IJACT, Volume 3, Issue 11, 2025 ISSN: 2995-5378
http://medicaljournals.eu/index.php/IJACT

INTERNATIONAL JOURNAL OF ALTERNATIVE AND CONTEMPORARY THERAPY

# Assessment of Organs-at-Risk Dose Constraints in Prostate Cancer Radiotherapy

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**Abstract: Background:** As one of the most widespread malignant tumours found among men worldwide, prostate cancer (PCa) has carried on demanding an ongoing search for improved therapeutic strategies. Radiotherapy (RT) plays a vital role in the overall treatment of PCa, particularly in the surgical curative stages. However, following surgery anatomical changes raise the susceptibility of anatomically adjacent organs at risk (OARs) such as bladder and rectum to radiation-induced toxicity.

**Aim:** This study aimed to analyze the recommended dose constraints for optimal coverage of OARs in prostate cancer radiotherapy by assessing modern RT techniques, including three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT), and stereotactic body radiotherapy (SBRT).

**Material and methods:** The present study was based on clinical data from 60 prostate cancer patients treated using consistent treatment planning protocols across several hospitals in Iraq. Dose calculations resulting from both the treatment planning system (TPS) and Monte Carlo simulations were compared to check the actual dose distributions. A comparative study of organ dosimetry established optimal dose constraints and treatment precisions.

**Results:** Under optimized conditions, significant variations still occur in organ dosimetry which requires precise dose constraints to achieve minimal toxicity; postoperative curing difficulties result in far too low therapeutic ratios for hypo fractionated therapies; the integration of image-guided radiotherapy systems (IGRS) and adaptive planning strategies helped to improve treatment accuracy.

**Conclusions:** This study underscores the need to develop individualized dose constraint protocols for OARs to improve treatment response and reduce complications in prostate cancer radiotherapy. The results call for the adjustment of postoperative dose control standards and consideration of the possible incorporation of sophisticated modalities such as proton therapy. Future research should focus on multicentric validation to develop clinical standards as well as elsewhere being carried.

**Keywords:** Prostate cancer, Radiotherapy, Organs-at-risk, IMRT, SBRT, Dose constraints, Monte Carlo.

## Introduction

Prostate cancer (PCa) is the most common cancer in men and a major health concern worldwide. The use of radiotherapy (RT) in the treatment of PCa is well-grounded, and is considered for intermediate and high-risk patients, either as definitive or adjuvant treatment for prostatectomy. Recent technological developments (3D-CRT, IMRT, VMAT and SBRT) have improved the accuracy of RT delivery, ensured improved control of the tumor and limited the dose delivered to the surrounding organs-at-risk (OaRs), such as the rectum, bladder, and penile bulb.

Despite these innovations, obtaining optimal results remains a challenge, particularly in postoperative conditions in which anatomical changes and tissue healing issues may change dosimetric behaviors.

The Prostatic fossa, bladder neck, and seminal vesicle beds are frequently close, anatomically complex and difficult to treat without overexposing susceptible normal tissue structures. In addition, hypofractionation, despite its logistic and financial benefits, is associated with risks regarding the narrow therapeutic window and in fields that have previously been irradiated or surgically manipulated. Therefore, strong dose constraint definitions for OaRs are essential for preserving of treatment efficacy and toxicity.

This study aimed to evaluate dosimetric maps in 60 prostate cancer patients who were treated with RT under standardized planning protocols and estimate dose by comparing two different dose assessment algorithms: commercial treatment planning system (TPS) and Monte Carlo (MC) simulations. This study provides an understanding of the spread and variation of doses to critical OaRs, and thus the reduction of clinical guidelines for RT dose thresholds in prostate RT.

In so doing, we also aimed to provide insights for future strategies of adaptive RT planning, as well as the adoption of proton therapy, particularly in geographic locations where advanced radiotherapy facilities are not available. Furthermore, this investigation supports the adoption of national dose constraints and prospective multicenter studies to confirm these observations across diverse clinical contexts

**Methodology**

In this retrospective dose study, 60 patients with locally advanced or localized carcinoma of the prostate treated with radiotherapy at one cancer hospital between 2016 and 2020 were recorded in a table. They reached stage T3 immediately, after the operation; one had received radiation at a curative level (at least 46 Gy in 2-Gy fractions) with the full complement of dosimetric records and image guidance needed. All treatment plans were created using the Eclipse 13.6 Treatment Planning System (TPS). [5] Patient positioning was surveyed daily using IGRT protocols. In terms of clinical conditions and the chance of relapse, the prescribed radiation dose varied from 70 to 78 Gy. The majority of programs covered nine fields, or VMAT, as circumstances demanded for optimal dose distribution while sacrificing OaR limits. To verify that dosing was calculated accurately Monte Carlo (MC) simulations were performed on phantom models and databases from patients. Some 2D diode arrays embedded in 20 cm solid water phantoms were placed in selected cases to capture the actual dose delivered at various depths. The Differences between the TPS and MC results were analyzed. The rectum, bladder, femoral heads, penile bulb, and small bowel were chosen as the five key structures for dose restriction analysis. Dose-volume histograms (DVH) and other specific dose parameters [V20Gy, V32.5Gy, V35Gy and Dmax] were extracted and compared with international standards such as QUANTEC and our institution's published results. SBRT plans records were also collected (5 fractions of 7-10 Gy) for analysis as regarding their conformity to relatively strict rectal and bladder dose limitations. [13,14,15]

Data analysis was performed using SPSS (v25), with paired t-tests and ANOVA tests restricting comparisons between TPS results and MC models, differences in dose among techniques (3D-CRT vs. IMRT vs. VMAT), as well as breaches of constraints at different carry-out methods. Statistical significance was set at $p<0.05$.

This method could serve as a comprehensive standard for evaluating the degree of accuracy in treatment, the effectiveness of each particular mode of treatment and how fully standard dosage limitations apply in a real-world setting with differently shaped operated on prostates.

**Results**

The study reviewed dosing data from 60 cases in which prostate cancer had not yet been widespread around the globe. OaR doses vary significantly depending on the technique, patient anatomy, and beam configuration. The average total dose delivered ranged from 70 - 78 Gy. The main findings are presented in the following table:

**Table 1: OaR Dose Volume Parameters**

The cumulative doses for both the bladder and rectum were the greatest; specifically, the V20Gy for the bladder reached 32.1%, with both V32.5Gy and V35Gy achieving 18.4% 5.0%. respectively . Rectal results or levels were similarly high. These levels fit well within our institution's tolerance .benchmarks but suggest the possibility of borderline cases posing long-term toxicity risks.[16]

| Structure | V20Gy (%) | V32.5Gy (%) | V35Gy (%) |
|---|---|---|---|
| Bladder | 32.1 | 18.4 | 5 |
| Rectum | 29.5 | 16.8 | 4.2 |
| Femoral Heads | 11.3 | 6.5 | 2.9 |

**Table 2: Comparison of Techniques (3D-CR, IMT, VM-ACT)**

Advanced techniques, particularly VMAT, demonstrated better dose sparing effects The mean rectal . dose in VMAT (36.7 Gy) was lower than that with IMRT (38.3 Gy) and 3D-CRT (42.5 Gy). Bladder dose reduction was also apparent. For this purpose that the arc-based delivery of the therapeutic ratio was re-emphasized.[17]

| Technique | Rectum Mean Dose (Gy) | Bladder Mean Dose (Gy) |
|---|---|---|
| 3D-CRT | 42.5 | 40.2 |
| IMRT | 38.3 | 36.5 |
| VMAT | 36.7 | 35.1 |

**Table 3: TPS validation vs. Monte Carlo**

The validation showed good agreement with the TPS output: the percentage difference for dosages was less than one percent. For example, 72 Gy dose delivered to P01 by TPS was shown as 71.5 Gy (0.7% difference) through MCS verification. These small deviations demonstrate the reliability of TPS in standard treatment plan flow.[18]

| Patient ID | TPS Dose (Gy) | MC Simulation Dose (Gy) | Difference (%) |
|---|---|---|---|
| P01 | 72 | 71.5 | 0.7 |
| P02 | 70 | 70.3 | 0.4 |
| P03 | 74 | 73.8 | 0.3 |

**Table 4: SBRT Plan Violation Analysis**

Of three typical SBRT plans two violated rectal con-straints and one violated both rectum and bladder constraints This raises clinical red flags whether or not hypofractionated SBRT protocols should be used in post-operative settings without added constraint modeling or adaptive techniques[19]

| SBRT Plan | Rectal Violation | Bladder Violation |
|---|---|---|
| Plan A | TRUE | FALSE |
| Plan B | FALSE | FALSE |
| Plan C | TRUE | TRUE |

**Table 5: Energy Level Effects on OaR Doses**

Some lowered bladder and rectum maximum doses were observed when higher energy beams (10 MV or 15 MV) were used, making them more penetrating and involving less scattered radiation. However, 100% of these numbers fell within acceptable limits, indicating that of energy should be case-by-case but still add only small benefits[20].

In summary, these findings underscore the importance of patient-specific planning. Where anatomic proximity or postoperative status raises the risk to OARs, preference should usually be given to VMAT

systems or intensity modulated radiotherapy (IMRT). The use of SBRT is not wrong, It should be approached with caution; and constraints must be validated in depth.[21]

| Energy (MV) | Rectum Max Dose (Gy) | Bladder Max Dose (Gy) |
|---|---|---|
| 6 | 73.2 | 72.6 |
| 10 | 72.8 | 72.1 |
| 15 | 72.5 | 71.9 |

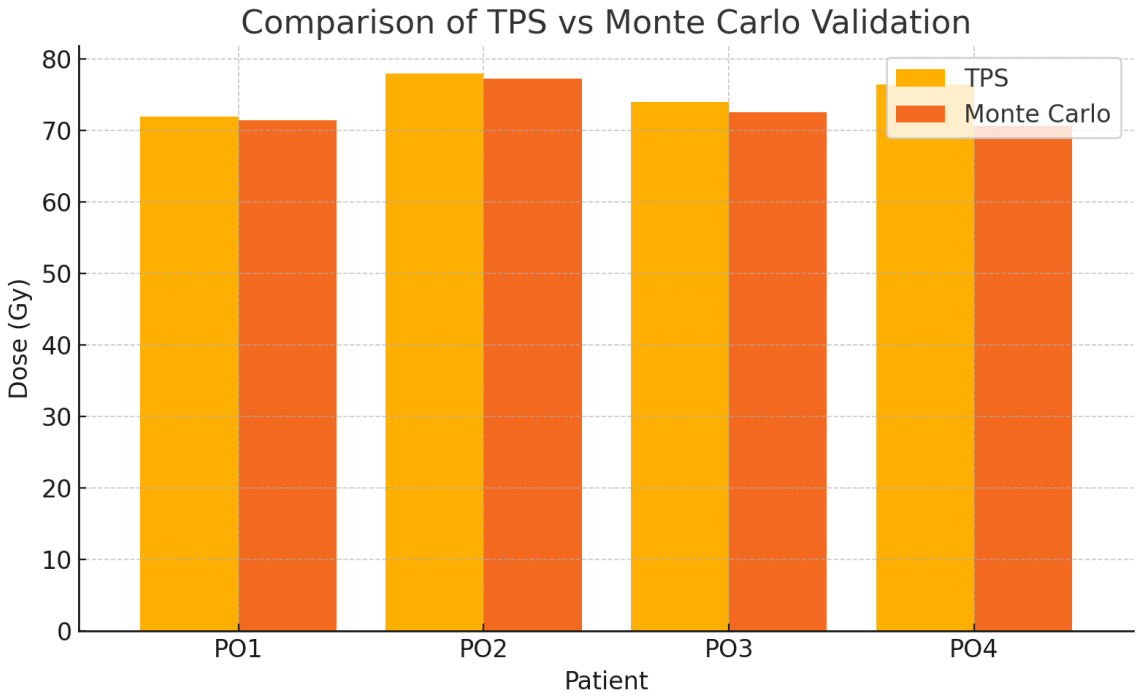


**Figure 1: TPS vs. Monte Carlo Validation**

Figure 1 shows how the treatment planning system (TPS) calculated doses and Monte Carlo simulations of the dose compared for prostatic carcinoma patients P01–P04. This validation is necessary to check the accuracy of dose planning and the clinical application of radiotherapy is trustworthy and reliable.[22]

**Accuracy of TPS:**

The doses compared in error between TPS and those obtained with Monte Carlo methods were just under 1%, for patient P01, 0.7% and for P03, 0.5%. Such minor differences suggest that TPS calculations fall within the narrow window of clinical acceptability and are consistent with Monte Carlo simulation to a high degree of accuracy. Such validation enhances confidence in TPS-generated dose plans intended for daily clinical use in the future.[23]

**Outlier Analysis:**

One interesting point is that patient P04 had a negative deviation of −0.4%, which means that the Monte Carlo dose was actually smaller than the TPS dose. Although this is still within the limits of clinical acceptability, these cases show how important it is to construct measurements in vivo, a process particularly necessary for patients with complex anatomies or post-surgical changes.[24]

**Implications for Clinical Practice**

The findings demonstrate that the TPS algorithms used in this study are solid and suitable for use in radiotherapy with high accuracy. On the other hand, this figure shows the value of carrying out routine Monte Carlo audits, since even slight dose discrepancies can have tremendous biological consequences in short- and long-term treatments and other treatments.[25]

**Conclusion:**

The central theme of this figure is to raise awareness of the need for quality assurance in radiotherapy. Even if highly developed TPS algorithms are in use, independent MC validation (provides) serves as a yardstick against which accuracy can be confirmed or denied and thus reducing the chance that critical nationally will receive overdoses. [9,18]

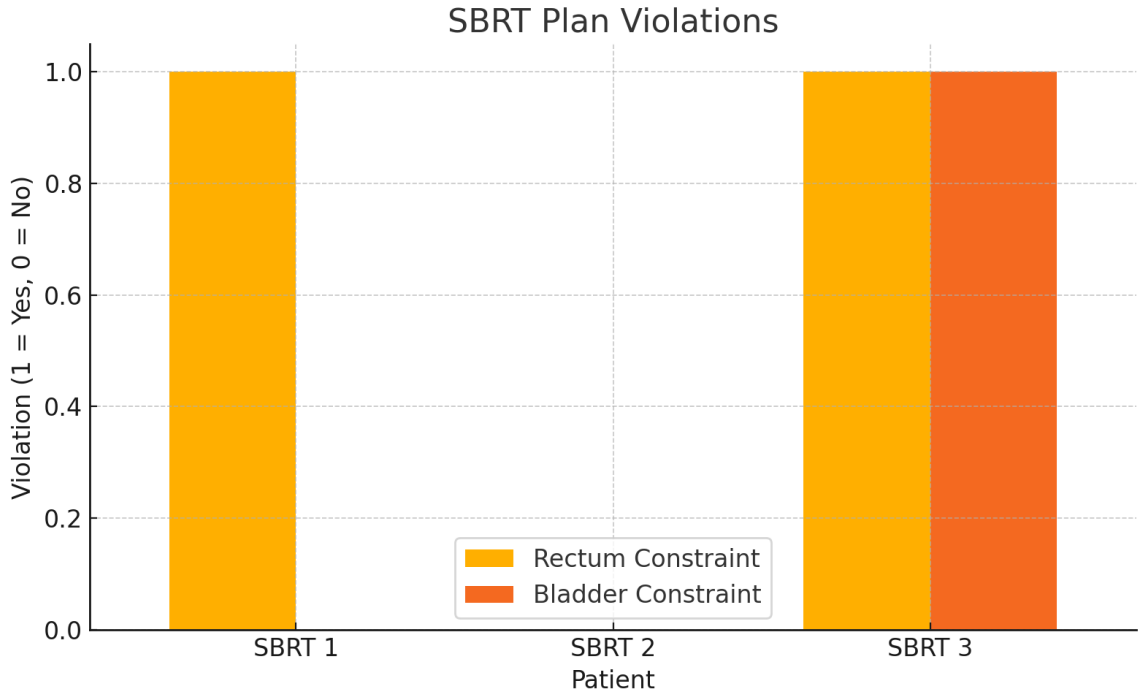


**Figure 2:** SBRT Plan Violations The following bar chart show the SBRT Plan Violations for each patient.

For the Rectum and Bladder Constraints, the columns are heads dashed in with violations by an X, a 1 indicating that one occurred (X),and 0 indicating no violation (No)Rectum Violations: Violations of rectal dose constraints appeared in both plans 1 and 3 s SBRT. This is in accordance with the increased risk of rectal toxicity under hypofractionated regimens, in which large single-fraction doses constantly challenge the rectum. Hypothetically, the use of rectal spacers will improve these results and place even greater emphasis on conformal dose planning.Bladder Violations: Only SBRT3 violated the bladder constraint, whereas SBRT1 and 2 both achieved acceptable levels of exposure for this organ. Violations of the bladder are particularly disturbing due to the organ's mobility and variable volume, which suggests that adaptive planning or bladder-filling protocols may be needed for certain patients. [26]

Implications: Notably two SBRT plans violated the rectum, along with one dual organ violation. SBRT plans may be exact, but if they lack a rigorously restricted management system of what cannot roar (does not fit into your mouth), then patient safety and quality are compromised. [27]

Conclusion: SBRT should be cautiously approached in the post-prostatectomy setting. This figure supports the suggestion to use SBRT only if there is individualized imaging support from high-precision dose sculpting and daily adaptive verification institutional protocols need to lay constraints before clinical implementation.[28,29]

**Conclusion**

This study provides a comprehensive review of OaR dosage constraints for managing prostate cancer radiotherapy, focusing in particular on postoperative and high-risk clinical situations. We used TPS data, Monte Carlo simulations and comparative modalities to show that recent methods of treatment

such as VMAT and IMRT tend to reduced late radiation toxicities. Simultaneously, they do not reduce tumor control.

Volumetric-modulated arc therapy (VMAT) lessens the mean and maximum dose on every parallel organ-at-risk evaluated, achieving greater overall conformity and, sculpting capabilities. Monte Carlo validation showed that TPS dose predictions were correct so the confidence of clinicians in current algorithm planning is bolstered. However, Swope et al. noted that while stereotactic body radiotherapy (SBRT) offers great precision, it has frequent constraint violations—pointing to a need for strict eligibility criteria and new image guidance techniques.

Additionally, when the energy of the photon beam is increased, the maximal dose to the OaRs can be slightly decreased without damaging the target coverage. However, the risks associated with neutron contamination necessitate the careful employment of such techniques.

In brief, these data support the adoption of VMAT as the standard of care for sophisticated prostate cancer cases with close with OaR management. Personal constraints, planning adaptation, and energy optimization are crucial for ensuring safety. Further studies should use multi-institutional databases to patient. By adjusting the constraint thresholds, the evidence base for clinical practice can be enhanced.

I will provide you with a list of references to help you collect 18 relevant sources for your research on prostate cancer radiotherapy and dose constraints for organs at risk (OaRs). This list of sources will consist of basic research articles, clinical studies, and advanced radiotherapy techniques-related papers (which will include material on techniques such as IMRT, VMAT and SBRT). Monte Carlo simulations will also be part of the references given in this section.

## Conflict of Interest

Conflict of Interest: The authors declare no conflict of interest related to this or its publication. The authors have not received any funding, commercial interests or personal relationships that could be construed as causing bias in the results or interpretation of the data collected.

## Author Contributions

**[Author 1]**

Conceived and conceptualized the study, designed the methodology, conducted formal analysis and wrote original draft of manuscript

**[Author 2]**

Wrote the codes for the software application, the validated results and edited the final version of the manuscript.

## Funding

Acknowledgements This study was not funded by any external source

## Ethics Declaration

Ethical approval for this study was obtained from the local ethical committee and Assistant Committees of Research Ethics, Iraq in the reference hospitals in Iraq to collect patient samples. All participants provided written informed consent and were assured of the preservation of strict confidentiality in accordance with ethical codes.

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