FOTELP-VOX-GA: Integrating Genetic Algorithms into Monte Carlo Dose Calculation for Prostate Cancer

Filip Andrić[1], Milena Živković[1], Tatjana Miladinović[2], Aleksandar Miladinović[2], Dragana Krstić[1], Ana Krstić[3], Katarina Janković[2], Katarina Krasić[2], Marija Živković Radojević[2,4*], Neda Milosavljević[2,4], Grujić Miloš[2]

[1]University of Kragujevac, Faculty of Science, Kragujevac, Serbia; e-mail: filip.andric@pmf.kg.ac.rs , milena.zivkovic@pmf.kg.ac.rs , dragana.krstic@pmf.kg.ac.rs
[2]University Clinical Center Kragujevac, Centre for Radiation Oncology, Kragujevac, Serbia; e-mail: tanja.miladinovic@uni.kg.ac.rs, miladinovic.al@gmail.com, k.jankovic1991@gmail.com, katarinakrasic@yahoo.com, makizivkovicmarija@gmail.com, neda.milosavljevic@yahoo.com, grujicmilos10@gmail.com
[3]Kvark doo, Kragujevac, Serbia; ana.krstic@kvark.rs
[4]University of Kragujevac, Faculty of Medical Sciences, Department of Clinical Oncology, Kragujevac, Serbia; makizivkovicmarija@gmail.com, neda.milosavljevic@yahoo.com

* *Corresponding author*

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Abstract: Achieving optimal dose distribution is essential in prostate radiotherapy, particularly with hypofractionated regimens. In this study, we present an AI-assisted dose optimisation framework, FOTELP-VOX-GA, integrating Monte Carlo simulation with a Genetic Algorithm. Comparing to a patient-specific VMAT (Volumetric Modulated Arc Therapy) plan, the method yielded dose estimates for the iliac bones, showing lower mean doses (1977.51 cGy) than those calculated by the Eclipse TPS (2092.1 cGy and 2085.3 cGy). The genetic optimization process achieved clinically acceptable deviations (2–10%) from prescribed doses to the tumor and surrounding tissues. These findings highlight the value of FOTELP-VOX-GA in supporting safe and personalized radiotherapy planning.

Keywords: Radiotherapy optimization, Prostate cancer, FOTELP-VOX-GA

1. Introduction

Prostate cancer is the second most common malignancy in men globally, with radiotherapy serving as a primary curative modality for the disease [1]. The primary goal of modern radiotherapy is to deliver a therapeutically effective dose to the tumor volume while minimizing exposure to surrounding healthy tissues and organs at risk (OARs), such as the bladder, rectum, femoral heads, and iliac bones [2]. Achieving this balance is particularly critical in hypofractionated treatment schemes, where higher doses per fraction increase the risk of toxicity.

Conventional treatment planning systems (TPS), Eclipse, use deterministic algorithms like the Anisotropic Analytical Algorithm (AAA) to compute dose

distributions. These methods are known for their efficiency and precision, even in anatomically heterogeneous areas or complex structures. Monte Carlo (MC) simulations are also widely recognised for their high level of dosimetric accuracy, as they simulate the random behavior of particle transport and interactions within biological tissue [3].

FOTELP-VOX, a voxel-based Monte Carlo platform, has been developed for detailed dose calculation using patient-specific CT data [4]. In this study, we propose an enhanced version of the FOTELP-VOX system, integrated with a Genetic Algorithm (GA), referred to as FOTELP-VOX-GA. The GA serves as an intelligent optimization engine that iteratively adjusts dose distribution parameters to improve conformity and minimize deviations from prescribed doses, particularly in sensitive regions like the iliac bones.

By combining the precision of Monte Carlo simulation with the adaptive power of AI-driven optimization, FOTELP-VOX-GA provides a robust framework for secondary dose verification and personalized treatment planning. This study aims to evaluate its performance in prostate cancer radiotherapy by comparing dose estimates obtained with Eclipse TPS and the proposed AI-enhanced Monte Carlo system.

2. Materials and methods

In this case study, VMAT plan was created using the Eclipse treatment planning system (v16.1, Varian Medical Systems) with the Anisotropic Analytical Algorithm. Two full arcs (6 MV beams, collimator angles 30° and 330°) were delivered on a Vital Beam linear accelerator (Varian) at the Center of Radiation Oncology, University Clinical Center Kragujevac, in 2024. The patient was treated supine, with preparation requiring an empty rectum and full bladder. Clinical target volumes (CTVs) were contoured based on CT scans: CTV1 included the prostate gland and lymph nodes, while CTV2 included the prostate gland only. Planning target volumes (PTVs) were created with a 5 mm margin. Organs at risk (OARs), including the bladder, rectum, anal canal, femoral heads, and iliac bones, were contoured. Prescribed doses were 44 Gy in 20 fractions to pelvic lymph nodes and 60 Gy in 20 fractions to the prostate gland.

Tumor and organ masks ensured precise dose delineation, with Hounsfield units used for tissue density adjustments. FOTELP-VOX-GA, employing a GA population size of 50, optimized dose distribution using Mean Square Error (MSE) metrics. Initial broad searches quickly reduced errors, followed by iterative refinement through crossover and mutation, achieving precise dose calculations for targeted anatomical regions.

3. Results and discussion

In radiation simulation optimization, defining the parameter search space, such as Euler angles and beam directions within [0°, 360°], is essential for accurately modeling beam orientation and minimizing dose to healthy tissue. Tumor center coordinates are constrained by patient-specific anatomical boundaries to ensure geometric validity and adaptability across clinical scenarios. The optimization process was conducted within a

predefined search space (Table 1), including Euler angles and beam direction parameters, all ranging from 0° to 360°, to control beam orientation and maximize target conformity.

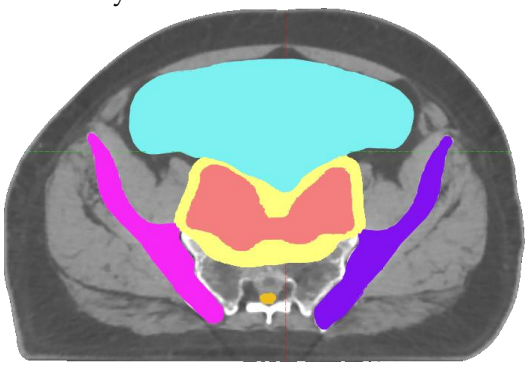

Figure 1. Color-coded mask of a specific CT simulation in layer highlighting target areas

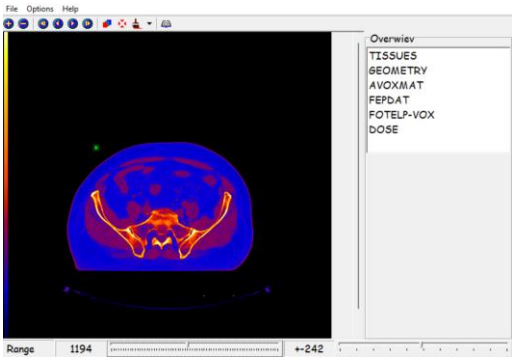

Figure 2. Steps for Monte Carlo FOTELP-VOX interface

Tumor center coordinates were restricted by anatomical boundaries derived from the CT data ([BODY_REACT_LEFT, RIGHT] and [BODY_REACT_TOP, BOTTOM]), ensuring geometric validity across patient-specific anatomies.

In the evaluated prostate cancer case, mean doses to the right and left iliac bones calculated by the Eclipse Treatment Planning System (TPS) were 2092.1 cGy and 2085.3 cGy, respectively. In comparison, the FOTELP-VOX-GA simulation estimated a mean dose of 1977.51 cGy for both iliac bones, indicating a noticeable reduction in absorbed dose to these critical structures. The genetic algorithm introduced within the FOTELP-VOX framework achieved dose variations ranging from 2% to 10% relative to the prescribed dose, which is considered clinically acceptable.

Table 1. Optimisation parameters.

Parameter	Range
euler_x	[0°, 360°]
euler_y	[0°, 360°]
euler_z	[0°, 360°]
beamDirection_x	[0°, 360°]
beamDirection_y	[0°, 360°]
tumorCenter_x	[BODY_REACT_LEFT, BODY_REACT_RIGHT]
tumorCenter_y	[BODY_REACT_TOP, BODY_REACT_BOTTOM]

From a clinical perspective, reducing mean dose to the iliac bones may translate into lower pelvic bone marrow toxicity, preserving hematopoietic reserve in patients who may require systemic therapy. In hypofractionated prostate radiotherapy, where fraction size magnifies the biological effect of dose deviations, the FOTELP-VOX-GA approach offers an added safety margin. Integration into routine workflows could involve its use as a secondary verification tool during plan evaluation, or as an adaptive optimization step in response to anatomical changes detected during treatment. For the urology–

radiation oncology interface, improved sparing of pelvic skeletal structures aligns with long-term survivorship goals, including maintenance of bone health. Future clinical studies should validate these dosimetric gains across larger cohorts and assess correlations with toxicity endpoints and patient-reported outcomes.

4. Conclusions

The integration of a GA with the FOTELP-VOX MC simulation framework offers a promising advancement in dose verification and optimization for prostate cancer radiotherapy. By combining the precision of Monte Carlo methods with the adaptive optimization capabilities of AI, the proposed FOTELP-VOX-GA system demonstrated improved accuracy in dose estimation, particularly for critical structures such as the iliac bones. These results suggest that the platform can serve as a reliable tool for secondary dose verification and may support the development of more personalized and adaptive radiotherapy plans. Further clinical validation on a larger patient group is warranted to confirm these findings and assess the impact on patient outcomes.

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