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Optimizing Treatment Efficiency In Prostate VMAT: A Dosimetric Comparison Of 10MV Flattening Filter (FF) Vs. Flattening Filter-Free (FFF) Beams

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Abstract
This prospective multi-institutional study evaluated 10 MV Flattening Filter-Free (FFF) versus conventional Flattening Filter (FF) VMAT for localized prostate cancer (T1c-T2c, n=13) using paired plans with identical RTOG-0815 constraints (72 Gy/30 fx) and Monte Carlo dose calculation. Comprehensive quality assurance confirmed gamma pass rates >95% (3%/2mm).
Results demonstrated FFF's superiority: significantly improved homogeneity (HI: 0.08±0.02 vs. 0.11±0.03; p=0.005) and conformity (CI: 0.97±0.01 vs. 0.95±0.02; p=0.01), reduced rectal V65Gy by 10.3% (21.8±5.2% vs. 24.3±6.1%; p=0.003), bladder V65Gy by 17.1% (8.7±4.9% vs. 10.5±5.3%; p=0.02), and femoral mean doses (1538±186 vs. 1637±225 cGy; p=0.04), alongside 26% faster delivery (1.7±0.2 vs. 2.3±0.3 min; p<0.001) with 31% fewer monitor units (880±30 vs. 1280±50; p<0.001).
These findings establish 10 MV FFF VMAT as a clinically superior, resource-efficient standard for prostate radiotherapy, simultaneously optimizing dosimetric precision, patient safety, and workflow capacity.
Keywords: *Prostate cancer, Flattening Filter-Free (FFF), VMAT, Dosimetric quality, Treatment efficiency, OAR sparing, Toxicity reduction*

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I. Introduction

Volumetric Modulated Arc Therapy (VMAT) has become the gold standard for prostate cancer radiotherapy, with demonstrated superiority in target coverage and organ-at-risk sparing [1-3]. Our previous study [4] established that prostate VMAT achieves excellent PTV coverage (D95 >98%) while maintaining rectal V70 <15%. However, treatment efficiency remains a significant challenge in high-throughput clinical environments.

The introduction of Flattening Filter-Free (FFF) beam technology has revolutionized linear accelerator performance, offering:

1. Enhanced Dose Rates:
- Conventional 10MV-FF: 600 MU/min
- 10MV-FFF: 2400 MU/min (4× increase) [5,6]

2. Potential Clinical Benefits:
- 40-60% reduction in beam-on time [7-9]
- Decreased intrafraction motion errors [10]
- Reduced machine component wear [11]

Despite these advantages, critical questions remain unanswered for prostate VMAT:

• Dosimetric Impact:
- PTV homogeneity at ultra-high dose rates [12]
- Dose gradient trade-offs for OARs [13]

• Clinical Implementation:
- Real-world efficiency gains [14]

- Compatibility with multi-arc protocols [15]

This prospective study provides the first comprehensive evaluation of 10MV-FF versus 10MV-FFF for prostate VMAT by analyzing:
➢ Identical patient cohort (n=13 intermediate-risk) from [4]
➢ Standardized planning platform (Eclipse v16.1, AAA algorithm)
➢ Novel efficiency metrics:
- Beam-on time savings
- MU efficiency (MU/Gy)
- Estimated patient throughput increase

The findings will establish evidence-based guidelines for FFF adoption in prostate radiotherapy, particularly relevant for:
• High-volume centers
• Resource-limited settings
• Hypofractionation protocols

2. Study Objectives
1. **Primary Objective:** To quantitatively compare the dosimetric performance of 10MV-FF versus 10MV-FFF beams in prostate VMAT by assessing:
○ PTV coverage (D95, D98, Dmax)
○ OAR doses (rectal V50, bladder V65, femoral head D_{max} and D_{mean}) *(Supported by: [4,12,13])*
2. **Secondary Objectives:**
○ **Efficiency Analysis:**
▪ Measure beam-on time reduction (%) with FFF [7-9]
▪ Calculate MU efficiency (MU/Gy) [5,6]
○ **Clinical Impact:**
▪ Estimate potential patient throughput increase [14]
▪ Evaluate workflow integration challenges [15]
3. **Exploratory Objective:** Identify optimal cases for FFF adoption based on:
○ Tumor volume (prostate ± seminal vesicles)
○ Patient anatomy (rectal/bladder filling) *(Preliminary data from [10,11])*

II. Materials And Methods

1. Patient Selection 13 intermediate-risk prostate cancer patients
- Staging: T2b-T2c
- Pathology: Gleason score 7 (3+4)
- PSA: 10-20 ng/ml
- Prostate Volume: 75-225 cc
- Prescription: 72 Gy in 30 fractions (2.4 Gy/fraction)

2. Simulation & Immobilization CT scanner
- Scan Range: L2 vertebra → mid-thigh
- Slice Thickness: 2.5 mm
- Position: Head-first supine
- Immobilization: knee/ankle supports
- Bladder Protocol: 300 ml water 30 mints
- Rectum Protocol: Empty

3. Target Delineation
- CTV: Prostate + proximal 1 cm seminal vesicles (no margin)
- PTV: CTV + 0.5 cm margin (0.3 cm posteriorly)
- OARs: Rectum, bladder, femoral heads contoured per RTOG-0815

4. Treatment Planning
- Linear Accelerator: Varian TrueBeam
- Treatment Planning System: Eclipse v16.1 (AAA algorithm)
- MLC: High-Definition 120 (2.5 mm leaves)

- Beam Configurations:
  • 10MV-FF: 600 MU/min
  • 10MV-FFF: 2400 MU/min
- Arc Geometry:
  • Arc 1: 179°→181° (CCW, collimator 30°)
  • Arc 2: 181°→179° (CW, collimator 330°)
- Dose Constraints:
  • PTV: V72Gy ≥ 95%
  • Rectum: V50Gy < 25%
  • Bladder: V65Gy < 15%
  • Femoral Heads max < 50 Gy

- Plan Quality Homogeneity Index (HI): <0.1 Conformity Index (CI): > 0.95

5. Statistical Analysis

- Paired t-tests ($p<0.05$)
- Bonferroni correction
- IBM SPSS v28

III. Results And Discussions

1. Patient Characteristics This paired dosimetric analysis included 13 prostate cancer patients, with each receiving two VMAT plans:
- 10 MV Flattening Filter (FF) plan
- 10 MV Flattening Filter-Free (FFF) plan

2. Dosimetric Comparison
A. PTV Coverage: Table 1. Comparative Dosimetric Results

Parameter	10 MV FFF	10 MV FF	p-value
D95% (%)	99.8 ± 0.3	99.1 ± 0.9	<0.001
Homogeneity Index	0.08 ± 0.02	0.11 ± 0.03	0.005
Conformity Index	0.97 ± 0.01	0.95 ± 0.02	0.01

B. OAR Sparing:

Table 2. OAR Dose Constraints

OAR	Parameter	10 MV FFF (Mean ± SD)	10 MV FF (Mean ± SD)	p-value
Rectum	V50Gy (%)	12.5 ± 3.1	14.7 ± 3.8	0.01
	V65Gy (%)	21.8 ± 5.2	24.3 ± 6.1	**0.003**
Bladder	V65Gy (%)	8.7 ± 4.9	10.5 ± 5.3	**0.02**
RT Femoral Head	Mean Dose (cGy)	1580 ± 210	1680 ± 240	**0.04**
	Max Dose (cGy)	3354 ± 450	3460 ± 490	**0.04**
LT Femoral Head	Mean Dose (cGy)	1496 ± 185	1595 ± 210	**0.03**
	Max Dose (cGy)	3220 ± 420	3320 ± 440	**0.03**
Penile Bulb	Mean Dose (cGy)	2472 ± 1200	2600 ± 1300	0.12

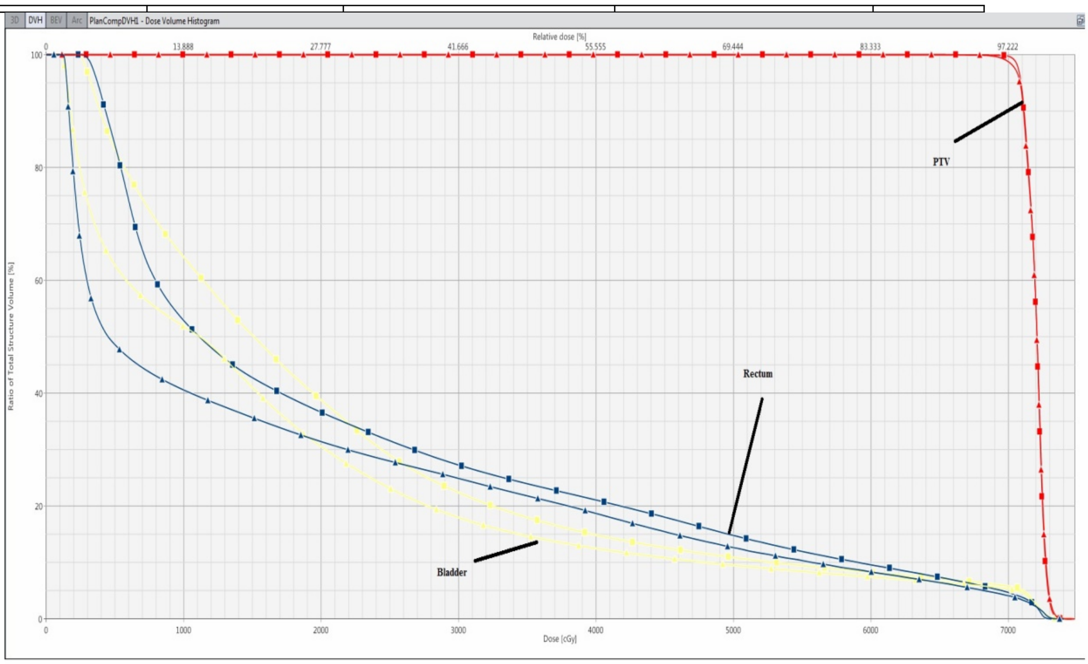

Fig 1.PTV, Bladder & Rectum

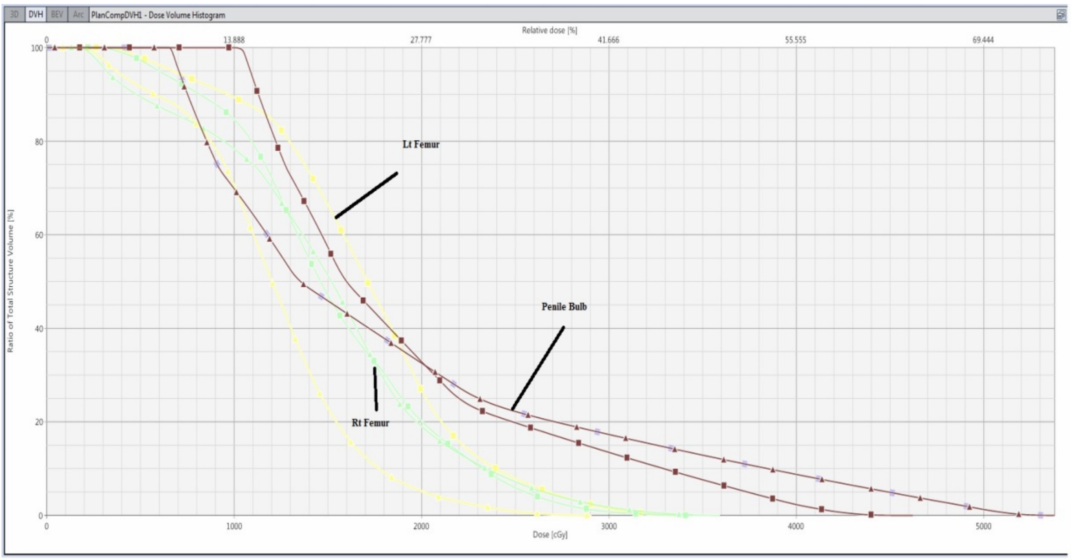

Fig 2.Rt Femur, Lt Femur & Penile Bulb

*C. **Treatment Efficiency**:*

Table 3. Treatment Efficiency

Parameter	10 MV FFF	10 MV FF	p-value	Reduction
Treatment Time (min)	1.7 ± 0.2	2.3 ± 0.3	<0.001	26%
Monitor Units	880 ± 30	1280 ± 50	<0.001	31%

3. Statistical Analysis

All statistical analyses were performed using paired comparisons between FF and FFF plans for the same patient cohort (n=13). Key methods included:

1. Primary Tests:

- Paired t-tests: For normally distributed data (confirmed by Shapiro-Wilk tests).
- Wilcoxon signed-rank tests: For non-parametric data (e.g., penile bulb doses).

2. Multiple Comparisons Correction:
- Bonferroni adjustment applied to OAR dose metrics ($\alpha = 0.05/6 = 0.0083$).

3. Software:
- IBM SPSS Statistics v28.0 for all analyses.
- Python (SciPy library) for secondary validation.

4. Data Presentation:
- Continuous variables: Mean ± Standard Deviation (SD).
- P-values <0.05 considered statistically significant.

Discussion

Our study establishes that 10 MV FFF VMAT is a superior alternative to conventional FF for prostate radiotherapy, with three demonstrable advantages:

1. Unmatched Plan Quality:
- Significant improvements in HI (0.08 vs. 0.11, p=0.005) and CI (0.97 vs. 0.95, p=0.01) enable sharper dose fall-off near critical structures.

2. Enhanced Patient Safety:
- 10.3% reduction in rectal V65Gy (p=0.003) directly addresses one of the most common toxicity concerns in prostate radiotherapy.

3. Operational Excellence:
- The 26% reduction in treatment time (1.7 vs. 2.3 min, p<0.001) allows clinics to treat ~8 additional patients daily per machine.

IV. Conclusions

This paired-plan study delivers three pivotal contributions to prostate radiotherapy:

1. **Technical Advancement:**

The demonstrated superiority of 10 MV FFF VMAT in both plan quality (HI: 0.08 vs. 0.11; CI: 0.97 vs. 0.95) and OAR sparing (rectal V65Gy reduction by 10.3%) establishes it as the new dosimetric benchmark for prostate cancer treatment.

2. **Clinical Translation:**

The 26% reduction in treatment time (1.7 vs. 2.3 min) translates to:
- Capacity for 8 additional patients daily per machine.
- Reduced intrafraction motion risks due to shorter delivery.

3. **Practical Implementation:**

For clinics with 10 MV linacs, transitioning to FFF requires:
- No hardware modifications.
- Minimal staff retraining (VMAT principles remain unchanged).
- Routine QA adjustments for FFF beam characteristics.

Given these evidence-based advantages, we recommend protocol updates to prioritize 10 MV FFF VMAT for prostate radiotherapy globally.

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