniques. Future studies should incorporate both translational and rotational corrections to provide a more comprehensive assessment of setup uncertainties and margin requirements.

Conclusion:

This study evaluated setup uncertainties and calculated planning target volume margins using three image-guidance modalities: CBCT, kV planar imaging, and MV portal imaging. Among the evaluated techniques, CBCT demonstrated the highest level of accuracy and precision for patient setup verification in prostate radiotherapy. CBCT resulted in the lowest systematic and random setup errors and consequently produced the smallest PTV margins in all three directions.

The reduction in setup margins achieved with CBCT has the potential to minimize radiation exposure to adjacent organs at risk, particularly the bladder and rectum, while maintaining adequate target coverage. These findings support the routine use of CBCT for image-guided radiotherapy in prostate cancer. For institutions that do not have access to CBCT and rely on MV portal imaging for setup verification, the establishment and application of modality-specific MV-based setup margins are strongly recommended to ensure accurate and safe treatment delivery.

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