MANDIBLE DOSE COMPARISON BETWEEN FOTELP-VOX SIMULATIONS AND IMRT IN HEAD AND NECK RADIOTHERAPY

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Abstract:

Determining the absorbed dose of scattered radiation in specific body organs and tissues during radiotherapy is crucial for minimizing potential damage. This study investigates whether the FOTELP-VOX Monte Carlo simulation software can accurately estimate the absorbed dose in the mandible of patients undergoing head and neck radiotherapy, and how closely these estimates align with expert-verified IMRT treatment plans. As a representative clinical scenario, the analysis focused on ten patients with parotid gland tumors, whose treatment plans were generated using the IMRT planning system at the Clinical Center. The dosimetric parameters analyzed include minimum dose, maximum dose, and mean dose to the mandible. The average mandibular volume was 60 ± 15 cm^3. Dose differences between FOTELP-VOX simulations and IMRT ranged from 5% to 8%, indicating good agreement even without prior expert adjustment. These results suggest that the absorbed dose to the mandible remains within acceptable limits, although careful planning remains essential to minimizing unnecessary exposure. The findings support the potential use of FOTELP-VOX as a supplementary dosimetric tool for quality assurance, particularly in estimating scattered dose to critical structures adjacent to the target volume. The simulation outcomes confirmed the software's capability to generate accurate three-dimensional dose distributions resulting from particle interactions within complex anatomical structures. Further improvements and clinical validation are necessary to enhance the robustness and clinical integration of this approach.

Keywords:

Head and Neck Radiotherapy, Mandible Dose Estimation, Monte Carlo Simulation, FOTELP-VOX, IMRT Technique.

INTRODUCTION

Radiotherapy for head and neck cancers requires precise dose delivery to the tumor while minimizing exposure to surrounding healthy tissues and critical organs. Among the most sensitive structures during such treatments are the salivary glands (parotid, submandibular, and sublingual glands), which are particularly vulnerable to radiation-induced damage. In 2022, their global incidence ranked 28th, with 55,083 cases, and their mortality ranked 27th, with 23,942 deaths [1]. The parotid glands, located in front of the ears, are the largest salivary glands, responsible for saliva production and oral health.

DOI: 10.15308/Sinteza-2025-193-199

Excessive radiation to these glands can lead to xerostomia (dry mouth), significantly affecting the patient's quality of life. Other important organs at risk (OARs) include the mandible, spinal cord, brainstem, optic nerves, and eyes. The protection of these structures is crucial during treatment planning to avoid complications such as osteoradionecrosis, especially in the case of the mandible [2]. Diagnostic procedures typically include physical examination, biopsy, and imaging techniques such as ultrasound, MRI, and CT, which assist oncologists in determining tumor size, location, and spread. Treatment strategies often involve surgical resection followed by radiation therapy, or radiotherapy alone when surgery is not feasible. Radiotherapy relies on high-energy photons, electrons, or other particles to destroy cancerous cells. For the parotid glands, the currently accepted dose threshold is around 26 Gy, although some studies indicate that higher doses may still allow partial functional preservation [3], while others propose lowering this threshold to 22.5 Gy to reduce the risk of irreversible damage [4]. While much attention has been given to direct dose delivery to the target and major glands, less focus has been placed on the impact of scattered radiation on adjacent healthy tissues—such as the mandible—which may still receive clinically relevant doses even if not directly targeted.

Modern radiation therapy relies on advanced planning systems to deliver high doses to tumors while sparing healthy tissue. Among these, Intensity-Modulated Radiation Therapy (IMRT) is one of the most widely used and clinically validated techniques. IMRT enables modulation of beam intensity from multiple directions, resulting in highly conformal dose distributions that significantly improve the sparing of critical structures compared to conventional approaches [5]. Using inverse planning algorithms and computer-controlled multileaf collimators, this technique allows for precise shaping of the dose to match the three-dimensional geometry of the tumor. Clinical studies have consistently confirmed its advantages in head and neck treatments, where IMRT has led to a notable reduction in the incidence of xerostomia and a decreased risk of mandibular osteoradionecrosis [6].

In addition to clinically implemented treatment planning systems, Monte Carlo (MC) simulations have become an essential tool in radiation dosimetry research due to their unmatched accuracy. Unlike conventional dose calculation algorithms based on approximations, MC methods simulate the physical interactions of individual particles as they travel through heterogeneous anatomical structures, taking into account effects such as Compton scattering, the photoelectric effect, and pair production. This high level of precision makes them the gold standard for dose estimation in radiotherapy, particularly in anatomically complex or heterogeneous regions. While the computational demands of MC simulations have traditionally limited their use in routine clinical workflows, they are increasingly employed for independent verification, research applications, and special clinical cases. Well-known general-purpose MC codes such as MCNP [7] [8], PHITS [9] [10], GEANT4 [11], PENELOPE [12], and EGSnrc [13] are widely used in medical physics for modeling radiation transport and dose distribution. A specialized tool within this family is FOTELP-VOX [14] (Photon, Electron, and Positron Monte Carlo Transport Simulation – Voxel-Based), a voxel-based extension of the general-purpose FOTELP code [15]. FOTELP-VOX enables detailed simulation of radiation transport through anatomically realistic patient models derived from CT imaging. This allows researchers to obtain accurate three-dimensional dose distributions in both tumors and surrounding tissues. Previous studies have shown that FOTELP-VOX can replicate clinical dose distributions in various anatomical sites with deviations typically ranging from 5% to 8% compared to commercial treatment planning systems [16] [17]. However, while the focus of most FOTELP-VOX applications has been on tumor dosimetry, the estimation of absorbed dose in surrounding healthy tissues, such as the mandible, has not been sufficiently explored. This is especially important given that scattered radiation and beam spillover can lead to non-negligible dose deposition in nearby structures, even when they are not the direct target of treatment.

In clinical practice, IMRT planning systems are used by experienced radiation oncologists and physicists to generate optimized dose distributions that meet therapeutic objectives while sparing healthy tissue. In this study, we investigate whether the FOTELP-VOX simulation tool can independently provide comparable estimations of absorbed dose—without requiring prior expert tuning or adjustment. As a case study within the broader context of head and neck radiotherapy, we analyzed patients diagnosed with parotid gland tumors, whose treatment plans were developed using the IMRT technique at a clinical center in Kragujevac. The mandible was contoured and analyzed in both approaches, focusing on key parameters such as minimum, maximum, and mean dose. This comparison serves not only to evaluate the accuracy of FOTELP-VOX in estimating dose to a critical organ at risk, but also to explore its potential applicability in practice—as a complementary Monte

Carlo-based tool for quality assurance and secondary verification, particularly when assessing scattered dose to structures outside the primary target volume. By demonstrating how closely FOTELP-VOX results align with expert-verified IMRT plans, even when used in a straightforward, non-specialist setup, this study contributes to bridging the gap between research-level simulations and practical clinical implementation. It highlights the feasibility of using high-fidelity voxel-based Monte Carlo simulations as a reliable supplement to conventional planning systems for evaluating dose to sensitive anatomical structures such as the mandible.

2. MATERIALS AND METHODS

This section provides an overview of the clinical data and simulation procedures used in this study. The analysis is based on real patient cases involving head and neck cancer treatment, with radiotherapy plans created using the IMRT system at the Clinical Center Kragujevac. The simulation workflow was performed using the FOTELP-VOX Monte Carlo software, with a focus on evaluating the absorbed dose in the mandible. The following subsections describe the origin and interpretation of the patient data, as well as the simulation process and analysis of its output.

2.1. PATIENTS AND TREATMENT DATA

The study included patients diagnosed with parotid gland tumors, selected as a representative case study within the broader context of head and neck radiotherapy. These patients were treated at the University Clinical Center in Kragujevac using the IMRT technique between February 2011 and June 2021. Basic demographic information, such as age and gender distribution, is presented in Table 1. The patient group was balanced by sex (50% males and 50% females), with a mean age of 68 years.

Patient immobilization was a critical step for ensuring precise dose delivery. In cases where anatomical irregularities required it, a custom-made bolus was used, allowing optimal adaptation to the skin surface and improving dose homogeneity in the target region. Following immobilization, CT imaging was performed using a GE Discovery scanner, with a slice thickness of 2.5 mm, which ensured sufficient resolution for accurate contouring of target volumes. The delineated volumes included the Gross Tumor Volume (GTV), Clinical Target Volume (CTV), Internal Target Volume (ITV), and Planning Target Volume (PTV). Radiotherapy planning was carried out using the Varian Eclipse software (version 15.6), which provided advanced tools for optimizing treatment delivery. The Photon Optimizer algorithm was applied to adapt the dose distribution according to anatomical variations, while the Anisotropic Analytical Algorithm (AAA), version 15.6.06, was used for final dose calculation, incorporating tissue heterogeneity. Figure 1 shows the three-dimensional dose distribution and isodose contours obtained during IMRT planning.

The primary therapeutic dose was directed to the CTV, which received a mean dose of 54 Gy (range: 50–56 Gy) in daily fractions of 1.8 to 2.0 Gy. The average equivalent dose in 2 Gy fractions (EQD2) was 50 Gy. CTV1 was adequately covered by a 90% isodose line, ensuring sufficient coverage of the tumor tissue. According to published clinical dose constraints (Brouwer et al., 2015), the maximum recommended dose for the mandible is 65 Gy, while the mean dose should remain below 60 Gy. Additionally, the volume of the mandible receiving 70 Gy (V70) should not exceed 1 cm^3, in order to reduce the risk of radiation-induced complications such as osteoradionecrosis.

Table 1. Characteristics of patients diagnosed with parotid gland tumors

Characteristic	Description	Value
Age (years)	Range	56-80
	Mean Age	68
Gender	Number of Males	5
	Number of Females	5
Tumor Dose	Primary	70 Gy (35 fractions)

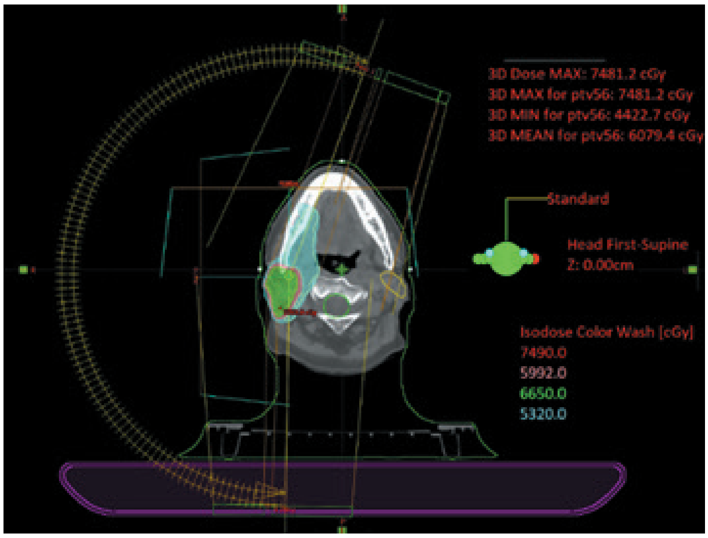

Figure 1. Three-dimensional dose distribution and isodose contours for the radiotherapy treatment

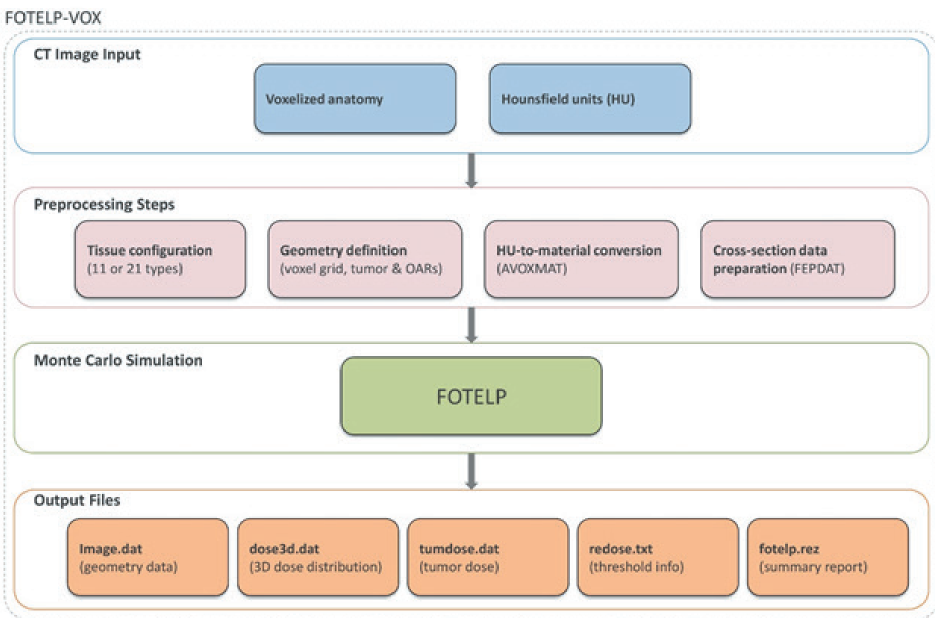

Figure 2. Overview of the FOTELP-VOX simulation workflow. The process includes CT-based voxelized geometry acquisition, preprocessing of tissue and geometry data, Monte Carlo simulation of particle transport, and generation of multiple output files for dosimetric analysis

2.2. FOTELP-VOX SIMULATION PROCESS

The FOTELP-VOX simulation process enables high-precision Monte Carlo modeling of particle transport and dose deposition based on anatomically realistic, CT-derived patient data. The workflow consists of four primary stages: CT image acquisition and voxelization, data preprocessing, FOTELP Monte Carlo simulation, and output analysis. The complete sequence is shown in Figure 2.

The process begins with importing CT images, which are converted into a voxelized representation of the patient's anatomy. Each voxel is assigned a value according to its Hounsfield number (HU), reflecting the radiological density of the tissue at that location [18]. These HU values are then used to infer material composition and tissue properties.

During preprocessing, the user selects a predefined tissue configuration file, containing either 11 or 21 material types, depending on the desired level of anatomical detail. The CT-derived voxel geometry is refined by defining a rectangular tissue region that encloses both the tumor and surrounding organs-at-risk (OARs), while minimizing the inclusion of surrounding air to improve computational efficiency. The AVOXMAT module converts HU values into material indices using a mapping formula such as:

$$MGn\ (i,j,k) = 10000\rho_n\ MH(i,j,k) \qquad (1)$$

where ρ_n is the density of a given tissue type, and $MH(i,j,k)$ is the Hounsfield number at a given voxel position (i,j,k). This process results in a material grid $MGn\ (i,j,k)$ that allows for high-fidelity modeling of heterogeneous tissue structures. Even small variations in HU values are preserved through unique material identifiers, enhancing the precision of dose estimation. The FEPDAT utility then prepares interaction cross-section data for photons and electrons, based on the defined tissue materials. These datasets are essential for the Monte Carlo simulation to accurately model physical processes such as Compton scattering, pair production, and photoelectric effect.

The third stage involves the execution of the Monte Carlo simulation using the FOTELP engine. It simulates the transport of photons or electrons through the voxelized patient model, iteratively computing their interactions and energy deposition in each voxel. The simulation continues until the statistical uncertainty of the dose values reaches acceptable thresholds. This enables high-resolution estimation of absorbed dose distributions throughout both target volumes and surrounding normal tissues.

In the final stage, FOTELP-VOX produces several output files essential for post-processing and clinical analysis. The *Image.dat* file contains geometric information used to reconstruct anatomical images. The *dose3d.dat* file stores a detailed three-dimensional dose distribution across the voxel grid, while *tumdose.dat* focuses specifically on the tumor region. The *redose.txt* file highlights voxels where the absorbed dose exceeds predefined safety limits, assisting in the identification of potential radiation hazards. The *fotelp.rez* file serves as a comprehensive summary, compiling simulation parameters, dose statistics, and verification data. These outputs collectively enable detailed analysis of absorbed dose distributions in both tumor and surrounding tissues, providing a foundation for further evaluation of treatment accuracy and safety.

3. RESULTS AND DISCUSSION

This study presents a dosimetric comparison between the FOTELP-VOX simulation and the clinical IMRT planning system for ten patients diagnosed with parotid gland tumors. The objective was to evaluate the agreement between these two approaches in estimating the absorbed dose in the mandible — a critical organ at risk in head and neck radiotherapy. For each patient, three key dosimetric parameters were analyzed: minimum dose (*MinD*), maximum dose (*MaxD*), and mean dose (*MeanD*) within the mandibular volume.

The results of the comparison are visualized in Figure 3, which presents individual patient data for each dosimetric parameter across both IMRT and FOTELP-VOX approaches. From the graphs, it is evident that the overall trends in dose distribution are consistent between the two techniques. FOTELP-VOX approximated the IMRT dose values with high similarity, especially for mean and minimum doses. Importantly, the maximum dose values estimated by FOTELP-VOX were consistently lower than those calculated by IMRT for all patients, with absolute differences typically ranging between 200 and 300 cGy. The observed deviations across all dosimetric parameters fall within the range of 5% to 8%, which is considered clinically acceptable for Monte Carlo-based methods.

Such agreement indicates that FOTELP-VOX, even when applied without prior tuning or expert intervention, can reliably replicate the clinically verified IMRT dose distributions. This reinforces its potential as an independent simulation tool for treatment plan verification or as a secondary check for critical organ dosimetry. The voxel-based modeling in FOTELP-VOX may also offer enhanced spatial resolution in three-dimensional dose distribution, particularly in anatomically complex regions such as the mandible.

From a clinical perspective, the observed differences are not expected to impact treatment safety, as all simulated doses remained below the established critical threshold of 65 Gy for the mandible, which is associated with the risk of osteoradionecrosis [2]. Nevertheless, precise dose estimation remains vital in treatment planning, especially for head and neck cases, where scattered radiation and out-of-field dose can affect surrounding bone and soft tissues. The ability of FOTELP-VOX to predict such effects with clinically acceptable accuracy supports its application in improving quality assurance protocols and in research focused on minimizing exposure to organs at risk.

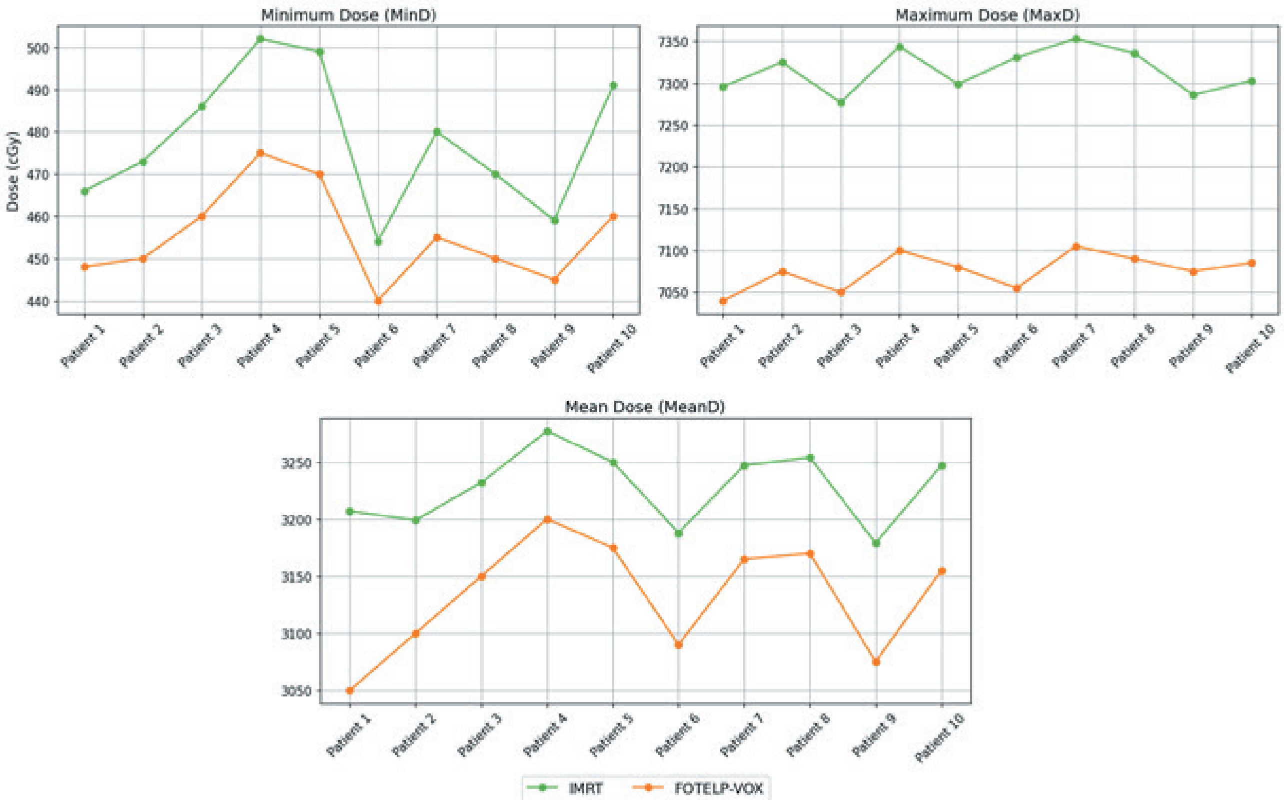

Figure 3. Comparison of IMRT and FOTELP-VOX dosimetric parameters per patient

4. CONCLUSION

This study evaluated the performance of the FOTELP-VOX Monte Carlo simulation software in estimating the absorbed dose to the mandible in head and neck radiotherapy. Using a case study of ten patients with parotid gland tumors, the absorbed dose distributions obtained with FOTELP-VOX were compared to clinically verified IMRT treatment plans. Across all analyzed patients, the simulation demonstrated a high degree of consistency with IMRT in terms of minimum, mean, and maximum dose to the mandible, with observed differences generally within 5–8%. These results confirm that FOTELP-VOX, even when used without prior expert calibration, can provide clinically relevant dose estimates for structures adjacent to the target volume. Due to its voxel-based modeling and use of patient-specific CT data, FOTELP-VOX offers high-resolution three-dimensional dose distributions, making it a promising tool for supplemental dose verification and quality assurance in radiotherapy planning. While the current application focused on the mandible as a representative organ at risk, the methodology may be extended to other critical structures affected by scattered and out-of-field radiation.

To ensure broader clinical adoption, further clinical validation of the FOTELP-VOX software across diverse anatomical scenarios is warranted. Future work could also focus on improving the usability and automation of the simulation process — for example, by incorporating automatic segmentation of tumors and organs at risk from imaging data. Additionally, tailoring simulation parameters dynamically based on the prescribed dose and anatomical complexity may further enhance the reliability and efficiency of FOTELP-VOX. These developments would facilitate its integration into clinical workflows and support more personalized and accurate treatment planning in modern radiotherapy.

5. ACKNOWLEDGEMENTS

This work was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia through the Agreements No. 451-03-66/2024-03/200122 and No. 451-03-65/2024-03/200122.

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