2026 JOINT AAPM | COMP MEETING
JULY 19–22 | VANCOUVER, BC

Limited Benefit of Same-Day Adaptive Planning in CyberKnife Prostate SBRT with Real-Time Fiducial Tracking

Hao Chen PhD, Xiaohu Mo MS, Simeng Suy PhD, Tianyu Zhao PhD, Sean Collins MD-PhD
[1]Morsani College of Medicine | USF Health, [2]Tampa General Hospital

USF Health
TGH Tampa General

Abstract

Purpose: Prostate stereotactic body radiation therapy (SBRT) is a well-established treatment for localized prostate cancer, achieving excellent tumor control through the delivery of high radiation doses in a small number of fractions. Owing to the prostate's low α/β ratio, SBRT offers favorable radiobiological advantages while maintaining low rates of severe genitourinary (GU) and gastrointestinal (GI) toxicity. However, the highly conformal nature of SBRT and its small planning target volume (PTV) margins require accurate motion management. Although CyberKnife provides continuous fiducial-based real-time tracking to compensate for intrafraction prostate motion, the dosimetric value of same-day adaptive replanning remains unclear.
Methods: This prospective dosimetric study will include at least 25 patients with localized prostate cancer treated with CyberKnife SBRT and fiducial-based tracking. Each patient will undergo a planning CT and up to five daily pre-treatment CT scans. The original treatment plan will be generated on the planning CT and recalculated on each daily CT following rigid fiducial registration, simulating delivered dose under a non-adaptive workflow. Daily contours of target volumes and organs at risk, including the rectum, bladder, and urethra, will be delineated. Dose–volume histogram (DVH) parameters and normal tissue complication probability (NTCP) estimates will be analyzed and compared.
Results: Preliminary dosimetric analysis indicates that target coverage is consistently maintained despite day-to-day anatomical variation. Variations in bladder and rectal filling result in only minor changes to dose distribution, with minimal impact on PTV coverage, hotspot location, OAR dose metrics, or NTCP estimates.
Conclusion: CyberKnife real-time fiducial tracking provides effective motion management for prostate SBRT. The findings suggest that routine same-day adaptive replanning may offer limited additional dosimetric benefit, supporting the feasibility of an efficient non-adaptive treatment approach.

Introduction

Stereotactic body radiation therapy (SBRT) has become a widely accepted treatment modality for localized prostate cancer because of its ability to deliver highly conformal, ablative radiation doses in only five fractions. The favorable radiobiology of prostate cancer, characterized by a low α/β ratio, contributes to excellent long-term disease control and low rates of severe toxicity. To safely implement SBRT, precise target localization is critical because treatment is delivered with narrow margins and steep dose gradients near the rectum, bladder, and urethra. Although image-guided radiotherapy effectively corrects interfraction positioning uncertainties, prostate motion during treatment can compromise dosimetric accuracy. CyberKnife addresses this challenge through continuous fiducial-based real-time tracking. The present study investigates whether same-day adaptive replanning provides meaningful dosimetric improvements beyond those already achieved with real-time motion tracking.

Methods and Materials

A total of 23 patients with localized prostate cancer eligible for CyberKnife SBRT will be enrolled. Inclusion criteria include suitability for fiducial-based tracking and the ability to undergo repeated CT imaging during treatment. Patients with substantial CT image degradation from metal artifacts, previous pelvic radiotherapy, or implanted devices incompatible with CT-based planning will be excluded.

Each patient will undergo six CT scans during the treatment course. A planning CT (PlanCT) will be acquired before treatment and used for target delineation and treatment planning. Subsequently, five daily CT scans (CT_1–CT_5) will be obtained immediately before each treatment fraction using the same imaging protocol. Treatment will be prescribed to deliver 36.25 Gy to the CTV and PTV, 39 Gy to the GTV, and 42.5 Gy to the dominant intraprostatic lesion (DIL) in five fractions.

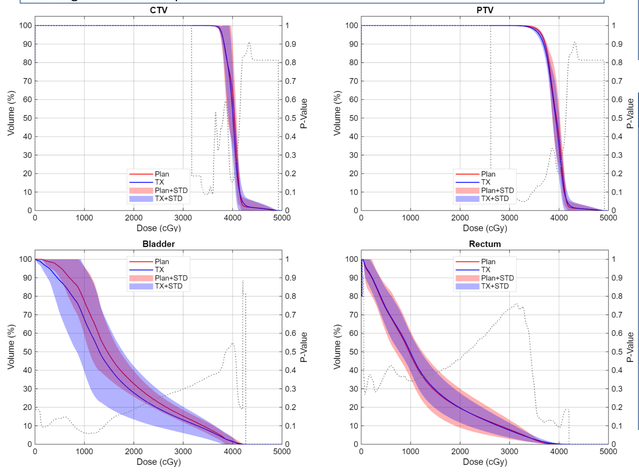
The reference treatment plan will be generated in the Precision Treatment Planning System (Accuray Precision, Madison, WI) following institutional CyberKnife prostate SBRT guidelines, including 3–5 mm planning margins and fiducial-based real-time tracking. For each treatment fraction, the daily CT will be rigidly registered to PlanCT using implanted fiducial markers. Target structures will be propagated and modified when required, while the rectum, bladder, urethra, and other relevant organs at risk (OARs) will be recontoured on every daily CT by trained personnel and reviewed by the attending radiation oncologist. Clinical and anatomical parameters, including target position shifts, rectal and bladder volume changes, and organ deformation, will also be recorded.

To estimate the actual delivered dose in a non-adaptive workflow, the original treatment plan, including beam geometries, monitor units, and optimization settings, will be recalculated on each daily CT dataset. Fraction-specific dose distributions and cumulative delivered doses will then be generated for each patient.

All original and recalculated plans will be exported to the Eclipse Treatment Planning System (Varian Medical Systems, Palo Alto, CA, USA) for detailed dosimetric evaluation. Dose–volume histogram (DVH) parameters will be extracted for target volumes and OARs, including PTV coverage, conformity, homogeneity, maximum and mean doses, and relevant dose-volume constraints. An in-house MATLAB program will be used to automate DVH comparisons, calculate cumulative dose metrics, and perform statistical analyses. Paired statistical tests will be applied to compare planned and delivered dose parameters, with significance assessed using p-values less than 0.05. Correlation analyses will be performed to identify anatomical factors, such as rectal distention, bladder filling variation, and prostate displacement, that are associated with clinically meaningful dosimetric deviations and may indicate situations where adaptive planning could provide a measurable benefit.

Results

Figures present the dose–volume histograms (DVHs) comparing the original treatment plan (Plan) with the recalculated delivered doses from five daily treatment CT scans (TX). Solid lines represent the mean DVHs for the planned and delivered doses, while the shaded regions indicate the corresponding standard deviations. The p-value curves assess statistical differences between the planned and delivered DVHs across the entire dose range.
The upper panels display DVHs for the clinical target volume (CTV) and planning target volume (PTV). For the CTV, dose coverage remained highly consistent throughout all evaluated fractions, with minimal variation in D95% and substantial overlap between the planned and delivered DVH curves. Similarly, PTV coverage was well maintained across treatment sessions. Although slight deviations were observed in the high-dose region of the PTV DVHs, these differences remained within clinically acceptable limits and did not compromise prescription dose coverage. Across the entire DVH range, p-values remained greater than 0.05, indicating no statistically significant differences between planned and delivered target doses.
The lower panels show DVHs for the bladder and rectum. Despite daily variations in organ filling, only modest fluctuations in dose distributions were observed. Overall, OAR dose metrics remained stable across fractions, with delivered doses closely matching the original treatment plan.



Discussion

The present analysis demonstrates excellent agreement between planned and delivered dose distributions for both target volumes and organs at risk during CyberKnife prostate radiotherapy. The strong overlap of the CTV DVHs and the minimal variation in D95% suggest that target coverage was consistently maintained throughout treatment. Likewise, the stable PTV DVHs indicate that daily anatomical changes had only a limited impact on the delivered dose distribution. The absence of statistically significant differences across the entire DVH curves ($p > 0.05$) further supports the robustness of dose delivery relative to the original treatment plan.
These findings highlight the effectiveness of fiducial-based real-time tracking in compensating for interfractional and intrafractional prostate motion. Because the CyberKnife system continuously localizes the target during treatment, it can correct for positional changes and maintain dose conformity even when patient anatomy varies between treatment sessions. As a result, the intended target coverage is preserved without requiring substantial increases in treatment margins.
The stability of bladder and rectal dose distributions is also clinically important. Daily changes in bladder and rectal filling are common sources of geometric uncertainty in prostate radiotherapy and can alter the spatial relationship between the prostate and surrounding organs. In this study, however, these anatomical variations produced only minor changes in OAR DVHs. The limited dosimetric impact suggests that real-time target tracking effectively mitigates the consequences of prostate displacement relative to adjacent normal tissues.

Conclusions

Our findings demonstrate that prostate SBRT delivered with CyberKnife real-time fiducial tracking maintains robust dosimetric performance despite intrafraction uncertainties, including patient motion and variations in rectal and bowel filling. Continuous target monitoring and automatic motion correction effectively preserve target coverage and organ-at-risk sparing throughout treatment delivery, minimizing the impact of day-to-day anatomical changes. Dosimetric analyses revealed only minor variations in target and normal tissue dose metrics, with no clinically meaningful differences observed. These results suggest that routine same-day adaptive replanning may provide limited additional clinical or dosimetric benefit when comprehensive real-time tracking is already incorporated into the treatment workflow. Eliminating unnecessary adaptive interventions could simplify treatment delivery, reduce planning and treatment times, and improve operational efficiency while maintaining high treatment quality. Overall, the data support the use of a streamlined non-adaptive CyberKnife SBRT workflow, enabling efficient and accurate prostate cancer treatment without compromising target coverage, normal tissue protection, or patient outcomes.

Contact

USF Health Morsani College of Medicine
560 Channelside Dr, Tampa, FL 33602
haoc@usf.edu
608 695 4309

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