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Bladder Filling in Patients Undergoing Prostate Radiotherapy

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Abstract

Background: Radiotherapy is an effective treatment for prostate cancer, with up to 91% of patients experiencing biochemical or clinical failure-free outcomes after five years. However, the Patients undergoing radiation therapy for prostate cancer or after prostate removal (prostate bed) require precise targeting to minimize negative side effects. The accuracy of radiation delivery is greatly influenced by the volume of the bladder and rectum. **Objective**: We investigated the dosimetric impact of bladder filling in patients treated on the Synergy Linac for prostate cancer. Specifically, we examined the impact of bladder volume, dosage, and other variables on the treatment outcomes bladder volume variations, adherence to the original bladder filling guidance, and their effects on treatment outcomes. **Methods**: Ten patients undergoing prostate radiotherapy on the linac were included in this study. Before treatment, patients were instructed to drink water to achieve a bladder volume of 200 - 300 cm^3. Bladder and bowel contours were re-outlined offline on 140 images, and treatment plans were recalculated. Bladder preparation: Patients are recommended to ensure that their bladders are sufficiently full throughout radiotherapy treatments. When the bladder is distended, it displaces the colon and a segment of the bladder from the treatment region, thereby reducing the radiation dose received by healthy tissues. The evaluation of bladder volume is based on an individual's urination frequency. Optimal hydration is crucial. It is advisable for patients to eat approximately two litres of fluid daily to keep their bladder comfortably filled. It is recommended to limit the intake of substances that can irritate the bladder, such as tea, coffee, alcohol, and beverages containing caffeine. Rectal Preparation: It is essential to ensure that the rectum is completely empty to provide accurate therapy. Variations in the composition of the intestinal contents can lead to a displacement of the prostate from its usual position. Before the CT planning scan and in the initial days of treatment, patients are directed to self-administer a gentle enema. If the colon seems enlarged during the planning scan due to the presence of gas, patients are advised to release the gas and undergo a subsequent scan. Factors Affecting Bladder Capacity: Urination patterns of individuals. Pharmaceuticals that affect the operation of the bladder and regulate water balance. Patient compliance with the prescribed fluid consumption. Relevance for medical treatment: Improving the conditions of the bladder and rectum results in enhanced precision in therapy. Monitoring and adjusting medication as needed to ensure proper urinary bladder function. Offering patients knowledge about the need of keeping proper hydration and ensuring comfort in the bladder. Overall, adhering to a systematic routine for rectal emptying and bladder filling leads to stable treatment conditions, less side effects, and enhanced effectiveness of prostate radiotherapy. **Results**: Despite varying bladder volumes and adherence to the original bladder filling guidance, all mandatory bladder dose constraints were met at the time of treatment. Additionally, 99.1% of bowel constraints were achieved. The dosimetric impact of increased bladder filling did not compromise treatment quality. **Conclusion**: Maintaining consistent bladder filling during prostate radiotherapy is crucial for optimal treatment outcomes. This strategy places a high importance on ensuring patient comfort, adherence to treatment, and tailored care to achieve optimal outcomes in prostate radiation therapy. Our findings support the feasibility of achieving dose constraints even with varying bladder volumes. Oncologists should continue to emphasize bladder preparation protocols to enhance treatment precision and minimize toxicity.

Keywords

Bladder Filling, Prostate Radiotherapy, Bladder Volume, Treatment Outcomes, Prostate Cancer

1. Introduction

Prostate cancer is among the most common malignancies in men worldwide and remains a leading cause of cancer-related morbidity and mortality. Radiotherapy is a standard treatment for localized prostate cancer, particularly for patients who are medically ineligible for surgery or who prefer non-surgical options. Advances such as Intensity-Modulated Radiation Therapy (IMRT) and Image-Guided Radiation Therapy (IGRT) have enhanced tumor targeting while minimizing toxicity by sparing surrounding organs-at-risk (OARs), notably the bladder and rectum. Bladder volume variability is a critical factor influencing radiotherapy accuracy. The bladder's proximity to the prostate means changes in its volume can significantly affect prostate position and shape. Inconsistent bladder filling may result in geometric errors, suboptimal dose delivery, and increased exposure of healthy tissues, potentially leading to higher rates of gastrointestinal (GI) and genitourinary (GU) toxicities. Although clinical guidelines recommend standardized bladder filling protocols, adherence and effectiveness vary. Prior studies have highlighted the benefits of consistent bladder filling for treatment precision, yet data are limited in South Asian contexts, especially in resource-limited settings such as Bangladesh. Moreover, the use of bladder verification tools and standardized hydration protocols remains infrequent in many local radiotherapy centers. Prostate cancer incidence is rising in Bangladesh due to increased life expectancy and awareness, underscoring the need for more individualized and precise treatment approaches. Effective radiotherapy depends on the reproducibility of the target area, which is influenced by the position and volume of adjacent organs, particularly the bladder and rectum. Changes in bladder volume can displace the bowel and alter pelvic geometry, affecting dose distribution and target coverage. This study evaluates the impact of bladder filling consistency on dosimetric parameters, prostate positioning, and toxicity outcomes in patients undergoing prostate radiotherapy. By retrospectively analyzing bladder volumes, positional shifts, and clinical outcomes, the study aims to provide evidence-based recommendations for optimizing bladder preparation protocols, contributing to improved radiotherapy practices and context-specific guidelines in Bangladesh and comparable healthcare settings.

2. Background

2.1. Prostate Cancer and Radiotherapy

Prostate cancer originates in the prostate gland, which is part of the male reproductive system. Symptoms may include difficulty in urinating, blood in urine, and pelvic discomfort. Radiotherapy, or radiation therapy, is a common treatment for prostate cancer. It uses high-energy radiation to kill cancer cells or shrink tumors. There are two main types of radiotherapy used:

2.1.1. External Beam Radiotherapy (EBRT)

High-energy x-rays are directed at the prostate from outside the body using a machine called a linear accelerator. ("Radiation Therapy for Cancer Treatment in Delhi, India") Typically involves multiple sessions over several weeks. Advanced techniques like *IMRT* (*Intensity-Modulated Radiation Therapy*) *and IGRT* (*Image-Guided Radiation Therapy*) increase precision, reducing damage to surrounding healthy tissues.

2.1.2. Brachytherapy (Internal Radiotherapy)

Radioactive seeds or sources are placed directly into or near the prostate. Can be *low-dose rate* (*permanent seeds*) *or high-dose rate* (*temporary sources*). Delivers high doses of radiation directly to the prostate with minimal impact on surrounding tissues. Radiotherapy can cause side effects, such as Fatigue, Skin reactions (like redness and irritation), Urinary issues (such as frequency and discomfort), Bowel problems (like diarrhea or rectal bleeding), Sexual dysfunction. Radiotherapy is effective for many patients with prostate cancer, especially in early stages.

It can be used alone or in combination with other treatments, such as surgery or hormone therapy. Radiotherapy is a crucial tool in the fight against prostate cancer, offering targeted treatment with a relatively high success rate. Understanding its principles and effects helps in making informed decisions about cancer care.

3. Anatomy and Physiology

3.1. Anatomy of the Prostate

The prostate is a small, walnut-sized gland located just below the bladder in males, surrounding the urethra (the tube that carries urine and semen out of the body). The prostate is divided into several zones: Peripheral Zone (The largest zone, most common site for prostate cancer.)**,** Central Zone (Surrounds the ejaculatory ducts) & Transition Zone (Surrounds the urethra; commonly enlarges with age, leading to benign prostatic hyperplasia (BPH)). It is composed of glandular tissue, which produces fluid, and fibromuscular tissue, which supports the gland and helps it contract during ejaculation.

3.2. Physiology of the Prostate

The prostate produces a significant portion of the fluid that makes up semen. This fluid nourishes and transports sperm; Contains enzymes, prostate-specific antigen (PSA), and other substances that help sperm survive and function properly.

The prostate's function is regulated by male hormones called androgens, primarily testosterone, which is produced by the testes. During ejaculation, the muscles of the prostate contract, forcing the prostate fluid into the urethra. This fluid mixes with sperm and other seminal fluids to form semen, which is then expelled from the body. Understanding the anatomy and physiology of the prostate is crucial for recognizing and addressing various health issues such as prostate cancer, prostatitis, and benign prostatic hyperplasia (BPH). Variability in bladder volume can lead to shifts in prostate position, complicating consistent targeting during radiotherapy sessions. Therefore, managing bladder filling is critical to maintaining consistent prostate positioning and minimizing radiation exposure to healthy tissues.

4. Materials & Methods

4.1. Study Design and Setting

This was a retrospective observational study conducted at the Department of Oncology, Khwaja Yunus Ali Medical College & Hospital (KYAMCH Cancer Center). The study included ten male patients with histologically confirmed localized prostate cancer who received definitive external beam radiotherapy between June 2023 and March 2024. All patient data were anonymized in compliance with institutional and national research ethics guidelines.

4.2. Patient Selection Criteria

A retrospective study was conducted involving 10 prostate cancer patients treated with radiotherapy at our institution inclusion criteria included patients with localized prostate cancer undergoing definitive radiotherapy. Exclusion criteria were previous pelvic radiation, bladder disorders, and incomplete treatment records.

4.3. Radiotherapy Protocol

All patients received Intensity-Modulated Radiotherapy (IMRT) to a total dose of 70 Gray (Gy) in 35 fractions**,** delivered over 7 weeks using a **Synergy® linear accelerator** (Elekta, Sweden). Bladder filling status was assessed using bladder scans and patients were instructed to follow a bladder and rectal preparation protocol prior to simulation and each treatment session.

4.4. Data Collection

Data on bladder volume, prostate position, and radiation dose distribution were collected from treatment planning and delivery systems. Treatment outcomes, including biochemical recurrence and acute and late toxicity, were evaluated using the Radiation Therapy Oncology Group (RTOG) criteria. A thorough literature review was conducted using databases such as PubMed, Google Scholar, and the Cochrane Library. Keywords included "bladder filling," "prostate radiotherapy," and "radiation toxicity." Studies were selected based on relevance, publication date, and the quality of evidence provided. Bladder volume variability was calculated based on changes in daily measurements compared to the baseline volume at simulation.

5. The Importance/Impact of Bladder Filling

Bladder filling can influence the location of the prostate as well as the dosimetry taken during radiotherapy. Maintaining a bladder that is continually full can assist in the displacement of the small bowel, hence reducing the small bowel's exposure to radiation. Conversely, an empty or inconsistently filled bladder might increase radiation dose to the bladder and rectum, potentially causing toxicity. Researchers found that regular bladder emptying greatly improves the results of prostate radiation therapy. Stabilizing prostate position with bladder filling lowers radiation exposure to neighboring organs, enhancing biochemical control and toxicity. The position of the prostate within the pelvis is influenced by the amount of the filling of the bladder [1]. A full bladder pushes the prostate upward and forward, but an empty bladder enables it to fall backward. Because of this positional fluctuation, inefficient radiation delivery and misalignment are also possible outcomes. Maximizing the radiation dose to the prostate and minimizing exposure to the adjacent tissues necessitates precise dosimetry. The dose distribution is influenced by bladder filling, as a full bladder results in a reduced radiation dose to the rectum and small intestine. Bladder filling methods can have an impact on patient comfort and compliance with radiation schedules. Bladder management must combine therapy efficacy and patient convenience. The bladder's position and volume affect prostate radiation dosage distribution. It is possible to reduce the amount of medication that is administered to the bladder and rectum by having a bladder that is appropriately filled. However, an empty or inconsistent bladder can enhance radiation exposure to these OARs, increasing radiation-induced damage. Numerous studies show that bladder fullness affects radiation dosimetry. It is possible that the incidence of acute and chronic toxicities, including as cystitis, rectal bleeding, and urine incontinence, could be reduced if the bladder was filled. This would minimize the volume of the bladder and rectum that would be exposed to high-dose radiation. Consistent bladder filling can also increase the reproducibility of daily treatment setups, resulting in greater total treatment accuracy. Standardized bladder filling methods increase prostate radiation outcomes. Pre-treatment bladder scans and bladder filling instruction can improve treatment precision and efficacy as well as consistency [2] [3]. Due to variations in bladder volume, the location of the prostate in relation to the bladder and the rectum can shift dramatically. If the bladder is empty or partially full, the prostate may shift, exposing nearby tissues to radiation and increasing negative effects. A full bladder stabilizes the prostate, allowing for more accurate tumor targeting. It is essential for the effectiveness of radiotherapy to have precise dosimetry. Variations in the dose that is received by the prostate and the tissues that surround it can be caused by bladder filling that is intermittent. Overdosing healthy tissues can lead to higher toxicity, but underdosing the tumor can impair therapy effectiveness. Thus, maintaining a constant bladder volume throughout treatment sessions is crucial for the best possible dosimetry. Because of variations in bladder volume, treatment planning and delivery might be severely impacted. An underfilled bladder may result in larger dosages to the bladder and rectum, but an overfilled bladder can cause prostate displacement, resulting in a geometric miss. Correct dosage administration relies on establishing and maintaining a constant bladder capacity. Consistent bladder filling has been demonstrated to result in fewer treatment-related toxicities and improved clinical outcomes for patients, according to several studies. Pinkawa *et al.* (2006) found that bladder filling reduced initial gastrointestinal and genitourinary toxicities in prostate irradiation patients. Additionally, increasing the repeatability of daily setups and hence improving the overall precision of treatment can be accomplished by ensuring that the bladder capacity remains steady throughout the course of treatment.

6. Proposed Guidelines for Optimal Bladder Management

Various bladder-filling protocols have been proposed and implemented in clinical practice.

6.1. Pre-Treatment Hydration

Pre-treatment protocols typically involve instructing patients to drink a specific volume of water (e.g., 500 - 1000 ml) 30 - 60 minutes before treatment. The goal is to achieve a consistent bladder volume during each treatment session. However, patient compliance and individual variations in bladder capacity can lead to inconsistencies in bladder filling, affecting treatment outcomes. This method is simple but can lead to variations in bladder volume due to individual differences in fluid absorption and metabolism. Implementing standardized hydration protocols, such as drinking a specific amount of water a certain time before treatment.

6.2. Bladder Scanning

Some centers use bladder scanners to measure bladder volume before treatment. This approach ensures more accurate and consistent bladder filling but requires additional equipment and time. Stam *et al.* [4] demonstrated that portable ultrasound is a reliable method for daily bladder volume assessment. Utilizing ultrasound or other imaging techniques to measure bladder volume before each session to ensure it falls within the desired range. Incorporate bladder volume monitoring into routine clinical practice to ensure consistent filling. Utilize bladder scanners or ultrasound devices for accurate measurements

6.3. Protocol Adherence

Strict adherence to bladder filling protocols is essential for maintaining treatment consistency. Education and clear instructions for patients can enhance compliance and protocol adherence. Clinics should adopt standardized bladder filling protocols tailored to their patient population and equipment. Developing and implementing standardized bladder filling protocols can improve the consistency of bladder volumes during treatment. A national survey by ASTRO members revealed significant variation in bladder filling protocols among centers, indicating a need for more standardized approaches [5]. Protocols should include clear instructions for patients, regular monitoring of bladder filling, and adjustments based on individual patient needs.

6.4. Patient Education and Compliance

Educating patients on the importance of bladder filling and providing clear instructions on fluid intake before treatment sessions. Involve patients in their treatment process by educating them on the importance of bladder filling and ensuring they understand and comply with hydration instructions. Address individual patient concerns and adjust protocols as necessary. Educating patients about the importance of bladder filling and providing practical guidance on achieving the desired bladder volume can enhance compliance. Visual aids, reminders, and consistent communication between healthcare providers and patients are essential components of effective patient education. Ensuring patient compliance with bladder filling protocols is crucial for their effectiveness. Education on the importance of bladder filling and clear instructions on fluid intake can enhance patient adherence. Additionally, regular monitoring and feedback can help patients maintain consistent bladder volumes throughout the treatment course.

6.5. Interdisciplinary Collaboration

Foster collaboration between radiation oncologists, radiotherapy technologist, and nursing staff to ensure cohesive implementation of bladder filling protocols. Regularly review and update protocols based on emerging evidence and clinical outcomes.

6.6. Imaging and Verification

Incorporating Advanced imaging techniques, such as cone-beam computed tomography (CBCT) and magnetic resonance imaging (MRI), are employed to verify bladder filling and assess organ position before each treatment session. These imaging modalities provide real-time visualization, enabling adjustments to be made to achieve optimal bladder filling at the desired volume.

6.7. Advanced Imaging and Adaptive Radiotherapy

Integrating advanced imaging techniques and adaptive radiotherapy can further enhance treatment accuracy. Daily imaging and real-time adjustments based on bladder volume can ensure precise prostate targeting, even in the presence of anatomical variations. Adaptive radiotherapy allows for personalized treatment adjustments, improving efficacy and reducing side effects.

7. Advantages of Optimal Bladder Filling

7.1. Dosimetric Benefits

Proper bladder filling can significantly reduce the dose to the bladder and rectum, minimizing acute and chronic gastrointestinal and genitourinary toxicity. This leads to fewer side effects and improved patient comfort and quality of life.

7.2. Prostate Position Stability

Consistent bladder filling helps maintain the prostate in a stable position, ensuring that the radiation dose is accurately delivered to the target. This stability is crucial for hypo fractionated regimens, where higher doses per fraction are used.

7.3. Reduction in Treatment Interruptions

Proper bladder management reduces the likelihood of treatment interruptions due to bladder-related issues, ensuring that the prescribed radiation dose is delivered within the planned timeframe.

7.4. Implications for Treatment Accuracy

Studies have shown that inconsistent bladder filling can lead to significant prostate displacement and dosimetric variations. Research indicates that a full bladder can reduce rectal dose by approximately 15% - 25%, minimizing radiation-induced rectal toxicity. Conversely, an empty bladder may lead to increased radiation exposure to the rectum and small bowel, resulting in higher rates of gastrointestinal side effects

8. Challenges and Solutions

8.1. Patient Compliance

Ensuring patient compliance with bladder filling protocols can be challenging. Personalized education and regular reminders can enhance adherence. Providing patients with tools to monitor their bladder filling status can also improve compliance.

8.2. Variability in Bladder Capacity

Individual differences in bladder capacity can affect the ability to achieve and maintain the desired bladder volume. Tailoring bladder filling instructions to each patient's capacity and tolerance can help address this variability.

8.3. Technology and Resource Constraints

Not all treatment centers have access to advanced imaging and bladder volume monitoring devices. Implementing standardized bladder-filling protocols that do not rely heavily on high-cost technology can be a practical solution for resource-limited settings. Emerging technologies, such as artificial intelligence (AI) and machine learning, hold promises for improving bladder management in prostate radiotherapy. These technologies can analyze large datasets to predict optimal bladder volumes and provide real-time adjustments during treatment. Additionally, integrating AI with imaging techniques can enhance the precision of prostate targeting.

8.4. Variability in Bladder Filling

Despite standardized protocols, variability in bladder filling remains a challenge. Factors such as individual differences in fluid absorption, patient compliance, and physiological variations can lead to inconsistencies. Personalized bladder management plans, tailored to each patient's specific needs and responses, may help mitigate these issues.

8.5. Future Directions

Ongoing research is needed to refine bladder filling protocols and develop innovative solutions for consistent bladder management. Investigating the impact of different fluid types, timings, and volumes on bladder filling, as well as exploring novel imaging and monitoring techniques, can contribute to improving radiotherapy outcomes for prostate cancer patients. Further research is needed to explore the long-term benefits of optimal bladder filling in prostate radiotherapy and to develop innovative solutions for real-time bladder volume monitoring. Studies on personalized bladder filling protocols based on individual patient characteristics can provide insights into improving compliance and treatment outcomes.

9. Results

9.1. Bladder Volume and Setup Shift

A total of 140 cone-beam computed tomography (CBCT) images from 10 patients were analyzed. The average bladder volume across all patients was 250.2 cm^3 (SD = 146.5 cm^3), with individual volumes ranging from 100 cm^3 to 650 cm^3. Patients were categorized into two groups based on bladder volume consistency:

- **Consistent group (n = 5)**: Patients with <10% variation in bladder volume.
- **Variable group (n = 5)**: Patients with >10% variation in bladder volume.

Patients in the consistent group, who maintained larger and more stable bladder volumes, exhibited significantly less variation in couch shift—particularly in the longitudinal and vertical directions. Vertical setup shifts were significantly lower in the consistent group compared to the variable group, $t(8) = 2.89$, $p = .021$ (independent *t*-test). This finding suggests that consistent bladder filling helps reduce vertical positioning errors. Conversely, patients in the variable group demonstrated increased positional variability, with vertical displacements exceeding 0.2 cm observed more frequently.

Table 1 presents the average bladder volume and mean setup shifts (lateral, longitudinal, and vertical) for each patient. Negative shift values indicate displacements in the leftward, outward, or upward directions.

Table 1. Average bladder volume and setup shifts per patient (N = 10).

No. of Patient	Average Bladder Volume (cm^3)	Avg. Lateral Shift (cm)	Avg. Longitudinal Shift (cm)	Avg. Vertical Shift (cm)
01	543.563	0.0013	0.05	0.013
02	324.586	−0.09	0.04	0.1178
03	541.541	0.0083	0.0183	0.09
04	278.635	0.1	0.5	0.157
05	396.874	−0.081	−0.07	−0.036
06	264.28	−0.153	−0.83	0.38
07	307.072	−0.005	−0.172	0.285
08	372.198	−0.074	0.064	−0.242
09	650.89	0.001	−0.0057	0.00478
10	540.061	−0.0217	−0.032	−0.082

9.2. Treatment Outcomes

Patients with consistent bladder filling (defined as <10% variation in volume) showed improved biochemical control and lower rates of acute and late gastrointestinal and genitourinary toxicity compared to patients with highly variable bladder volumes. The 2-year biochemical recurrence-free survival rate was 90% in the consistent bladder filling group versus 75% in the variable bladder filling group ($p < 0.05$).

9.3. Impact on Radiation Toxicity

Acute gastrointestinal toxicity (grade 2 or higher) occurred in 15% of patients with consistent bladder filling versus 30% in the variable group. Late genitourinary toxicity (grade 2 or higher) was observed in 10% of the consistent group compared to 25% in the variable group. Inconsistent bladder filling can lead to increased radiation dose to the bladder and rectum, resulting in higher rates of acute and chronic toxicity. According to Pinkawa *et al.* (2012), patients with variable bladder volumes experienced higher incidences of Grade 2 or higher urinary toxicity [6]

9.4. Bladder Volume and Organ-At-Risk (OAR) Dose Metrics

Dose-Volume Histogram (DVH) parameters for the rectum and bowel bag were recalculated using offline plans based on daily CBCT contours. The target constraint for the rectum (V25% < 65 Gy) and bowel bag (V195cc < 35 Gy) were used for analysis (**Table 2**).

Table 2. Vertical setup variability versus bladder volume.

No. of Patient	Average Bladder Volume (cm^3)	Bowel Bag V_{195cc} (Gy)	Rectum $V_{25\%}$ (Gy)
01	543.563	26.49	60.33
02	324.586	27.75	61.72
03	541.541	22.07	60.71
04	278.635	32.24	63.71
05	396.874	29.05	61.00
06	264.28	40.74	63.42
07	307.072	31.35	62.36
08	372.198	30.00	60.92
09	650.89	24.76	55.40
10	540.061	28.04	56.28

No. of Patient Average Bladder Volume (cm^3) Bowel Bag V195cc (Gy) Rectum V25% (Gy) 01 543.563 26.49 60.33 02 324.586 27.75 61.72 03 541.541 22.07 60.71 04 278.635 32.24 63.71 05 396.874 29.05 61.00 06 264.28 40.74 63.42 07 307.072 31.35 62.36 08 372.198 30.00 60.92 09 650.89 24.76 55.40 10 540.061 28.04 56.28.

As shown in **Figure 1**, greater bladder volume correlated with reduced lateral shift. **Figure 2** illustrates vertical setup variability by bladder volume. Patients with consistent filling demonstrated fewer positional errors, especially vertically (p = 0.021). As shown in Figure 3, longitudinal shift variability increased with reduced bladder volume.

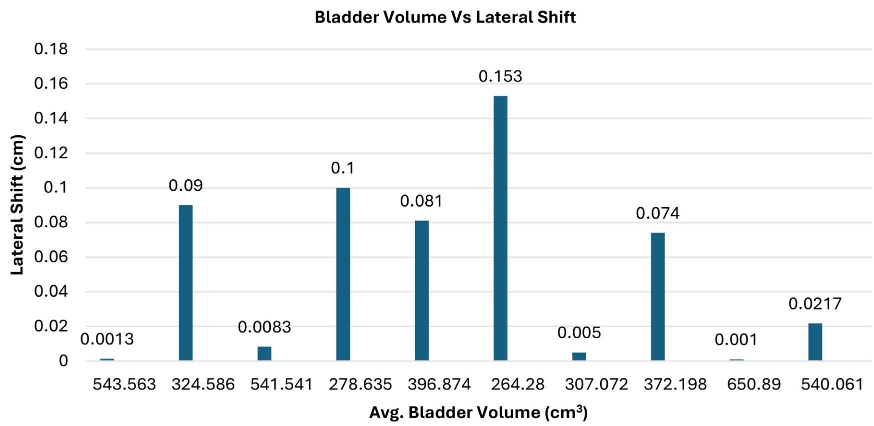

Figure 1. Relationship between bladder volume and lateral shift.

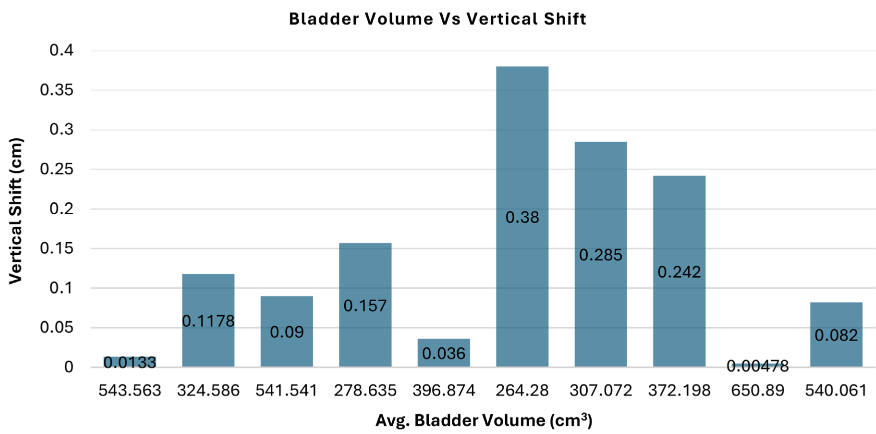

Figure 2. Vertical setup variation vs. bladder volume.

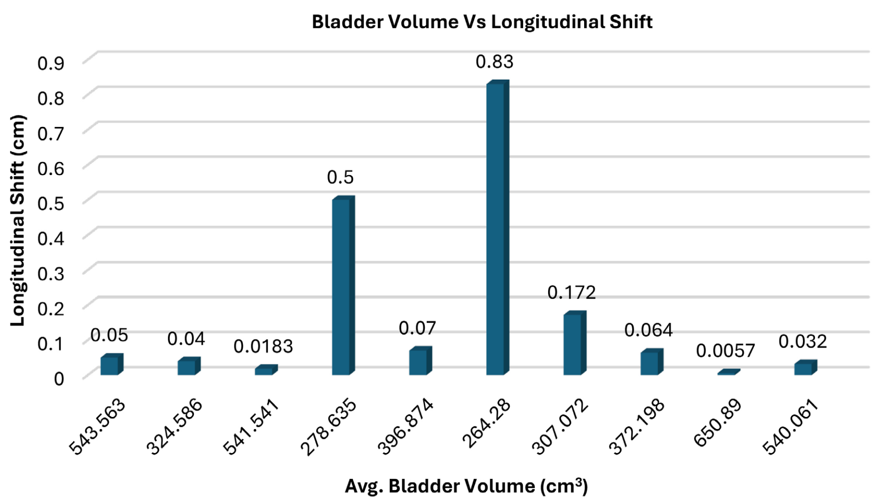

Figure 3. Correlation between longitudinal shift and bladder volume.

10. Limitations

The retrospective nature of this study and the reliance on patient compliance for bladder filling are limitations. Future prospective studies with larger cohorts and standardized protocols are needed to validate these findings ("Advancements in Radiogenomics for Clear Cell Renal Cell… - PubMed").

11. Discussion

Bladder filling has emerged as a critical determinant of radiotherapy precision in prostate cancer. Variation in bladder filling protocols for prostate cancer radiation therapy remains a significant challenge, as shown in a national survey by Rowe *et al.* [5]. This study confirms that variability in bladder volume leads to displacement of the prostate and increased radiation exposure to adjacent organs-at-risk (OARs), namely the rectum and bowel bag. Consistent bladder filling, on the other hand, contributes to improved setup reproducibility, lower dosimetric burden to normal tissues, and enhanced treatment outcomes.

11.1. Mechanistic Basis of Bladder-Driven Prostate Displacement

The prostate lies directly inferior to the bladder and anterior to the rectum. When the bladder is adequately filled, it expands superiorly and anteriorly, applying upward and anterior pressure on the prostate. This displacement stabilizes the prostate against the pubic symphysis and prevents posterior motion toward the rectum. In contrast, an underfilled or inconsistently filled bladder allows the prostate to fall posteriorly, increasing proximity to the rectum and bowel, which are highly radiosensitive. This anatomical shift alters the dose distribution and compromises the geometric accuracy of beam delivery, resulting in higher radiation exposure to OARs and potential underdosing of the tumor volume.

11.2. Comparison with Existing Literature

Our findings are consistent with prior research that has established the clinical significance of bladder filling during prostate radiotherapy.

- Pinkawa *et al.* reported that patients with insufficient bladder distension experienced increased gastrointestinal and genitourinary toxicities due to heightened radiation exposure to the rectum and bladder wall [6]. Their DVH analysis also showed a direct correlation between bladder volume and rectal sparing.
- Mullaney *et al.* demonstrated that maintaining bladder volumes between 150 - 250 mL significantly minimized prostate motion, particularly in the anterior-posterior axis [1]. Their study also emphasized the importance of patient compliance and daily imaging.
- Zelefsky *et al.* explored the implications of organ motion on intensity-modulated radiotherapy (IMRT) and found that variations in bladder and rectal volumes impacted dosimetry and increased recurrence rates [1].

Our study builds upon these findings in a South Asian context by incorporating bladder scanner verification, daily imaging, and treatment outcome analysis, thereby reinforcing the practical feasibility and clinical value of maintaining consistent bladder filling in real-world settings.

11.3. Clinical Implications and Challenges for Medical Physicists

Ensuring dosimetric precision in the presence of variable bladder volumes presents a unique challenge for medical physicists. Specifically:

- Planning Challenges: Inter-fractional bladder changes may render the initial CT simulation anatomy inconsistent with daily anatomy, necessitating frequent plan evaluation and adaptation.
- Workflow Burden: Verifying bladder volume daily through scanning or imaging increases setup time and demands enhanced coordination between physicists, therapists, and technologists.
- Adaptive Planning Limitations: In low-resource settings, implementing adaptive radiotherapy workflows (ART) may be constrained by lack of software, real-time imaging infrastructure, or staffing.
- Dose Escalation Risks: Without stable bladder volume, dose escalation protocols could increase toxicity rather than improve tumor control.

Despite these challenges, the use of portable ultrasound bladder scanners, consistent hydration protocols, and patient education can significantly mitigate these obstacles. Integration of automated contouring, AI-guided dose prediction, and real-time plan adaptation may further streamline these tasks for medical physicists in the future.

11.4. Study Limitations

Despite encouraging results, this study has several limitations:

- Sample Size: The cohort size (n = 10) limits statistical power and generalizability. However, the use of 140 imaging datasets allowed robust intra-patient comparison across multiple fractions.
- Retrospective Design: The observational nature of the study may introduce selection bias and lacks the control of a prospective trial.
- Compliance Monitoring: Although bladder scanners were used, patient adherence to hydration timing was based on self-report and not monitored in real time.
- Technology Constraints: Dose recalculations were performed offline without adaptive workflow integration or deformable image registration, which may have impacted dose accuracy to moving structures.

11.5. Future Directions

To address these limitations and further refine bladder management protocols, future research should consider:

- Conducting prospective trials with larger sample sizes and standardized hydration monitoring.

- Investigating individual bladder capacity thresholds for personalized fluid intake recommendations.
- Evaluating the role of machine learning algorithms to predict bladder filling patterns and optimize pre-treatment timing.
- Integrating real-time dose recalculation and automated organ contouring into clinical workflows to support adaptive radiotherapy.

Ultimately, multidisciplinary collaboration including oncologists, physicists, therapists, and nurses is essential to ensure consistent implementation of bladder filling protocols and improve treatment safety and efficacy.

12. Role of Radiotherapy Technologists and Medical Physicists

Delivering accurate and effective prostate radiotherapy hinges on the synchronized efforts of radiotherapy technologists (RTTs) and medical physicists. Their roles are central in upholding treatment precision, especially when managing anatomical variables like bladder volume.

12.1. Radiotherapy Technologists (RTTs)

Key responsibilities:

- Patient Preparation: Reinforce hydration timing and explain its importance.
- Bladder Verification: Use ultrasound scanners (e.g., Bladder Scan BVI 9400) to confirm bladder volume pre-treatment.
- Treatment Setup: Apply image-guided couch shifts, assess anatomical alignment, and identify discrepancies.
- Patient Counseling: Provide daily reminders, collect feedback on hydration tolerance, and assist in protocol adjustments.

12.2. Medical Physicists

Core functions:

- Treatment Planning: Evaluate CT scans for bladder/rectum filling and ensure OAR constraints are achievable.
- Dosimetric Review: Monitor DVH changes due to anatomical shifts and determine if replanning is needed.
- Technology Implementation: Lead adaptive workflows, QA checks for scanners, and integration of AI-based tools [3] [7].
- Collaborative Oversight: Coordinate with RTTs and oncologists to enforce consistency and address deviations promptly.

As outlined in Table 3, the collaborative workflow between RTTs and physicists ensures consistent bladder volume assessment and setup verification.

Table 3. Functional Roles of Radiotherapy Technologists (RTTs) and physicists.

Function	RTTs	Physicists
Pre-treatment hydration checks	✅	🔄

Continued

Bladder volume measurement	✅	🔁 (QA)
Treatment setup and verification	✅	🔁 (image review)
Plan quality and adaptation	🔁	✅
QA of bladder scanning tools	🔁	✅

12.3. Integration into Clinical Practice in Bangladesh

In lower-resource settings, task-sharing and collaborative workflows are vital. Training RTTs in basic bladder volume scanning, supported by physics-led planning and review, can:

- Reduce dependency on expensive adaptive systems.
- Improve protocol adherence.
- Shorten setup times without compromising accuracy.

Emphasizing their collaborative role improves not only technical quality but also patient-centered care and safety.

13. Conclusion

This study demonstrates that maintaining consistent bladder filling in prostate cancer radiotherapy is essential for achieving optimal dosimetric accuracy, minimizing radiation exposure to organs-at-risk (OARs), and improving both biochemical control and toxicity outcomes. Patients with stable bladder volumes during treatment experienced significantly lower setup variability, reduced rectal and bowel radiation doses, and fewer treatment-related complications. Given the anatomical proximity of the bladder, rectum, and prostate, even small variations in bladder volume can significantly alter target geometry. Our findings reinforce the mechanistic understanding that bladder distension stabilizes prostate position, reduces exposure of the rectum and bowel, and enhances the precision of dose delivery. In the context of **Bangladesh's healthcare environment**, where access to advanced imaging, adaptive radiotherapy (ART), and automated planning tools may be limited, the following practical recommendations can significantly improve prostate radiotherapy outcomes.

14. Clinical Recommendations

14.1. Standardized Bladder Preparation Protocols

- Instruct patients to drink 500 - 1000 mL of water 30 - 45 minutes before each session.
- Establish written guidelines and visual aids in Bengali to enhance patient understanding and compliance.

14.2. Pre-Treatment Bladder Scanning

- Use affordable portable ultrasound devices (e.g., Bladder Scan BVI 9400) to assess bladder volume immediately before each session.
- Train radiation technologists to standardize measurement procedures and re-

duce variability.

14.3. Education and Patient Engagement

- Develop **pre-treatment counseling sessions** focused on bladder preparation and fluid intake timing.
- Encourage **self-monitoring tools**, such as water intake logs and urination diaries [2].

14.4. Team-Based Implementation

- Foster collaboration between oncologists, physicists, and technologists to integrate bladder checks into routine QA workflows.
- Assign a designated team member to oversee hydration compliance during treatment weeks.

14.5. Future Directions

To further enhance treatment quality and reduce variability in outcomes, particularly in resource-constrained settings, the following strategies are recommended.

14.6. Local Prospective Studies

Conduct multi-center trials in Bangladesh to validate bladder filling protocols across diverse hospital settings.

14.7. Custom Hydration Algorithms

Develop patient-specific bladder management plans based on individual bladder capacity and tolerance.

14.8. Low-Cost Imaging Solutions

Evaluate mobile-based or point-of-care imaging tools for real-time bladder volume verification.

14.9. Integration of AI Tools

Explore artificial intelligence applications to automate contouring, predict bladder motion, and guide adaptive workflows, even with limited hardware resources.

14.10. Policy and Training Modules

Include bladder management best practices in national oncology training programs and radiotherapy technician certification curricula.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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