ABSORBED DOSE DISTRIBUTION IN HUMAN EYE SIMULATED BY FOTELP-VOX CODE AND VERIFIED BY VOLUMETRIC MODULATED ARC THERAPY TREATMENT PLAN

by

Milena P. ŽIVKOVIĆ [1]**, *Tatjana B. MILADINOVIĆ*** [2]**,**
Aleksandar M. MILADINOVIĆ [3]**, *Una J. MOLNAR*** [4]**, *and Dragana Ž. KRSTIĆ*** [1*]

[1] Faculty of Science, University of Kragujevac, Kragujevac, Serbia
[2] Institute for Information Technologies, University of Kragujevac, Kragujevac, Serbia
[3] Medical Physics Department, University Clinical Center Kragujevac, Kragujevac, Serbia
[4] Centre for Radiology, Clinical Centre of Vojvodina, Novi Sad, Serbia

Scientific paper
https://doi.org/10.2298/NTRP2201078Z

This paper illustrates the potential of the FOTELP-VOX code, a modification of the general-purpose FOTELP code, combining Monte Carlo techniques to simulate particle transportation from an external source through the internal organs, resulting in a 3-D absorbed dose distribution. The study shows the comparison of results obtained by FOTELP software and the volumetric modulated arc therapy technique. This planning technique with two full arcs was applied, and the plan was created to destroy the diseased tissue in the eye tumor bed and avoid damage to surrounding healthy tissue, for one patient. The dose coverage, homogeneity index, conformity index of the target, and the dose volumes of critical structures were calculated. Good agreement of the results for absorbed dose in the human eye was obtained using these two techniques.

Key words: ocular cancer, FOTELP-VOX code, absorbed dose, volumetric modulated arc therapy

INTRODUCTION

Monte Carlo based programs have been the dominant tools in numerical experiments simulating radiation fields, and especially in radiotherapy planning, in recent years [1, 2]. Particle transport simulation problems may be classified into two categories. The first category includes simulations in which the irradiation medium's geometry is determined by technical construction using standard geometric shapes (plates, disks, spheres, cylinders, *etc*.). Another transport simulation topic is the organs of live beings, which constitute a collection of geometric ones [3]. Because of the use of computed tomography (CT) in the treatment plan, several advances in radiotherapy have been noted in dose distribution, optimization, and patient positioning. This was accomplished by estimating and adjusting the radiation dose to get the optimal dose distribution for the intended growth while preserving healthy cells [4]. The absorbed dose in ocular cancer may be calculated using voxelization of CT images. The preparation of simulation data is based on the dimensions and number of voxels, as well as Hounsfield numbers [5, 6].

Ocular cancer is a rare tumor, and its treatment is a challenge because of a necessity to destroy the tumor with minimum visual loss. Primary ocular cancers arise inside the eyeball. Secondary ocular cancers occur somewhere in the body and then spreads to the eye. Lung, and breast cancer most commonly spread to the eye [7]. Secondary cancer is more common than primary ocular cancer. In adults, patients of both sexes are equally represented, while their average age at the time of diagnosis is about 60 years and the most common type of this cancer is primary intraocular.

Treatments for this type of cancer include surgery, chemotherapy or radiotherapy, or a combination of these because even after surgery, there is a risk of microscopic tumor cells in the tumor bed. Most recurrences are located in the nearness to the tumor bed. That is why it is important to provide that a postoperative tumor bed is irradiated with appropriate radiotherapy techniques. The conventional radiotherapy technique, in the past, used a single enface electron beam or AP beam. Delivering radiation was performed using wedged anterior and lateral fields directed at the target volume. However, this is technically very difficult due to the location of cancer. The development of technology has allowed advances in radiotherapy that have enabled more accurate and conformal dose deliv-

---

* Corresponding author, e-mail: dragana.krstic@pmf.kg.ac.rs

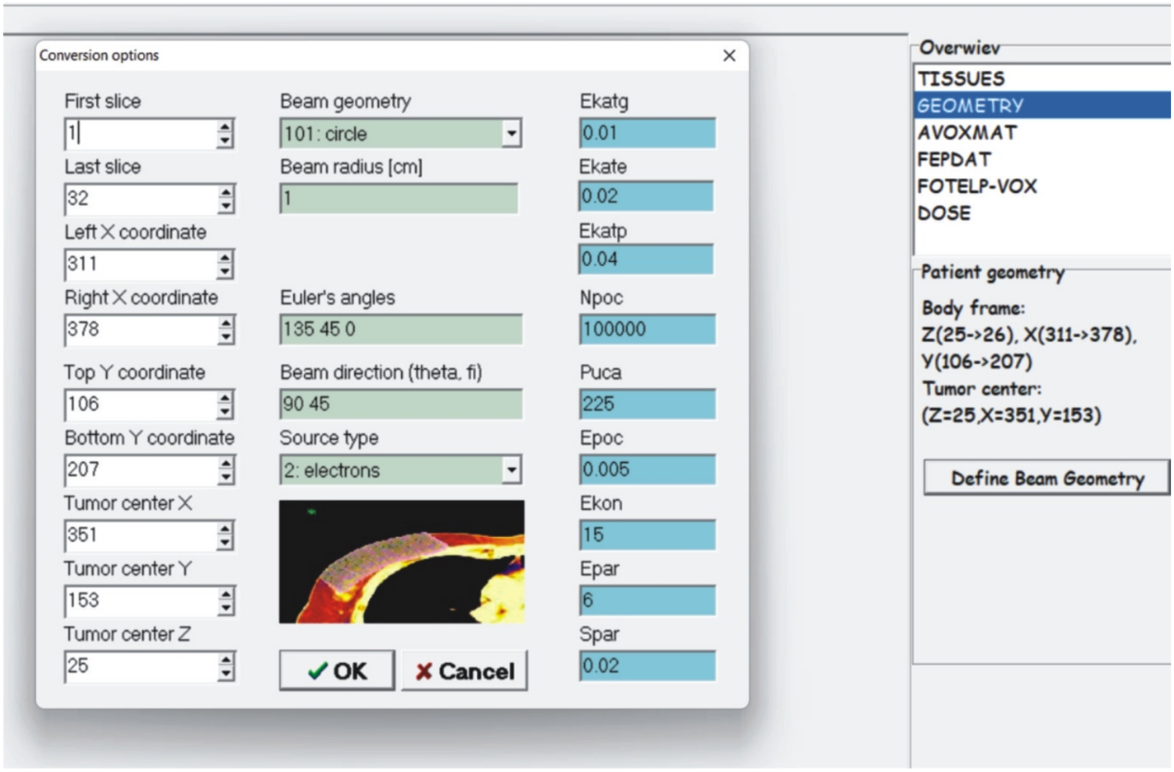
ery in the case of ocular cancer [8, 9]. Especially the volumetric modulated arc therapy (VMAT) technique that uses continuous changing multileaf collimator (MLC) movement, gantry rotation, and dose rate with less monitor units (MU) and delivery time [10], allowing greater sparing organs at risk of achieving good tumor coverage [11]. For this purpose, it is possible to use systems designed for routine clinical use, which utilize in-house designed worksheets for dose calculation based on relevant parameters introduced by the ICRP publications [12, 13].

Several scientific studies have shown the advantage of applying the VMAT technique in the treatment of ocular cancer [14, 15], In this paper, the dosimetric results obtained using the FOTELP program and the VMAT planning system at the University Clinical Center Kragujevac were compared. The presented results in this study confirm that this program could help in the implementation of Monte Carlo methods in clinical practice.

MATERIALS AND METHOD

The use of voxels in the FOTELP program requires the limitation of a portion of the space so that an environment within a parallelepiped can be irradiated with a particle source. If the source is located outside of the irradiated region, the mentioned space should include a portion of the surrounding air. A particle's interaction with the initial voxel is identified by the voxel related to the density. The addresses of the voxel are then assigned dimensions and six planes to its parallelepiped in each co-ordinate system. The technique continues until the particle's fate is complete, after verifying whether the particle on that path has any interactions and modeling these processes. This technique utilizes voxel addresses and temporary voxel placement co-ordinate levels. This prevents planes that define fixed geometry in other programs from being loaded into the geometry. The GEMVOX function is used by the FOTELP program to temporarily place only that current voxel in the co-ordinate system. As a result, memory space is saved, and the simulation takes place with only one voxel. To simulate particle delivery, it uses Monte Carlo techniques. When particles are carried from an external source via the human body, as a result, the absorbed dose has a 3-D distribution. A user can choose between a photon or electron beam of any shape before this stimulation. On the other hand, the energy should be more than 1 keV to allow for the computation of the 3-D distribution. The CT data is used to characterize the anatomy of the patient.

Figure 1 illustrates the FOTELP-VOX software interface, with all the possibilities for monitoring particle transport. The FOTELP-VOX offers two predefined tissue configuration files: one containing 11 tissues and the other containing 21 tissues. The user can simply choose which file to use in the simulation. Selecting this step displays the information about the patient's geometry. Generally, the user must load a CT image.



First slice: 1
Last slice: 32
Left X coordinate: 311
Right X coordinate: 378
Top Y coordinate: 106
Bottom Y coordinate: 207
Tumor center X: 351
Tumor center Y: 153
Tumor center Z: 25
Beam geometry: 101: circle
Beam radius [cm]: 1
Euler's angles: 135 45 0
Beam direction (theta, fi): 90 45
Source type: 2: electrons
Ekatg: 0.01
Ekate: 0.02
Ekatp: 0.04
Npoc: 100000
Puca: 225
Epoc: 0.005
Ekon: 15
Epar: 6
Spar: 0.02

Patient geometry
Body frame:
Z(25->26), X(311->378),
Y(106->207)
Tumor center:
(Z=25,X=351,Y=153)

Figure 1. View of the photon dose planning menu in FOTELP-VOX

A relevant tissue rectangle should contain all voxels of the patient's tissue, but at the same time, it should have minimal size, with as little air around the body as possible. The program displays the initial rectangle after the image is loaded. Users can modify the rectangle's *X-Y* position and size. The user must also determine the first and last slice of the tissue rectangle. The next step is defining the tumor center.

After the patient geometry has been defined, the user launches AVOXMAT which prepares the selected portion of the CT image for simulation by translating Hounsfield's numbers into corresponding material indexes applying from file MATERIAL.dat, and file FEPDAT.inp file as input file for the Fepdat code running. A user must run the FEPDAT application after running the AVOXMAT program. FEPDAT prepares the transition probabilities and input files for all selected materials (tissues) needed for the later Monte Carlo simulation by FOTELP-VOX code. When all previous steps are completed, FOTELP-VOX starts the Monte Carlo simulation. This step can be repeated with previously prepared data if the uncertainty is not satisfactory. After the simulation is finished, deposited doses in CT-defined voxels (file REDOSE.txt) will be displayed over the CT data. Program DICVOX and VOXELVIEW load CT data as at the beginning, and then read REDOSE.txt to make anatomical images via image dose distribution, normalized to the maximum in each slice.

Users can change the palette for the deposited dose display as well as the transparency level fig. 2. File REDOSE.txt contains the deposited doses in tumor cube voxels. This file can be displayed by clicking on the *Show* button. Also, by selecting this option the tumor dose and statistical uncertainty will be displayed.

A patient with confirmed left eye primary ocular cancer is included in this research and he was immobilized in the supine position using a thermoplastic mask and according to standard procedures scanned with CT (GE Discovery CT590, GE Healthcare, United States) with a 2.5 mm slice spacing. Gross target volume (GTV) was defined as gross tumor volume using CT and MRI scans. Planning target volume (PTV) was delineated with a 5 mm margin from GTV. The location of the tumor bed was in the left eyeball, the PTV volume was 39.7 cm^3 (the volume of the eyeball is 6.2 mL). Also, the radiation oncologist contoured organs at risk (OAR) right lens, right eyeball, optic nerve, optic chiasm, pituitary, brain, and brainstem. Treatment planning was to optimize coverage of at least 95 % of PTV with 95 % of the prescription dose and provide maximum protection for organs at risk. The prescription was normalized to 60 Gy at 30 fractions at 6 MV and two full arcs VMAT plan was generated for the patient using the ECLIPSE version (15.6) (Varian Medical Systems, Palo Alto, CA). Using DVH diagrams, and calculated values of CI, HI, and DHI indexes, a quantitative evaluation of the plan was performed. The radiation conformity index (CI) is a measure of target coverage and the conformity of the high dose region to the PTV, and it is defined as [13]

$$CI_{\mathrm{RTOG}} \quad \frac{V_{\mathrm{RI}}}{V_{\mathrm{PTV}}} \tag{1}$$

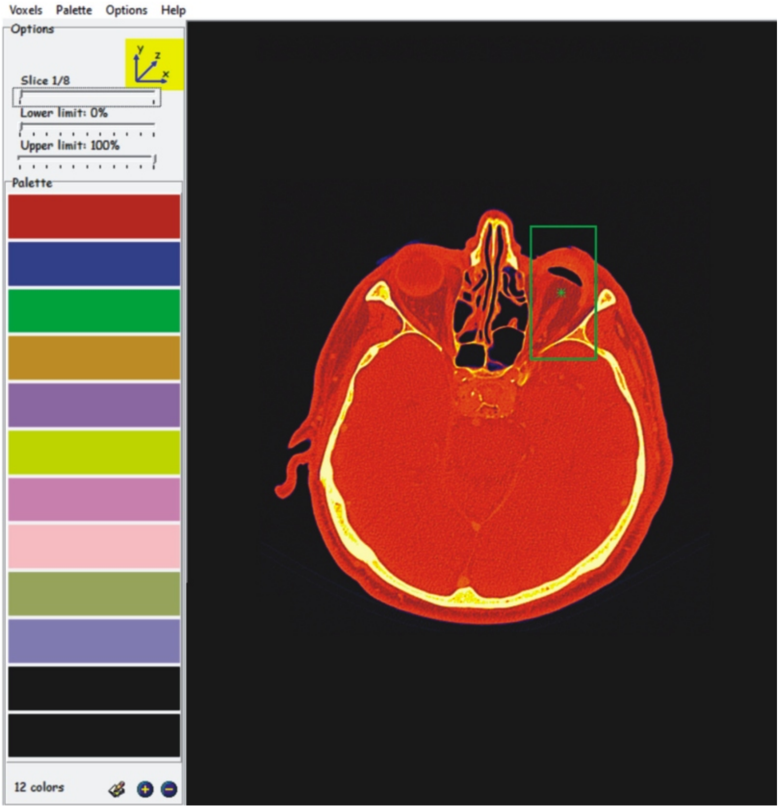


Figure 2. The appearance of the VOXVIEW program interface

where V_{RI} reference isodose volume, V_{PTV} [cm^3] PTV target volume. Perfect conformance gives $CI = 1$ while lower values of CI mean poorer plan quality.

The homogeneity index (HI) is a ratio between the maximum dose in the target volume and the reference isodose [16] was calculated as

$$HI_{\text{RTOG}} \quad \frac{I_{\max}}{RI} \tag{2}$$

where $I_{\max}$ is the maximum isodose in the target, and RI is the reference isodose. Smaller values of HI indicate better dose homogeneity in the PTV.

Dose homogeneity index (DHI) is defined as a ratio between the dose reached in 95 % of the PTV volume ($D \quad 95\,\%$) and the dose reached in 5 % ($D \quad 95\,\%$) of the PTV volume

$$\text{DHI} \quad \frac{D \quad 95\,\%\,(\text{within PTV})}{D \quad 5\,\%\,(\text{within PTV})} \tag{3}$$

RESULTS AND DISCUSSION

Ocular cancer can be a significant example of how voxelized geometry can be used in radiotherapy. As an illustration of the use of CT data to simulate transport by the FOTELP-VOX program in voxelized geometry, CT data of a patient eye is used. A CT scan of the patient's head was used, with voxel sizes of 0.5 mm, 0.5 mm, and 1.0 mm. The melanoma was thought to be spherically formed and located at the bottom of the eye. A therapy plan was created using FOTELP-VOX software and a 1 cm radius cylindrical photon beam with a mean energy of 6 MV. A total of 108 photon histories were used in the simulation.

The planning acceptance criteria for OAR are listed in tab. 1. Planners adjusted the planning goals for individual cases in consultation with the attending physicians due to variability in the anatomic relationship between PTV and OAR across each case.

Table 1. The OAR planning acceptance criteria, VMAT and FOTELP-VOX delivery parameters and mean dose in target tumor

OAR	FOTELP-VOX (in Gy)	VMAT (in Gy)
Contralateral lens, $D_{\max} < 10$ Gy	3.2	2.5
Contralateral eyeball, $D_{\max} < 45$ Gy	12.3	13.3
Brainstem, $D_{\max} < 54$ Gy, D1 < 59 Gy	24.5	22.8
Optic nerve, $D_{\max} < 54$ Gy	27.2	25.2
Chiasm, $D_{\max} < 54$ Gy	31.9	30.8
Pituitary, $D_{\max} < 50$ Gy	25.21	28.0
Spinal cord, $D_{\max} < 48$ Gy	1.2	0.9
Brain, $D_{\max} < 68$ Gy	67.5	63.6
D_{mean}	62.5	60.8

As shown in tab. 1. FOTELP-VOX and VMAT meet the clinical requirements, and they are compromised so that other OAR like the brain also meet the requirements. The absorbed doses were determined, with the difference between these two techniques ranging from 2.5 % to 25.0 %.

For a selected patient, fig. 3 shows dose distributions represented by 95 % isodose lines from the two full arcs VMAT.

A standard dose-volume histogram (DVH) was used to evaluate the clinical treatment plan, fig. 4. In this case the irradiation of the eye, DVH calculation indicated that the treatment plan satisfied the dose-volume constraint placed on the tumor bed. The DVH showed that about 50 % of the right eye volume received 5.2 Gy, the right lens received 3.2 Gy in maximum, while about 6.3 % of the brain received 60 Gy.

Coverage of PTV for the VMAT technique was within the limits of clinical acceptability with a V95 of 99.6 % The HI, DHI and CI were, 1.076, 0.959, and 1.204, respectively. Maximum isodose in the target Imax, and RI is reference isodose was 6457.0 and 6000.0. The number of MU per field was 242 and 246.

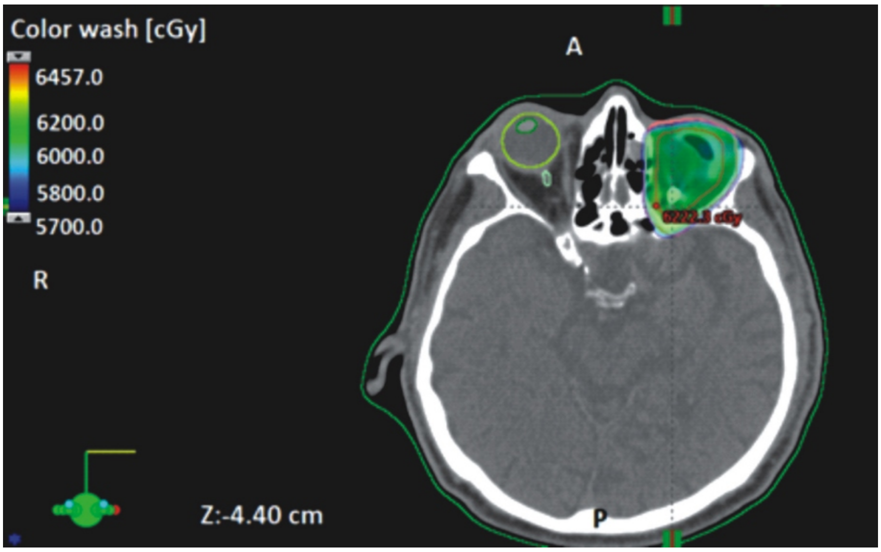


Figure 3. Dose distribution in VMAT for one intraocular cancer patient

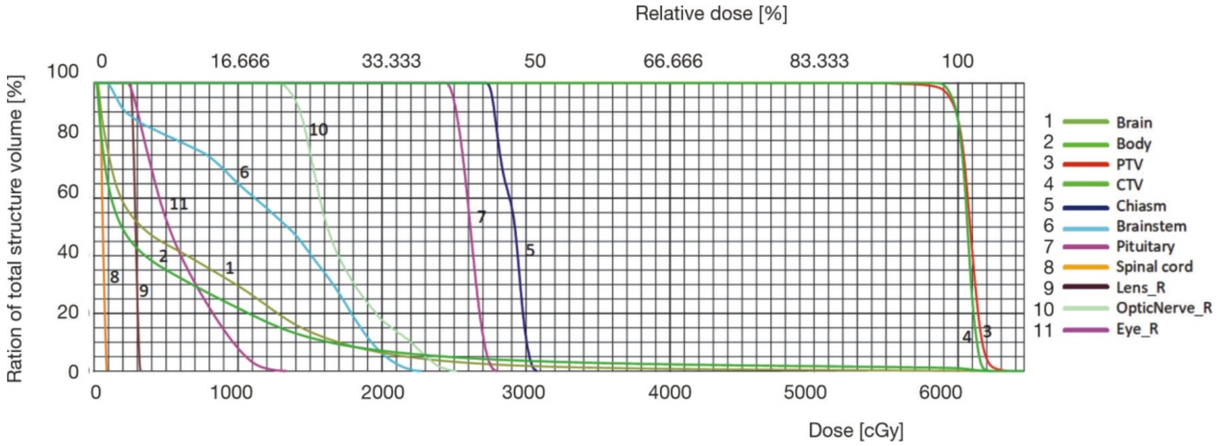


Figure 4. Cumulative DVH

Table 2. Target coverage

PTV	VMAT
D_{max} [cGy]	6457.0
D_{mean} [cGy]	6077.7
V95 [%]	99.6
D2 [cGy]	6224.3
D50 [cGy]	6083.6
D98 [cGy]	5885.3
V_{RI} [cm^3]	47.8
V_{PTV} [cm^3]	39.7
$D_{95\,\%\,\mathrm{(within\ PTV)}}$ [cGy]	5941.4
$D_{5\,\%\,\mathrm{(within\ PTV)}}$ [cGy]	6192.4
I_{max} [cGy]	6457.0
RI [cGy]	6000.0
HI	1.076
DHI	0.959
CI	1.204

These, as well as other dosimetric parameters, can be found in tab. 2.

The VMAT technique gave good but mixed results for sparing organs at risk. The contralateral eyeball and spinal cord are irradiated at a very low dose.

CONCLUSION

The main objective of this paper is to illustrate the potential of the programs in the treatment of eye melanoma. The FOTELP-VOX is voxelized geometry Monte Carlo transport algorithm based on CT data. In the treatment of intraocular cancer, a radiotherapy plan can be made using the VMAT technique. The VMAT achieved good homogeneity and conformity for target volume and delivered a small dose to the contralateral lens and eyeball. However, it increased the low dose volume of the OAR.

ACKNOWLEDGMENT

This work was supported by the Serbian Ministry of Education, Science and Technological Development (Agreement No. 451-03-68/2022-14/200122) and the University of Kragujevac – Institute for Information Technologies (Agreement No. 451-03-68/2022-14/200378.), through the grants by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

The authors would like to thank Prof. dr Radovan D. Ilić, who introduced us to the technology of the Monte Carlo method and made possible the use of all versions of the FOTELP software package. We would also like to express our gratitude for his unselfish professional assistance, persistence, and understanding during the paper writing.

AUTHORS' CONTRIBUTIONS

Conceived and designed the computations: R. D. Ilić; performed the computations: D. Ž. Krstić and M. P. Živković, analyzed the data: D. Ž. Krstić, A. M. Miladinović, U. J. Molnar, M. P. Živković, and T. B. Miladinović, authored the paper: D. Ž. Krstić, M. P. Živković, A. M. Miladinović, and T. B. Miladinović.

REFERENCES

[1] Sempau, J., *et al*., DPM, A Fast, Accurate Monte Carlo Code Optimized for Photon and Electron Radiotherapy Treatment Planning Dose Calculation, *Phys Med Biol, 45* (2000), 8, pp. 2263-2291

[2] Rogers, D. W. O., Fifty Years of Monte Carlo Simulations for Medical Physics, *Phys Med Biol, 51* (2006), 13, pp. R287-R301

[3] Ilić, R. D., *et al*., The Monte Carlo SRNA-VOX Code for 3-D Proton Dose Distribution in Voxelized Geometry Using CT Data, *Phys Med Biol, 51* (2005), 5, pp. 1011-1017

[4] Pereira, G. C., Traughber, M., Muzic, R. F., The Role of Imaging in Radiation Therapy Planning: Past, Present, and Future, *Biomed Res Int, 2014* (2014), ID231090

[5] Schneider, W., *et al*., Correlation Between CT Numbers and Tissue Parameters Needed for Monte Carlo Simulations of Clinical Dose Distributions, *Phys Med Biol, 45* (2000), Feb., pp. 459-478

[6] Ilić, R., Proton Therapy Monte Carlo SRNA-VOX code, *Nucl Technol Radiat, 27* (2012), 4, pp. 355-367

[7] Dieckmann, K., *et al*., A Linac-Based Stereotactic Irradiation Technique of Uveal Melanoma, *Radiother Oncol, 61* (2001), 1, pp. 49-56

[8] Mouw, K.W., *et al*., Proton Radiation Therapy for the Treatment of Retinoblastoma, *Int J Radiat Oncol Biol Phys, 90* (2014), 4, pp. 863-9

[9] Munier, F. L., *et al*., New Developments in External Beam Radiotherapy for Retinoblastoma: from Lens to Normal Tissue-Sparing Techniques, *Clin Experiment Ophthalmol, 36* (2008), 1, pp. 78-89

[10] Palma, D., *et al*., Volumetric Modulated arc Therapy for Delivery of Prostate Radiotherapy: Comparison with Intensity-Modulated Radiotherapy and Three-Dimensional Conformal Radiotherapy, *Int J Radiat Oncol Biol Phys, 72* (2008), 4, pp. 996-1001

[11] Wu, Z., *et al*., Dosimetric Benefits of IMRT and VMAT in the Treatment of Middle Thoracic Esophageal Cancer: is the Conformal Radiotherapy Still an Alternative Option?, *J Appl Clin Med Phys, 15* (2014), 3, pp. 93-101

[12] Debeljuh, D., *et al*., Iagnostic Nuclear Medicine Procedures: Implementation and First Results, *Nucl Technol Radiat, 35* (2020), 4, pp. 380-385

[13] ***, International Commission on Radiological Protection, The Recommendations of the International Commission on Radiological Protection, ICRP Publications 103, Annals ICRP, 37, 2007

[14] Eldebawy, E., *et al*., Dosimetric Study of Current Treatment Options for Radiotherapy in Retinoblastoma, *Int J Radiat Oncol Biol Phys, 82* (2012), 3, e501-e505

[15] Deng, Z., *et al*., Dosimetric Advantage of Volumetric Modulated arc Therapy in the Treatment of Intraocular Cancer, *Radiat Oncol, 12* (2017), 1, p. 83

[16] Petrova, D., Smickovska, S., Lazarevska, E., Conformity Index and Homogeneity Index of the Postoperative Whole Breast Radiotherapy, *Open Access Maced J Med Sci, 5* (2017), 6, pp. 736-739

Received on April 19, 2022
Accepted on May 13, 2022

**Милена П. ЖИВКОВИЋ, Татјана Б. МИЛАДИНОВИЋ,
Александар М. МИЛАДИНОВИЋ, Уна Ј. МОЛНАР, Драгана Ж. КРСТИЋ**

РАСПОДЕЛА АПСОРБОВАНЕ ДОЗЕ У ЉУДСКОМ ОКУ СИМУЛИРАНА КОДОМ FOTELP-VOX И ВЕРИФИКОВАНА ВОЛУМЕНСКИ МОДУЛИСАНИМ ЛУЧНИМ ПЛАНОМ ТЕРАПИЈЕ

У овом раду илустровали смо потенцијал FOTELP-VOX кода, модификације FOTELP кода опште намене, који комбинује Монте Карло технике за симулацију транспорта честица из спољашњег извора кроз унутрашње органе. Као резултат добијамо тродимензионалну дистрибуцију апсорбоване дозе. Студија показује поређење резултата добијених софтвером FOTELP и VMAT (Volumetric Modulated Arc Therapy) техником. Примењена је техника планирања VMAT-а са два пуна лука и направљен је план како би се уништило оболело ткиво у лежишту тумора ока и избегло оштећење околног здравог ткива, за једног пацијента. Израчунати су покривеност дозом, индекс хомогености, индекс усклађености мете и запремине дозе критичних структура. Добра сагласност резултата за апсорбовану дозу у људском оку добијена је коришћењем ове две технике.

Кључне речи: меланом ока, FOTELP-VOX код, айсорбована доза, VMAT