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Computational modelling of cervix uterus radiation procedure using a virtual anthropomorphic phantom and the MCNPX code

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Abstract. There is a serious, and growing, concern about the increased risk of the emergence of a secondary cancer, radio-induced, associated with radiotherapy treatments. To assess the radiation doses to organs outside the target volume, in this work, several computational exposure scenarios were modelled, based on Monte Carlo simulation (MCNPX code). A Varian 2100c accelerator, and a female virtual anthropomorphic phantom were used, in a simulated treatment of cervical cancer. The determination of the dispersed dose would be important for assessing the risk in different organs or tissues. Four treatment fields were applied, varying the gantry angle. It was possible to observe that the conversion factors for equivalent dose were higher for the AP projection. For the RLAT and LLAT projections, the results were similar, fact that may be attributed to the symmetrical distributions of the organs in relation to the radiation source. The results presented in this work showed that the computational exposure scenario provides a versatile and accurate tool to estimate in a ready way the absorbed doses during a cervical treatment.

1. Introduction

According to Bray *et al.* [1] the uterine cancer is the sixth most common cancer type in women worldwide. In Brazil, this scenario is the same, according to the National Cancer Institute (INCA). This type of tumor is the third most frequent among the women population, behind the breast and colorectal cancer. It occupies the fourth place in the cause of women death [2]. With the diagnosis of cervical cancer, treatment options vary depending on the stage, external radiotherapy is indicated. Despite the treatment efficiency, radiotherapy may cause injuries at patients, since healthy tissues located closer, or inside, the treated area are exposed to the photon beam. These effects are characterized as acute effects, such as erythema or a late effect such as a secondary tumor. As presented in several works in the literature [3 - 8], the determination of the dispersed dose would be important for assessing the risk

and biological consequences in different organs or tissues. This subject is of great concern, mainly when new treatment techniques may increase the leakage radiation to patients.

The absorbed doses to organs and tissues outside the radiation planning field are unavoidable during the treatment and may contribute to the induction of a secondary cancer. These doses are derived from the scattered radiation throughout the patient's body, walls, floor and ceiling of the radiotherapy room, head, collimators and other structures of the LINAC [9].

Most studies found in the literature are focused on the determination of absorbed dose distributions inside the treatment planned area [10,11]. These works aimed the modelling of the main components of the beam line, such as the target, primary collimator, jaws, and the flattening filter. The presence of the patient, which is more important to scattered radiation, was not considered.

The Monte Carlo (MC) simulation has been widely used to model primary treatment fields of various LINAC models, such as Varian, Siemens and Elekta [4]. To determine the doses in different organs and tissues, the Monte Carlo simulation is used coupled with virtual anthropomorphic phantoms. The aim of this study is to estimate the absorbed doses in tissues and organs located outside the volume of the radiotherapeutic planning. In this study the 2D planning mode was considered for uterine cervix cancer. For this, a computational model was be developed using Monte Carlo simulation coupled with the computational anthropomorphic phantom (FASH3), representing the patient, and a Varian 2100c LINAC. The results are presented in the format of conversion factors (CF).

2. Materials and Methods

2.1. Computational model description

In this work the MCNPX software (version 2.7.0) [12] was used to model the scenario with a medical Varian 2100c LINAC. The photon and electron transport was carried out based on the ENDF/B-VI8 cross section libraries, with a cutoff energy of 0.01MeV (CUT:P 0.01) for photons and 0.1MeV for electrons (CUT:E 0.1). The photon transport was considered including photoelectric absorption with the possibility of fluorescent emission and Auger electron, coherent and incoherent scattering. The Varian 2100c LINAC, using a 6 MV photon beam, was modelled with the target, wedge filter, jaws and a detailed 80 leaf multi-leaf collimator (MLC) [5,6]. The primary and secondary collimators, as well as other structures that may affect the leakage and scattering radiation were also considered. The validation was obtained comparing the simulated results with those obtained experimentally.

A 8 x 8 x 3 m^3 radiotherapy room with walls and concrete ceiling (density = 2.43 g/cm^3) with 1 m thickness was modelled, as well as the extra slabs for primary radiation shielding. In addition, the floor has 20 cm thick concrete. Besides the equipment, the room was filled with atmospheric air (density = 0.001205 g/cm^3). Figure 1 presents the computational scenario with the adult phantom an the positioning table, the gantry of the LINAC, the positioning table made of carbon fiber, with 10 cm thickness, 17 cm wide and 200 cm length, supported by a metallic base. The adult patient was represented by a female virtual anthropomorphic phantom, developed at the Federal University of Pernambuco (UFPE – Brazil) [13]. This phantom has 60 kg of body mass and 1.63 m of height and is composed of more than a hundred organs and tissues with dosimetric importance. Is was formed with voxels of dimensions 2.4 x 2.4 x 2.4 cm^3, each one. To avoid unnecessary exposure of the patient's arms and, consequently, higher doses in the red bone marrow (RBM) and bone surface (BS), as performed in a real treatment, the arms of this phantom were removed.

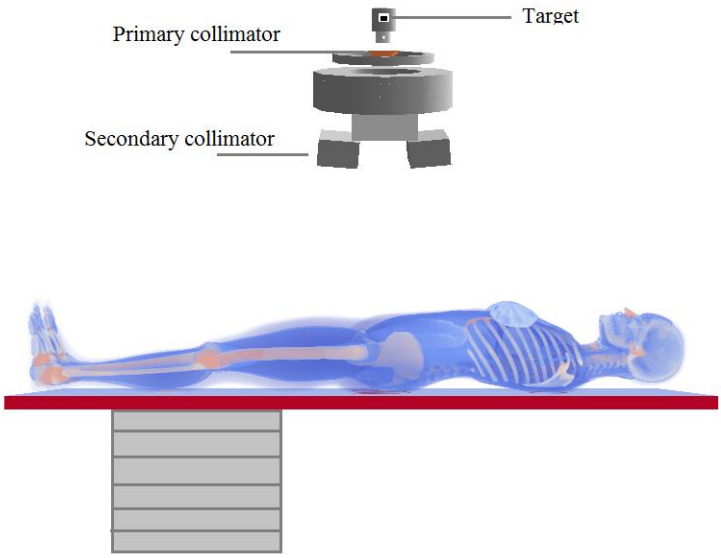


Figure 1. Computational model employed in this work for the radiotherapy procedure.

During the treatment, four treatment fields were applied. The radiation field was directed to the uterus. The treatment fields, and gantry angles, were: 16 cm ×16 cm (projections antero-posterior (AP/0°) and postero-anterior (PA/180°) and 16 cm ×12 cm (projections right lateral (RLAT/90°) and left lateral (LLAT/270º). The MCNP mesh tally was used to determine the photons fluence profile and test the beam collimation, with the LINAC operating at 6MV with the MLC.

2.2. Scenario validation

The validation of the beam properties was done by means of comparisons of the percentage depth dose (PDD) and dose profiles (Off-axis), calculated with the results of experimental measurements. The PDD results were simulated at various depths within a water phantom, using the tally *F8 (MeV/particle-source) to evaluate the energy deposited in the water along the central axis of the field. To determine the PDD and the Off-axis isodose, it was necessary to model a set of voxels to represent the radiation detectors. The first set consists of 400 voxels distributed along the central axis and the second set with 100 voxels along the axial axis. The energy deposited in each voxel of the central axis and the axial axis were used to determine the PDD and Off-axis, respectively. For the determination of the PDD, voxels of dimensions 2.5 x 2.5 x 0.1 cm^3 were used, and 1.0 x 1.0 x 0.4 cm^3 voxels were used for Off-axis calculations. The PDD calculations were made with the detectors spaced 1 mm apart, and during experimental measurements, they were spaced 0.5 cm apart. The spatial distribution of the electron source along the xy axis was the Gaussian with a half height width (FWHM) of 0.13 cm. The PDD and Off-axis simulations were performed using a PMMA phantom of dimensions 40 x 40 x 40 cm^3 filled with water. The phantom has open top and 1 cm thick PMMA. The Varian 2100c LINAC was operated (experimentally) with a voltage of 6 MV and the photon beam irradiating a field of 10 x 10 cm^2 with a source-surface distance (SSD) of 100 cm. Figure 2 shows the computational model used to determine the dose profile (Off-axis) and PDD.

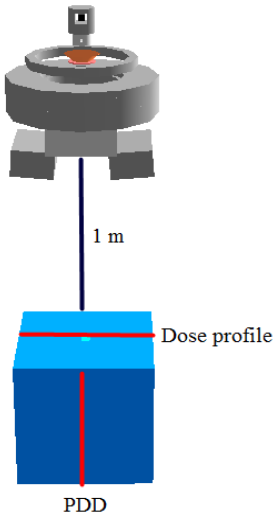


Figure 2: Computational model used in determination of the PDD and Off-axis ratio.

The PDP and Off-axis measurements were performed using a Farmer ionization chamber (model FC65/P) with a sensitive volume of 0.6 cm³. The PDD was measured with the ionization chamber positioned along the central axis with depths ranging from 0.5 to 30 cm in 0.5 cm steps. The Off-axis was measured along the axial axis with 0.025 cm steps. PDD and Off-axis were normalized by the absorbed dose at 10 cm depth on the central axis.

2.3. Dosimetric Calculations

In this study, a set of absorbed doses in organs and tissue located inside, or in the proximity, of the target area during cervix uterus radiotherapy for an adult patient was determined. The dosimetric results were due to the primary photons and secondary electrons that were scattered. The absolute dose of a set of organs and tissues with dosimetric importance, recommended by the International Commission on Radiological Protection [14], were calculated using Equation 1. The assumed prescribed treatment delivered 45 Gy to the target area of the cervix uterus. This amount was divided into 28 fractions, where each day 1.8 fractions were delivered, over 25 days that were divided in groups of 5 days in a row, as normally carried out in these treatments.

$$D(Gy) = \frac{D_T}{D_C} x D_P \quad (1)$$

D_T is the estimated absorbed dose in each organ or tissue T, D_C is the dose in the uterine colon volume and D_P is the total dose prescribed for all radiotherapy treatment. In this study, the ratio $\frac{D_T}{D_C}$ is determined as the conversion factor (CF).

The dose deposition was determined using the tally F6:p (MeV/g/particle), which could be converted into Gy, for all organs and tissues, except for the red bone marrow (RBM), where the tally ∗F4 (MeV/cm^2/particle) was used. For all simulations, to determine the organ doses 5.0E+08 particles histories were used, to achieve satisfactory results accuracy. To assess the beam properties (PDD, Off-axis ratio and photon fluence) 1.0E+09 particles histories were used, providing results with less than 2% uncertainty.

3. Results and Discussion

3.1. Dosimetric properties of the simulated radiation beam

Figure 3 shows the comparison between the PDD curves calculated with the MCNPX and those measured with the ionization chamber, at various depths in the water phantom, for a field size of 10 x

10 cm². The results were normalized to a dose corresponding to a depth of 10 cm (d_{10}), a region of more stability than d_{max}. The difference between the experimental and simulated results is within ± 2%.

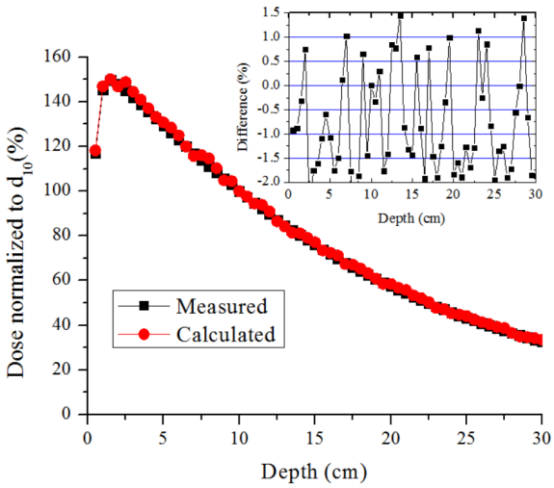


Figure 3. Measured and calculated (MCNPX) PDD for a Varian 2100c with 6 MV beam.

The lateral profiles, measured and calculated, at a depth of 10 cm are shown in Figure 4. It is noted that the distances of the detectors decrease with respect to the center of the beam. The simulated Off-axis is slightly overestimated in the region between -5 and -2.5 cm and 2.5 and 5 cm. These differences (< 4%) between the simulated and experimental results are attributed to the small volume of the detectors, immersed in the water phantom however, this does not affect the quality of the results. In the overall set of results, the Off-axis ratio is practically uniform in the field of 10 x 10 cm², showing that the geometry of the flattening filter and the modelled collimators are correct. In the regions near the edge, the calculated and experimental results presented differences of less than 2%.

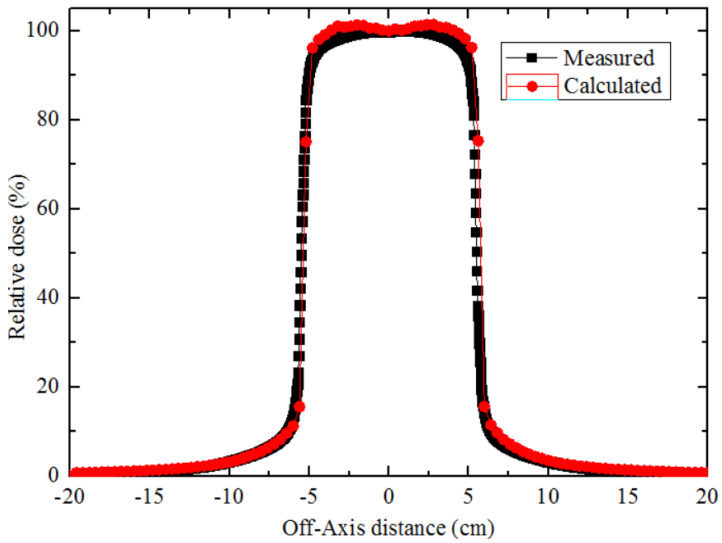
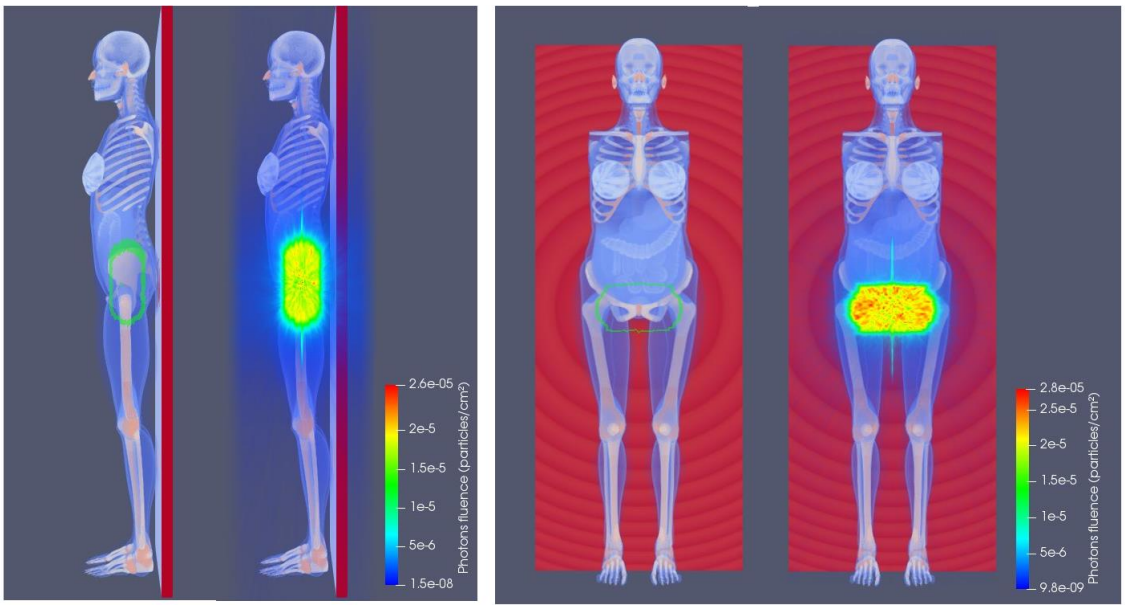


Figure 4. Measured and calculated (MCNPX) lateral profile – Varian 2100c LINAC with 6 MV beam and (10 x 10) cm² field.

Besides the dose profile, the beam collimation, for the 16×16 (AP/PA) and 16 x 12 cm^2 (RLAT/LLAT) reference fields with the MLC were also evaluated. In this part of the work, a mesh tally MCNPX command was utilized. This command allowed the creation of the photon fluence maps for the four projections that were studied in this work. In Figure 5, it is possible to view that the radiation field margins with MLC are properly delimited, which confirm the correct collimation.



(a) (b)

Figure 5. Photon fluence maps (particles/cm^2): View of the beam collimation for right lateral projection RLAT (a) and antero-posterior AP projection (b) of the treated region of the FASH3 anthropomorphic phantom.

3.2. Dosimetric results

In this study, the CF values were calculated, as a function of the gantry angle, for absorbed doses of a set of organs and tissues located inside and outside the treatment region of an adult patient with uterine cancer, submitted to a photon beam of 6 MV. The results of these factors by projection and the absorbed dose of the complete treatment are shown in Table 1. Using the mean CF value, by projection of each organ, the absolute absorbed dose was determined for the major organs and tissues of dosimetric importance suggested by the ICRP 103 [14] were determined.

It is possible to observe that the highest dose values were obtained for organs located near, or within, the irradiated volume (uterine colon), such as large intestine (colon), small intestine, gonads and bladder. The doses calculated for the bladder (44.3 Gy) and gonads (45.6 Gy), which are within the irradiated area, received a dose similar to the prescribed dose of the uterine colon (45 Gy). Another important fact is that for the same field size (AP/PA), the results of the CF values for AP/0° projection, were mostly higher than for the PA/180° projection. In these cases, the gantry is under the table, which may shield the low energy photons. The spine of the patient may also shield these photons, reducing the dose for the organs located in this region. For the RLAT/90º and LLAT/270º projections, the CF values were mostly similar, fact that can be attributed to the symmetrical distributions of the organs in relation to the radiation source. For the same irradiation conditions, the skin and the bone surface, which are evenly distributed throughout the human body, the differences in CF values were small, i.e., they do not depend on the irradiation position. In addition to these differences, it is important to note

that the breasts, organs located superficially and distant from the target organ, obtained an average absorbed dose of 0.30 Gy, which is a value close to the mean value calculated for the heart (0.29 Gy), which is deeper. This fact can be associated with the contribution of scattered radiation from the collimators and the leakage radiation of the LINAC head. The organs relatively distant from the non-targeted ones presented the lowest CF values, since they received just the scattered radiation.

The percentage relative uncertainty of each organ and tissue estimated by the MCNPX code is presented between parentheses. The eye and eyes lenses have relatively small volumes and, therefore, the statistical uncertainties of these organs were the largest, and they varied between 7% and 27%. For all other organs and tissues, in all evaluated situations, the uncertainties in the CF values were below 4%.

Table 1. CF values for absorbed doses per beam projection for a treatment using a 2D planning system. The relative uncertainties of the simulations are shown in parentheses.

	Conversion Factor (CF)				Average
Organs and tissues	**AP**	**LLAT**	**PA**	**RLAT**	**dose (Gy)**
Bone marrow	2.55E-02 (0.3%)	5.26E-02 (0.4%)	2.67E-02 (0.3%)	5.94E-02 (0.4%)	1.85E+00
Colon	2.52E-01 (0.1%)	2.93E-01 (0.2%)	2.74E-01 (0.1%)	2.89E-01 (0.2%)	1.25E+01
Lung	6.46E-03 (0.4%)	5.63E-03 (0.6%)	6.76E-03 (0.4%)	5.53E-03 (0.6%)	2.74E-01
Stomach	2.36E-02 (0.5%)	1.63E-02 (0.8%)	1.92E-02 (0.5%)	1.66E-02 (0.8%)	8.51E-01
Breast	9.05E-03 (0.6%)	6.03E-03 (1.0%)	5.69E-03 (0.7%)	6.14E-03 (1.0%)	3.03E-01
Remainder tissues	1.80E-02 (0.0%)	2.37E-02 (0.1%)	1.60E-02 (0.1%)	2.29E-02 (0.1%)	9.07E-01
Gonads	1.08E+00 (0.3%)	1.03E+00 (0.5%)	8.92E-01 (0.3%)	1.05E+00 (0.4%)	4.56E+01
Bladder	1.14E+00 (0.2%)	9.12E-01 (0.3%)	9.07E-01 (0.2%)	9.85E-01 (0.3%)	4.43E+01
Oesophagus	5.84E-03 (1.5%)	5.44E-03 (2.1%)	5.62E-03 (1.3%)	5.48E-03 (2.3%)	2.52E-01
Liver	2.09E-02 (0.4%)	1.16E-02 (0.6%)	1.73E-02 (0.4%)	1.17E-02 (0.6%)	6.93E-01
Thyroid	4.81E-03 (2.6%)	2.87E-03 (4.1%)	2.54E-03 (3.3%)	2.53E-03 (4.0%)	1.43E-01
Bone surface	1.26E-01 (0.1%)	1.89E-01 (0.1%)	1.03E-01 (0.1%)	1.91E-01 (0.1%)	6.85E+00
Brain	1.66E-03 (1.1%)	1.87E-03 (1.3%)	1.23E-03 (1.3%)	1.89E-03 (1.3%)	7.48E-02
Salivary glands	3.72E-03 (1.7%)	2.63E-03 (2.2%)	1.68E-03 (2.3%)	2.63E-03 (2.1%)	1.20E-01
Skin	9.01E-02 (0.1%)	7.55E-02 (0.1%)	6.94E-02 (0.1%)	7.77E-02 (0.1%)	3.52E+00
Uterus	1.00E+00 (0.2%)	1.00E+00 (0.2%)	1.00E+00 (0.2%)	1.00E+00 (0.2%)	4.50E+01
Heart	7.26E-03 (0.9%)	5.99E-03 (1.2%)	6.44E-03 (0.8%)	5.88E-03 (1.2%)	2.88E-01
Thymus	6.71E-03 (2.3%)	4.59E-03 (3.3%)	4.40E-03 (1.8%)	4.67E-03 (3.4%)	2.29E-01
Pancreas	5.33E-02 (0.5%)	2.32E-02 (1.0%)	4.25E-02 (0.5%)	2.35E-02 (1.0%)	1.60E+00
Spleen	1.49E-02 (1.0%)	1.40E-02 (1.1%)	1.36E-02 (1.0%)	1.36E-02 (1.1%)	6.30E-01
Lymphatic nodes	1.65E-01 (0.1%)	1.90E-01 (0.2%)	1.19E-01 (0.1%)	2.33E-01 (0.2%)	7.95E+00
Adrenals	1.60E-02 (1.8%)	1.20E-02 (2.3%)	1.57E-02 (1.6%)	1.19E-02 (2.3%)	6.25E-01
Gall bladder	4.57E-02 (1.0%)	1.74E-02 (1.5%)	3.25E-02 (1.0%)	1.79E-02 (1.6%)	1.28E+00
Region extra-thoracic	3.69E-03 (2.5%)	2.20E-03 (4.2%)	1.68E-03 (3.5%)	2.28E-03 (4.0%)	1.11E-01
Kidneys	2.31E-02 (0.5%)	1.74E-02 (0.8%)	2.35E-02 (0.4%)	1.67E-02 (0.9%)	9.09E-01
Oral mucosa	3.27E-03 (2.2%)	2.56E-03 (2.8%)	1.35E-03 (2.8%)	2.68E-03 (2.9%)	1.11E-01
Small intestine	2.91E-01 (0.1%)	2.39E-01 (0.2%)	1.97E-01 (0.1%)	3.12E-01 (0.2%)	1.17E+01
Muscle	1.62E-02 (0.0%)	2.21E-02 (0.1%)	1.47E-02 (0.1%)	2.09E-02 (0.1%)	8.31E-01
Eyes	3.03E-03 (3.3%)	2.05E-03 (4.8%)	8.79E-04 (6.5%)	2.15E-03 (6.0%)	9.12E-02
Eye lens	3.08E-03 (8.8%)	2.09E-03 (16%)	1.09E-03 (27%)	1.79E-03 (14%)	9.05E-02

4. Conclusions

In this work, a set of conversion factors and absorbed doses were determined using the Monte Carlo simulation and an anthropomorphic phantom, to represent a patient undergoing a radiotherapy treatment of uterine colon. The computational modelled scenario was composed of a virtual anthropomorphic phantom and a Varian Clinac 2100c LINAC with a 6 MV beam.

The gantry angles affect considerably the results. The majority of the organs near or inside the target volume were those that received the highest radiation doses. Regarding the influence of the gantry angle, the higher CF values were obtained for the AP/0º projection. Usually, the absorbed dose of the organs depends on the location, distribution of the organs in the body and the distance of the treated volume. Comparing the dose values with the prescribed value for the uterine colon, the organs and tissues outside the treated region that received the highest doses were the large intestine (28%), small intestine (26%), the lymph nodes and the bone surface (15%).

During the treatment, it is impossible to measure experimentally the doses due to the scattered radiation within the patient's body. Therefore, the CF values calculated in this study will be useful to readily estimate the absorbed doses during a uterine colon treatment. Besides the traditional analytical planning systems, the computational modelling presented in this study may be an alternative tool for dosimetry calculations.

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