# FOTELP-VOX 2024: COMPREHENSIVE OVERVIEW OF ITS CAPABILITIES AND APPLICATIONS

by

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**The FOTELP-VOX program is a Monte Carlo simulation tool designed for precise radiation dose calculations in medical physics. It allows for the accurate modeling of photon, electron, and positron transport through human tissues by using CT scan data to define patient anatomy. This study presents the application of FOTELP-VOX in simulating absorbed dose distributions in various clinical scenarios, including radiotherapy treatment planning for salivary gland tumors, eye melanoma and breast cancer. The results demonstrate the program's capability to replicate complex dose distributions with high accuracy, in comparison with clinical techniques like volumetric modulated arc therapy and 3-D conformal radiotherapy. FOTELP-VOX 2024 has demonstrated excellent performances when compared to clinical center results, showing a variation of only 5-8 %, which confirms its accuracy in simulating dose deposition and treatment planning. There is also the potential for incorporating optimization techniques to further enhance the precision and efficiency of radiotherapy treatment planning, contributing to improved patient care outcomes.**

*Key words: FOTELP-VOX, Monte Carlo simulation, radiation therapy, absorbed dose, CT data, dose distribution*

## INTRODUCTION

Monte Carlo methods are widely regarded as one of the most reliable approaches for simulating particle transport and interactions, particularly in fields like radiotherapy and radiation protection. These stochastic techniques allow for the detailed modeling of complex physical processes, where deterministic methods fail. In medical physics, Monte Carlo simulations are critical for accurately predicting dose distributions in tissues, which directly influences the safety and effectiveness of radiation treatments. Over the past few decades, the use of these methods in clinical settings has grown substantially, driven by the need for precision in both diagnostics and therapeutic interventions [1, 2]. In the field of medical physics and radiation therapy, several software tools have been developed in order to simulate particle transport and accurately calculate radiation doses. Programs such as EGSnrc, Geant4, and MCNP have been widely used for Monte Carlo simulations in clinical settings and research [3-5]. These tools are essential for modeling the interactions of radiation with matter, optimizing treatment plans, and ensuring the safety of patients. However, each of these software solutions has its advantages and limitations, particularly in terms of user interface, accuracy, and computational speed.

The FOTELP, an acronym for photon, electron, and positron transport, is a software tool developed for Monte Carlo particle transport simulation. Originating in Serbia, FOTELP is specialized for the use in medical physics, particularly radiotherapy. Its development began in the late 1980′s and early 1990′s under the leadership of Ilić [6]. Initially, the program was designed in response to the need for accurate and efficient methods for modeling the interactions of photons, electrons, and positrons with matter, which are critical for optimizing radiation therapy procedures. Over the years, FOTELP has undergone numerous improvements. Early versions were based on fundamental Monte Carlo techniques, while later versions incorporated more advanced algorithms to improve simulation, accuracy and speed. The development of the program has been driven both by technological advancements and the growing demands of users in medical physics, radiation protection, and the nuclear industry. The motivation for

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FOTELP's development stems from the need for tools that enable detailed and precise analyses of particle interactions with matter, which are essential for accurate dose calculations in radiation therapy. This program has been instrumental in facilitating accurate radiation dose calculations, providing researchers and clinicians with a tool for improving therapeutic procedures and ensuring patient safety. The document is available at [7]. The FOTELP's initial applications included simulations in medical physics for optimizing radiation therapy [8, 9]. The program was used to estimate the radiation doses received by patients during treatment, enabling more precise therapy planning and reducing the risk of adverse effects. Additionally, FOTELP has proven valuable in radiation protection, allowing experts to assess exposure levels and design effective safety measures. Furthermore, FOTELP plays a significant role in education and training for new generations of medical physicists and radiotherapists. Its simulation capabilities provide a valuable platform for students and professionals to gain deep insights into the complexities of radiotherapy treatment before facing real clinical challenges.

The program has evolved through various versions, with a particular focus on FOTELP-VOX, a specialized version designed for particle transport simulation through the human body. This version uses advanced Monte Carlo techniques to precisely model the absorbed dose of protons, electrons, and positrons. Before simulation, users can select between photon or electron beams, adjust beam shape (circular or rectangular), and set energy levels (greater than 1 keV). FOTELP-VOX uses CT data to define patient anatomy and voxel composition, allowing for detailed calculations of 3-D absorbed dose distributions in tissue. This approach enables precise modeling of particle interactions with tissue and energy deposition in each voxel, providing essential insights into medical dosimetry and radiotherapy [10, 11].

The next significant development in the program was the integration of optimization algorithms to enhance the efficiency and accuracy of the simulations. By incorporating genetic algorithms (GA), Bayesian optimization, and random search, FOTELP- VOX was further optimized to reduce the need for manual parameter adjustments and improve the precision of radiation dose calculations. These algorithms allow for automatic fine-tuning of parameters such as beam orientation, energy levels, and tissue characteristics, significantly improving the treatment planning while minimizing exposure of the surrounding healthy tissues [12].

The aim of this paper is to present the FOTELP-VOX 2024 program, highlighting its capabilities and advancements in simulating particle transport and calculating 3-D absorbed dose distributions in medical applications. We also compare the program's performance with previous versions, emphasizing improvements in accuracy and computational efficiency. By showcasing its application in complex anatomical structures, we aim to demonstrate how FOTELP-VOX 2024 significantly enhances the precision and reliability of dose calculations, making it a crucial tool for both clinical radiotherapy and the training of medical physicists.

## MATERIALS AND METHOD

The FOTELP-VOX 2024 program is designed to guide users through a sequence of structured steps, tab. 1, each crucial for conducting accurate Monte Carlo simulations. Each step is clearly represented in the main program interface, ensuring a smooth workflow from data input to simulation output. Compared to previous versions, FOTELP-VOX 2024 is a new module based on Python scripts for automating the data preparation and processing for FOTELP-VOX simulations. This addition allows easier and faster setup of geometric models and simulation parameters, particularly by integrating DICOM data. The new module significantly enhances the efficiency of simulations and improves the accuracy of dose assessment, especially in complex anatomical structures.

Additionally, the DICVOX step enables the program to read CT data and create the HOUND.TXT file,

**Table 1. Key steps in the FOTELP-VOX 2024 simulation process**

| Step | Description | Key action |
|---|---|---|
| Tissue selection | Choose from predefined tissue configuration files, representing different tissue types. | Selection of either 11 or 21 tissue types based on CT data. |
| Geometry | Upload CT scans, define a rectangular region around tissues, and delineate the tumor and organs at risk (OAR). | Set voxel dimensions and specify first and last slices to be included. |
| AVOXMAT | Convert Hounsfield numbers (CT values) to material indices for accurate tissue representation. | Convert anatomical data into material properties used in the simulation. |
| FEPDAT | Prepare transition probabilities and input files for Monte Carlo simulation based on selected tissues and geometry. | Generate input files for photon, electron, and positron interactions with tissues. |
| Monte Carlo simulation | Run the simulation, where particles interact with the tissue, providing detailed modeling of radiation dose distribution. | Monte Carlo method calculates absorbed dose within each voxel. |
| Dose visualization | Display the absorbed dose distribution in 3-D across the tumor and surrounding tissues, providing a clear picture of radiation exposure and coverage. | Visualization of dose maps, allowing for the treatment plan assessment and refinement. |

which contains detailed information about the number of slices, pixel dimensions, and voxel size. This file structure plays a key role in defining the geometry of the patient's body and the radiation source. The program also allows users to define parameters such as the Euler angles for beam orientation, polar and azimuthal angles for particle emission, and beam geometry (whether circular or rectangular). This level of customization provides precise control over how radiation interacts with the patient's tissues.

Key variables in the simulation include voxel dimensions, which are defined in the *X*- *Y*- and *Z*-directions and are critical for accurate spatial representation of tissues. Additionally, energy parameters, such as initial and final particle energies and energy cutoff levels, play a vital role in determining how particles behave within the tissue. The source characteristics, including the number of particles in the source and the emission time, are also essential for replicating real-life conditions during therapy. These factors collectively ensure the precision and reliability of the simulation results. The precision of the simulation relies heavily on Hounsfield numbers from the CT scans [13]. These values differentiate between various materials within the human body, ensuring that the program accurately models the transport of photons, electrons, and positrons through different tissues.

## Selection of random values according to distribution

In Monte Carlo simulations, particularly when modeling particle transport, random values are drawn from specific probability distributions. These random values help simulate different outcomes that particles may encounter as they move through a material. However, the process of generating random values from these distributions needs to be efficient, as it is repeated thousands or even millions of times to achieve reliable results. Monte Carlo simulations are statistical models that use random sampling to solve physical and mathematical problems, particularly when direct calculation is difficult or impossible [14]. In the context of radiation transport simulations (like those used in FOTELP-VOX), the behavior of particles such as electrons, photons, or positrons is simulated based on probabilistic interactions. To ensure that results are statistically valid, a large number of particles must be tracked, which makes the process of selecting random numbers a crucial part of the simulation. The process of simulating particle transport is computationally expensive, meaning it requires a lot of time and computer power. Since one of the slowest parts of the simulation is the geometry module (which handles particle interactions with physical boundaries), it is important to make other aspects of the simulation-like random value selection-efficient. This helps to reduce overall computation time and improves the performance of the simulation.

The FOTELP-VOX code uses two primary methods for selecting random values from their distributions:

- *Nejman rejection method*: This method is highly efficient for distributions that depend on a single random variable. It works by generating candidate values and rejecting those that do not fit the desired distribution.
- *Inverse distributions*: For other random variables, FOTELP-VOX uses a method known as inverse distribution sampling. Here, the cumulative probability distribution is precomputed and stored in tables. When a random value needs to be selected, it is done by using these precomputed tables, making the process faster. This is particularly useful when the same random distributions are needed repeatedly, as it eliminates the need to calculate the distribution each time.

The inverse distribution method works by dividing the cumulative distribution function (CDF) into increments, either linear or logarithmic, depending on the nature of the distribution. Each increment corresponds to a range of possible random values. When a random number is drawn (typically between 0 and 1), the precomputed tables are used to determine which range this number falls into, and the corresponding random variable is selected.

Here's an example: Suppose we need to select a random photon emission angle for a photon created during bremsstrahlung radiation. First, the energy of the photon is determined (labeled as *EZ*), and the energy of the electron that created the photon (labeled as *EP*) is also known. Using these energies, the random angle is chosen from a table of precomputed values. The process can be mathematically described by using logarithmic increments, where *J* represents the index of the selected angle from the table of precomputed values. The value of *J* is determined based on the logarithmic distribution of increments

$$J = 1 + RK \cdot \frac{\log_{10}(EZ/EP)}{ALEM} \tag{1}$$

where *EZ* is the energy of the photon, *EP* – the energy of the electron, *RK* – the number of increments in the distribution, and *ALEM* – the a constant related to the material properties

The random variable is then selected from a table *YS*(*M*, *N*, *K*, *J*), where *M* corresponds to the material index, *N* corresponds to the energy index, and *K* represents the bremsstrahlung radiation.

In FOTELP-VOX, particles interact with materials based on cross-sections, which are probabilities for specific interactions (like scattering or absorption) to occur. To simulate particle behavior, it is necessary to find the cross-section value that corresponds to a given energy. The process of searching for this value is similar to the selection of random values from distributions. If a particle has energy *EP*, and the cross-sections depend on energy *S* (*I*, *K*), the goal is to find the index *K* that is closest to the particle's energy *EP*. This is done by using a logarithmic scale, which speeds up the search process.

The formula used is

$$RATA = 1.0 + \frac{\log(EP / EKON)}{ALE} \tag{2}$$

$$JATA = RATA, K = NMAX - JATA \tag{3}$$

where *RATA* helps to determine the index for the nearest energy, *NMAX* is the maximum number of energy points in the distribution, and *JATA* gives the index for the nearest lower energy value in the table.

To make the simulation as efficient as possible, FOTELP-VOX precomputes certain values, such as differences between neighboring cross-sections (*e. g*., EGT(K+1) – EGT(K)). These precomputed values are stored and used throughout the simulation, which reduces the number of calculations needed during runtime. Instead of recalculating these values each time, the precomputed difference is used, which improves the speed of the simulation.

### The PENGEOM geometry routines

Older versions of the FOTELP-VOX code used a geometry module known as RFG.FOR to describe how particles move between different material zones. Starting with version FOTELP-2K3, the code switched to using a more advanced geometry package called PENGEOM, which is part of the PENELOPE code family [15]. This geometry package is responsible for determining the material zone through which the particle is moving and the distance to the nearest zone boundary. The ELECTRONS, PHOTONS, and POSITRONS sections of the code interact with routines like LOCATE and STEP to calculate the particle's movement and track its position. By using the PENGEOM routines, the code can accurately model the path of particles through complex geometries, ensuring that the simulation results match closely the real-world scenarios. The FOTPEN.GEO file is designed to define geometry and material regions (zones) for the simulation purposes. However, discrepancies frequently arise when the dimensions of these regions are sourced from design drawings rather than from drawings properly aligned with the coordinate system. Additionally, errors may occur when dimensions along the co-ordinate axes are not correctly summed. To ensure the accuracy of the geometry and material definitions, it is recommended to utilize verification tools such as PENTEST or PENVIEW, which facilitate precise control and validation of the data contained within the FOTPEN.GEO file.

### Integration of artificial intelligence and algorithms

The FOTELP-VOX 2024 program has the potential to integrate advanced AI techniques and optimization algorithms to streamline its Monte Carlo simulations, reducing the need for multiple manual runs to achieve optimal results. Each simulation parameter directly influences the behavior of radiation, its distribution, and its effectiveness in tumor treatment, with the aim of delivering precise results while minimizing harm to surrounding tissues. To achieve this, FOTELP-VOX uses random search, Bayesian optimization, and GA to optimize wide range of parameters, tab. 2.

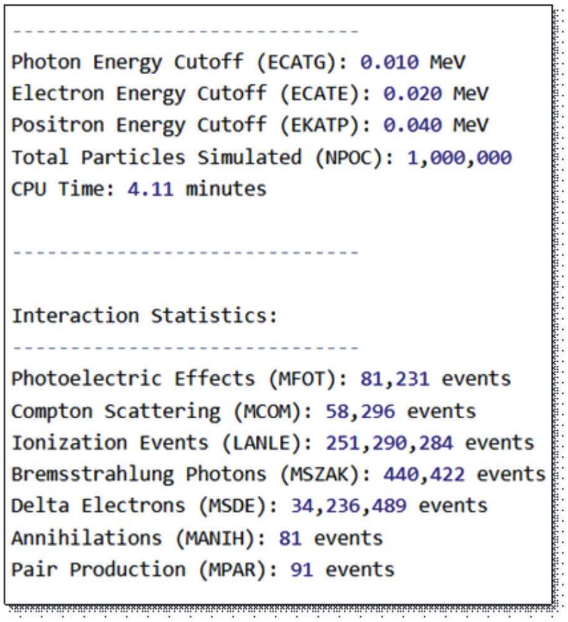
The software's ability to handle complex parameter adjustments, such as beam orientation, tumor positioning, and tissue characteristics, directly impacts the precision and effectiveness of radiation therapy. Using optimization algorithms like GA, Bayesian optimization, and random search, the program reduces the potential for human error and enhances consistency in treatment planning.

## RESULTS AND DISCUSSION

When a user receives the output from the FOTELP-VOX program, the results provide a comprehensive breakdown of key parameters and statistical data essential for analyzing particle transport and interactions within the simulated medium, fig. 1. The output begins by presenting the simulation parameters, which include the energy cutoffs for photons, electrons, and positrons (*ECATG, ECATE, EKATP*), defining the minimum energy at which particles are tracked. Additionally, the output specifies the number of particle histories used in the simulation (NPOC), which ensures statistical accuracy, as well as the total CPU time required to complete the simulation, indicating the program's computational efficiency. Next, the user is presented with collision statistics, which provide a detailed account of various particle interactions. This includes the number of photoelectric absorption events, where photons are absorbed within the tissue, Compton scattering events, which involve photons

**Table 2. Optimization parameters**

| Parameters | Range |
|---|---|
| Euler *x* | [0, 180] |
| Euler *y* | [0, 180] |
| Euler *z* | [0, 180] |
| Beam direction *x* | [0, 180] |
| Beam direction *y* | [0, 180] |
| Tumor center *x* | [BODY REACT LEFT, BODY REACT RIGHT] |
| Tumor center *y* | [BODY REACT TOP, BODY REACT BOTTOM] |



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Photon Energy Cutoff (ECATG): 0.010 MeV
Electron Energy Cutoff (ECATE): 0.020 MeV
Positron Energy Cutoff (EKATP): 0.040 MeV
Total Particles Simulated (NPOC): 1,000,000
CPU Time: 4.11 minutes


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Interaction Statistics:
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Photoelectric Effects (MFOT): 81,231 events
Compton Scattering (MCOM): 58,296 events
Ionization Events (LANLE): 251,290,284 events
Bremsstrahlung Photons (MSZAK): 440,422 events
Delta Electrons (MSDE): 34,236,489 events
Annihilations (MANIH): 81 events
Pair Production (MPAR): 91 events
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**Figure 1. Visual representation of FOTELP simulation parameters and interaction statistics**

scattering off electrons, and pair production and annihilation events related to positrons. The output also includes the count of coherent scattering events, where photons scatter without energy loss. These statistics are critical for understanding how radiation is deposited within the medium. The electron and positron interactions section provides insight into behavior of these particles during the simulation. It includes the number of ionization events, where electrons knock off atomic electrons, producing secondary effects, and the production of delta electrons (secondary electrons), which further contribute to dose deposition. Additionally, bremsstrahlung radiation, which occurs when electrons decelerate and emit photons, is recorded. These interactions are essential for accurately modeling radiation effects in tissues. The output also includes information on Auger electrons and relaxation processes, detailing any atomic relaxation events that occurred, including the emission of X-rays. Although these interactions may be less frequent, they play a significant role in certain types of radiation therapy calculations. Finally, the CPU time at the end of the output provides the information to the user how long the simulation took to complete. This information is important for evaluating the program's efficiency, particularly when dealing with complex geometries or large numbers of particle histories.

## Eye dose distribution

Ocular melanoma, though rare, presents a serious challenge in ophthalmic oncology due to the complexity of treating the tumor while attempting to preserve the patient's vision [16]. The precise targeting of tumors like ocular melanoma requires advanced tools to ensure accurate dose distribution. The results obtained using the FOTELP-VOX code have demonstrated its accuracy and reliability in simulating 3-D absorbed dose distributions in such complex anatomical regions. A comparison between FOTELP-VOX and volumetric modulated arc therapy (VMAT) was performed [11]. The treatment plan, which employed two full arcs, aimed to maximize dose delivery to the tumor bed while sparing surrounding healthy tissue. Key dosimetric parameters, including dose coverage, homogeneity index, conformity index of the target, and the dose volumes of critical structures, were calculated for both techniques. The absorbed doses were determined, with the difference between these two techniques ranging from 2.5 % to 25.0 %, confirming that the FOTELP-VOX program can accurately replicate the complex dose distributions required in radiotherapy.

## Humerus dose distribution

Additionally, the FOTELP-VOX code was used to assess the absorbed dose in the humerus of female patients undergoing postoperative radiotherapy for breast cancer [10]. In this study, five patients were treated using the 3-D conformal radiotherapy (3D-CRT) technique, and their treatment plans were generated using the ECLIPSE version 15.6 system. The FOTELP-VOX simulations calculated the absorbed dose in both the tumor and the humerus, fig. 2. The absorbed doses for PTV and OAR were calculated, and the variation between the two methods was between 0.1 % and 20 % and indicated that the absorbed dose in the humerus remained below the set dose limits for this bone structure, confirming that the technique adequately protected this critical structure.

## Salivary glands dose distribution and verification

Verification of the dose distribution was performed by comparing the simulation results with clinical data obtained from the Clinical Center, ensuring the accuracy and reliability of the treatment plans. The FOTELP-VOX 2024 code was applied to assess dose distribution in patients undergoing radiotherapy for salivary gland tumors. A total of 10 patients were treated with prescribed doses of 56 Gy and 70 Gy, focusing on the accurate delivery of radiation to the tumor site. Key dosimetric parameters, including *MinD* (minimum dose), *MaxD* (maximum dose), *D95* (dose covering 95 % of the target volume), and *D100* (dose covering 100 % of the target volume), were analyzed to evaluate treatment efficacy. The simulation pro-

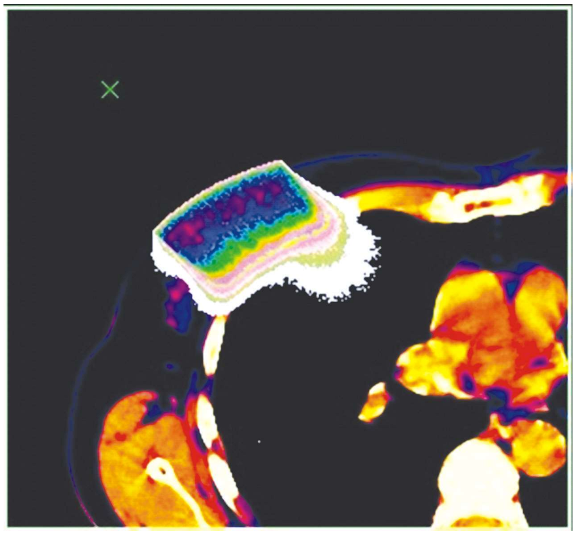

**Figure 2. The 3-D dose distribution visualization in patient CT scan**

vided detailed insights into the distribution of radiation within the tumor and surrounding tissues, aiding in the refinement of treatment plans.

Figure 3 illustrates the 3-D isodose distribution for a patient undergoing radiotherapy for a salivary gland tumor, with dose levels represented through color gradients. The upper left quadrant shows an axial view, highlighting the spread of the radiation dose across the tumor and surrounding tissues. The upper right quadrant provides a 3-D perspective, offering a comprehensive visualization of the dose distribution within the treatment area. The lower left quadrant features a coronal view, presenting the radiation dose distribution in a frontal plane, with detailed differentiation between target volumes and organs at risk. Finally, the lower right quadrant shows a sagittal view, emphasizing the vertical dose distribution and offering insight into the alignment of the radiation beam with the tumor and adjacent structures.

The FOTELP-VOX 2024 method generally results in absorbed dose variations compared to intensity modulated radiation therapy (IMRT), a technique that modulates radiation beam intensities to achieve a highly conformal dose distribution and optimizing tumor coverage. These differences are relatively small, not exceeding 5-8 % in most cases, fig. 4.

Compared to older versions, the FOTELP-VOX 2024 code produces much smaller differences, demonstrating improved consistency and accuracy. Using the FOTELP-VOX code, different energy levels and radiation fields were modeled to simulate their interaction with the anatomical structures. This approach ensured that the tumor received the optimal dose, while exposure to critical organs, such as the spinal cord and brainstem, was minimized.

## CONCLUSION

The FOTELP-VOX 2024 program has proven to be an exceptionally reliable tool for particle transport simulations and the calculation of 3-D absorbed dose distributions in complex anatomical structures. Its application in medical physics allows precise modeling of photon, electron, and positron interactions with tissues, which is critical for optimizing therapeutic procedures and ensuring the safety and effectiveness of radiation therapy treatments. The results from FOTELP-VOX simulations demonstrate its accuracy and versatility, making it an invaluable resource in both clinical and research settings. It can be effectively used for the training of medical physicists, providing them with an easily used platform to simulate and understand complex radiotherapy scenarios.

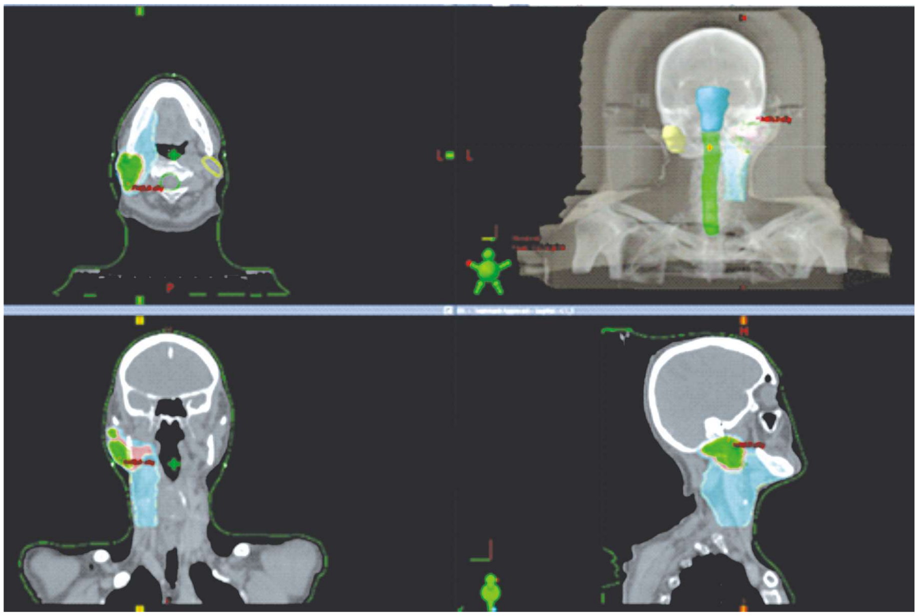

**Figure 3. Target volume definition and radiotherapy dose distribution in a case of the parotid gland**

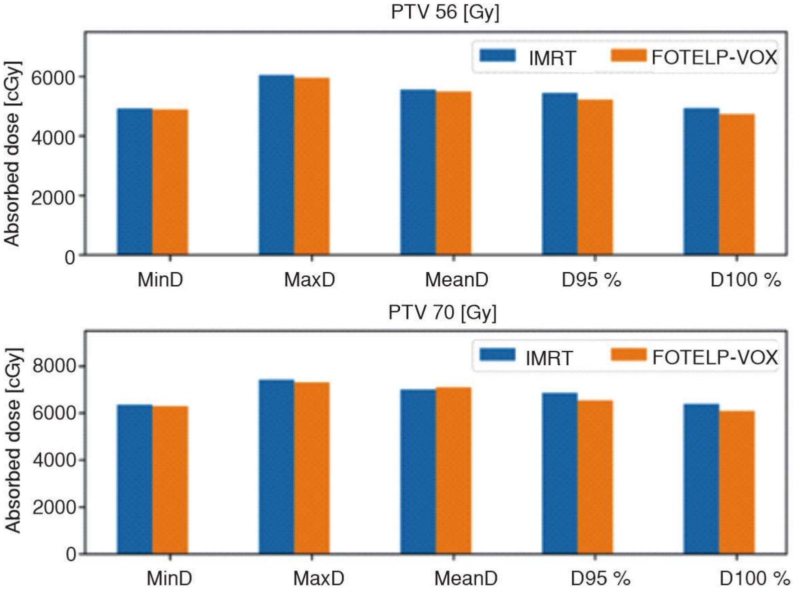

**Figure 4. Comparison of dosimetric parameters between IMRT and FOTELP-VOX**

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M. P. Živković: software modification, computations, simulations, data analysis, writing – original draft. T. B. Miladinović: CT scan provision, data analysis, writing – review and editing. Ž. M. Cimbaljević: software modification, writing – review and editing. M. A. E. Aichouche: writing – review. B. A. Pirković: software modification, scientific expertise, writing – review and editing. D. Ž. Krstić: data analysis, scientific expertise writing – review and editing.

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# FOTELP-VOX 2024 – СВЕОБУХВАТАН ПРЕГЛЕД ЊЕГОВИХ МОГУЋНОСТИ И ПРИМЕНА

Програм FOTELP-VOX је софтвер који користи Монте Карло симулације, осмишљен за прецизно рачунање доза зрачења у медицинској физици. Омогућава тачно моделовање транспорта фотона, електрона и позитрона кроз људска ткива, користећи СТ снимке за дефинисање анатомије пацијента. Овај рад приказује примену FOTELP-VOX програма у симулацији расподела апсорбоване дозе у различитим клиничким сценаријима, укључујући планирање терапије зрачењем за туморе пљувачних жлезда, меланом ока и рак дојке. Резултати показују способност програма да реплицира сложене расподеле доза са високим нивоом прецизности, упоређујући се повољно са клиничким техникама као што су волуметријска модулисана лучна терапија и тродимензионална конформална радиотерапија. FOTELP-VOX 2024 је показао добро слагање са резултатима добијених из Универзитетског клиничког центра у Крагујевцу, са одступањем од само 5-8 %, што потврђује његову тачност у симулацији депозиције дозе и планирању третмана. Такође постоји потенцијал за укључивање техника оптимизације како би се додатно побољшала прецизност и ефикасност планирања третмана радиотерапијом, доприносећи побољшању исхода неге пацијената.

*Кључне речи: FOTELP-VOX, Монте Карло симулација, терапија зрачењем, апсорбована доза, СТ снимак, расподела дозе*