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Dosimetric comparison of different allocations of I-125 source for brain tumor brachytherapy: a comprehensive simulation study using MCNP and TLD evaluation

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ABSTRACT

Introduction: Brachytherapy has proven to be an effective method for the treatment of brain tumours. Given the presence of sensitive organs in the brain that control vital bodily functions, it becomes paramount to optimize the dose distribution of these radiation sources. This study aims to evaluate the dose distribution characteristics of different implantation of I-125 sources using Monte Carlo simulations for the treatment of brain tumours.

Materials and Methods: In this study, we first calibrated GR-207A TLDs using an orthovoltage machine operating at 100 keV energy, deriving the calibration curve. Subsequently, I-125 (Model IR-Seed2) source manufactured by Iran was exposed to TLDs within a Perspex phantom for 48 hours, and absorbed doses were determined in the perpendicular direction to the source's longitudinal axis at various distances. Next, patient head simulations were conducted in the MCNPX code using DICOM CT images and the Scan2MCNP program to assess different number of I-125 sources implantation. The simulation accuracy was evaluated using the third type Mesh Tally method and data obtained from TLD measurements.

Results: The dose distribution achieved with the implantation of four I-125 sources within the tumour exhibited a superior response compared to configurations involving one or two sources for the treatment of brain tumours. Additionally, this approach significantly reduced the required source implantation time.

Conclusion: Using one or two sources within the tumour is not suitable for brain tumour treatment due to significant damage and the risk of necrosis. In contrast, using four sources provides a better dose distribution and is a superior approach for brain tumour treatment.

Key words: brachytherapy, brain tumour, I-125, MCNP, Scan2MCNP, TLD

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INTRODUCTION

Over 100 types of brain tumours have been identified to date. Severe brain tumours often exhibit resistance to conventional treatments such as surgery, chemotherapy, and external radiotherapy. While radiosurgery offers the best local control for such cases, it can lead to substantial tissue damage and side-effects on the nervous system, consequently diminishing patient survival rates and quality of life [1, 2].

The fundamental objectives of radiotherapy encompass the delivery of an adequate radiation dose to cancerous cells while minimizing damage to healthy tissues [3]. Brachytherapy, involving the precise placement of radioactive sources inside the tumour and the delivery of the majority of radiation energy over very short distances, effectively aligns with these goals. The use of brachytherapy for brain tumour treatment was pioneered by Mundinger in 1960, initially employing Ir-192 sources. However, in 1979, Mundinger's research demonstrated superior outcomes when using I-125 sources instead of Ir-192. Consequently, I-125 sources have become the standard choice for brain tumour treatment [4].

Given the presence of critical organs within the brain that govern various bodily functions, the precise implantation of radiation sources and the resulting dose distribution take on heightened significance compared to other anatomical regions. The dosimetry parameters of, I-125 (Model IR-Seed2) sources manufactured by Iran align with international standards and are comparable to similar standard sources. Consequently, this study focuses on

evaluating Iranian-manufactured I-125 (Model IR-Seed2) sources for brain tumour treatment through Monte Carlo simulations, with a particular emphasis on assessing dose distribution for various number of I-125 sources implantation configurations [5].

MATERIAL AND METHODS

In this study, treatment planning of brain tumours by I-125 (Model IR-Seed2) source manufactured by Iran was performed using by Scan2MCNP program in the MCNPX code for different source allocation. In the following, the calibration of TLDs was performed and to evaluate the validity of the simulations, Perspex phantom and TLD (Thermoluminescent Dosimeter) were employed.

IR-Seed2 I-125 source

The IR-Seed2 I-125 source is composed of a cylindrical titanium capsule measuring 48 mm in length and 0.8 mm in diameter. Internally, the source boasts a diameter of 0.7 mm and contains six resin beads with a diameter of 0.5 mm. The surface of these beads is superficially coated with I-125 [5].

TLD calibration

The accuracy of the simulations was evaluated using GR-207A TLDs. These TLDs were in the form with diameter of 4.5 mm and a thickness of 0.8 mm, and demonstrating a linear response in the range of 10^{-6} to 12 Gy [6]. The TLD data obtained from the LTM TLD reader (Fimel, Vélizy, France), and represented as numbers in Normalized Counts (NC) or simply counts, exhibiting inherent random variations. To determine the absorbed dose, both individual and group calibrations were performed.

For individual calibration, ECC coefficients were calculated. The irradiation was performed in a Perspex phantom under the condition of a 15 cm^2 × 15 cm^2 field size at 100 cm Source To Surface Distance (SSD) and depth of 2 cm, and of the 6 mV energy. Ten Perspex slabs (each with a thickness of 1 cm) were placed under the TLDs to create a complete electron equilibrium condition. Subsequently, the TLDs were read using an LMT reader, and ECC or correction coefficients were computed for each TLD using the following equation:

$$〖ECC〗_j = \left(< TLR >\right) 〖TLR〗_j$$

Where:

〖ECC〗_j: The individual calibration coefficient of number j TLD

TLR: The average of TLDs reading at equal radiation.

〖TLR〗_j: The response of number j TLD to equal radiation

The group calibration of the TLDs was performed utilizing an Orth voltage machine operating at 100 kVp energy and a dose rate of 186.6 units. To ensure electron equilibrium conditions, two Perspex sheets were placed beneath the TLDs. Subsequent to irradiation, the TLDs were subjected to reading by an LMT reader, and the calibration curve for the TLDs was established based on the ECC coefficients, particularly in the context of 100 kVp energy.

Scan2MCNP software

The initial step in Monte Carlo-based simulations involves the crucial task of importing patient data into the MCNP program. Scan2MCNP software plays a pivotal role in this context. It is capable of converting DICOM images derived from MRI and CT imaging systems into an input file compatible with the MCNP code.

Scan2MCNP software boasts a comprehensive library encompassing a diverse array of materials, each accompanied by their respective densities. This library includes a wide spectrum of materials, such as various gases, liquids, metals, and body tissues like bone, soft bone, soft tissue, lung, and more.

Each image within this framework is characterized by grayscale values ranging from 0 to 256. For instance, pixels appearing white in the images possess a colour intensity value of 256 and correspond to bone tissue. Conversely, pixels appearing black exhibit a colour intensity value of 0, signifying air. The remaining pixels exhibit

a diverse range of colour intensities falling between 0 and 256, each indicative of different materials employed in the simulation [7, 8].

Upon implementing the Crop command and applying meshing within the Scan2MCNP program, the total count of cells that are simulated in MCNPX is precisely 243,089. These individual cells each possess dimensions measuring 0.094 cm × 0.094 cm × 0.2 cm. This specific cell size is well-suited for conducting investigations pertaining to low-energy brachytherapy.

Monte Carlo calculations

In this study, simulations were conducted using the Monte Carlo N-Particle radiation transport code MCNPX 2.7.0, developed by The Los Alamos National Laboratory (LANL). MCNPX offers various tally options for calculating diverse physical properties within the simulation. To reduce the volume of inputting data, especially in cases with a large number of cells, the mesh tally method is applicable. Consequently, the MCNP simulation utilized the third type of mesh tally, involving the tracking of 1010 particles.

The simulations provided average absorbed dose values within each voxel, focusing on a case where each radiation source had an activity of 3 mCi. The output from MCNPX was in MeV/cm^3, which required normalization by density to obtain absorbed dose values. The photon spectrum for I-125 used in MCNPX simulations was derived from ICRU-38, with an energy cut-off set at δ=5 keV, accounting for characteristic X-ray production in titanium [9, 10].

To validate the accuracy of the MCNPX simulations, absorbed dose calculations were performed for water within a Perspex medium, generating data that could be compared to TLD measurements. The simulation code was executed with 1010 particles, ensuring that the program's average error across all cells remained below 5%.

The results from the MCNPX simulations, presented as isodose curves, were visualized using MATLAB software version 7.9.0 (R2009b). This involved employing various MATLAB commands such as reshape, resize, imrotate, and rcond to process and superimpose the isodose curves onto the patient's MR images, enhancing the visualization of the simulation outcomes.

Phantom

To evaluate the concordance between the MCNP simulations and TLD measurements, a phantom composed of Perspex material with a density of 1.19 g/cm^3 and a chemical composition comprising 8% Hydrogen (H), 60% Carbon (C), and 32% Oxygen (O) was fabricated [11]. As depicted in Figure, the phantom featured a centrally positioned groove designated for the placement of the radiation source (Figure 1). Additionally, grooves were meticulously carved at distances of 0.5 cm, 1 cm, 1.5 cm, 2 cm, 3 cm, 4 cm, and 5 cm along the perpendicular axis to accommodate the TLDs.

Fig. 1. The phantom used for the I-125 source dosimetry

The simulation of the I-125 source using the MCNPX code was carried out within a Perspex phantom measuring 11 cm^3 × 11 cm^3 × 11 cm^3, closely resembling the practical irradiation conditions with a lattice-based structure simulation.

Placement of sources in the tumour

The typical approach for treating brain tumours in patients involves the implantation of a solitary I-125 source within the affected area. Therefore, in the simulation process, the focus extended beyond merely considering the size, shape, and volume of the tumour. Instead, simulations were conducted to explore different numbers of I-125 source implantation. Initially, a simulation was performed with a single source placed at the tumour's centeR. Subsequently, simulations were conducted with 2, and 4 sources implanted within the tumour region, each positioned 1 cm apart from one another. Figure illustrates the simulation involving the placement of two sources within the tumour using the MCNPX code (Figure 2).

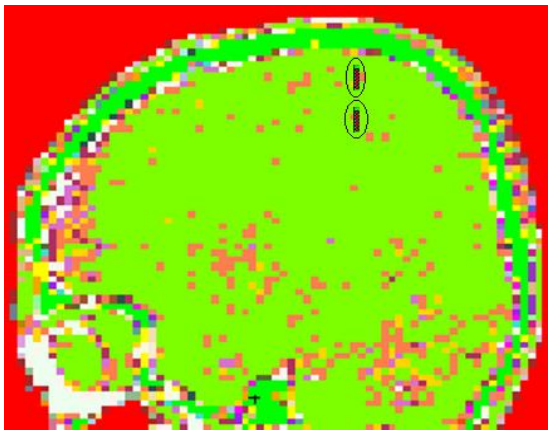

Fig. 2. In the MCNPX code, two sources were inserted within the tumor

Treatment time calculation

In brachytherapy, the timing and spatial arrangement of radiation sources play a critical role in determining the administered radiation doses. To address this, detailed medical information from a low-grade patient with a tumour volume of 17 cm^3 was provided by an oncologist. The prescribed dose at the tumour's periphery was set at 6000 cGy. Given that the source possessed an activity level of 3 mCi, the treatment duration was calculated using MCNP data.

Utilizing the dose rate and the prescribed dose as reference points, the treatment time was determined using Equation 2. Within the context of the mesh tally method in the code's output calculation, the results were initially obtained per particle. These values were then converted into delivered doses using Equation 1, which subsequently allowed for the calculation of the treatment time as defined in Equation 2.

$$Dose\ (cGy) = A*3.7\times E010\times T(s)\times 1.6E-019\times F\times M \quad (1)$$

$$Time(h) = (D(rad))/(D(rad/h)) \quad (2)$$

In this context, a denotes the source's activity in mCi (millicuries), T represents the duration of source irradiation, F signifies the value derived from the MCNPX code, and M stands for the absorption coefficient of the radioactive material, specifically 1.47 for I-125 [12].

Simulation accuracy

I-125 source was simulated in the center of a Perspex sphere with a 10 cm diameter. Absorbed dose values were collected in the perpendicular direction to the source axis using a third type of square mesh. Meshing was performed with cubic voxels measuring 0.8 mm in length, covering the entire space around the source up to a distance of 7 cm.

Patient DICOM Images

In this study, the patient's CT images were employed to simulate the body, while 3D Scan2MCNP software was employed for simulating the brain. The head of a patient with a brain tumour was simulated using 41 CT images from the patient's dataset. The tumour in this particular case had a circular shape with an estimated radius of 1.6 cm and an approximate volume of 17.5 cm^3. Figure provides a visual representation of the patient's CT and MR images (Figure 3).

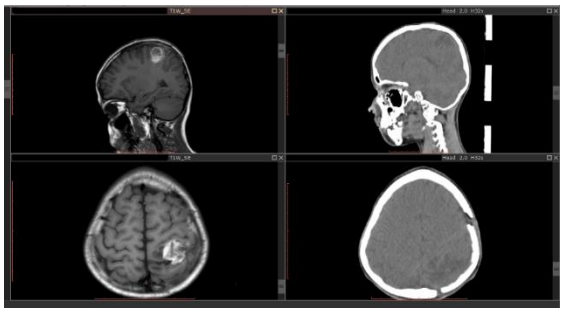

Fig. 3. CT and MR images of patient with brain tumour

RESULTS

By multiplying the ECC coefficient for each TLD by the corresponding reading, the impact of random variations could be minimized, resulting in a more consistent value. Table displays the correction coefficients that were computed for each TLD, The ECC values in individual calibration indicate that they are in the range of $0.993 \leq ECC \leq 1.022$ (Table 1). These values are close to 1, indicating a low deviation. While Figure illustrates the calibration curve for the TLDs at 120 kVp (Figure 4).

Tab. 1. The ECC correction coefficients for TLD calibration

TLD NO	ECC	TLD NO	ECC
1	0.964	10	1.021
2	0.999	11	1.019
3	0.972	12	0.993
4	1.002	13	0.978
5	1.001	14	0.997
6	0.992	15	1.015
7	1.01	16	1.022
8	0.976	17	1.022
9	1.024	18	1.011

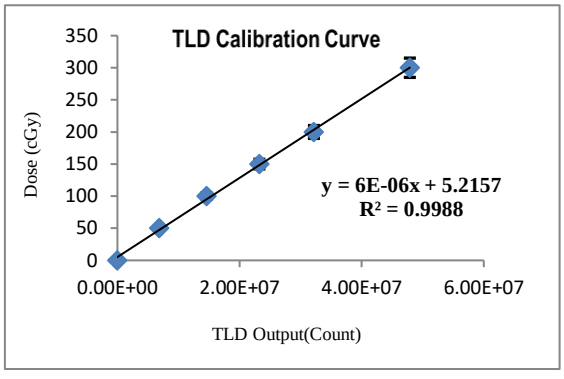

Fig. 4. TLDs calibration curve

To verify the precision of the MCNPX simulations, calculations of absorbed doses were conducted for water within a Perspex medium, yielding data suitable for comparison with TLD measurements. Table represents the dosimetry results of TLD and simulation in MCNPX code in the perpendicular direction of source axis at different distances (Table 2).

Tab. 2. The comparison of simulation and TLD results

Distance from center of source (cm)	MCNPX calculated with Mesh tally (cGy)	TLD measured (cGy)	Difference TLD & Mesh tally %
0.5	406.64	433.7	6.2
1	93.69	100.02	6.3
1.5	40.09	42.63	5.9
2	20.61	22.3	7.5
3	5.39	6.06	11
4	2.02	2.21	8.5
5	1.16	1.302	10.9

Table represents dose delivery to different volumes during total treatment time. DVH of a source implant was showed in (Table 3 Figure 5).

Tab. 3. Dose delivery to tumour in single source implant

Treatment time (Day)	Dose (Gy) calculate MCNP	Volume Dose (cm^3)	Tumor Volume (cm^3)
550	600	1.44	17.2
550	200	7.03	17.2
550	100	18.13	17.2
550	60	44.2	17.2

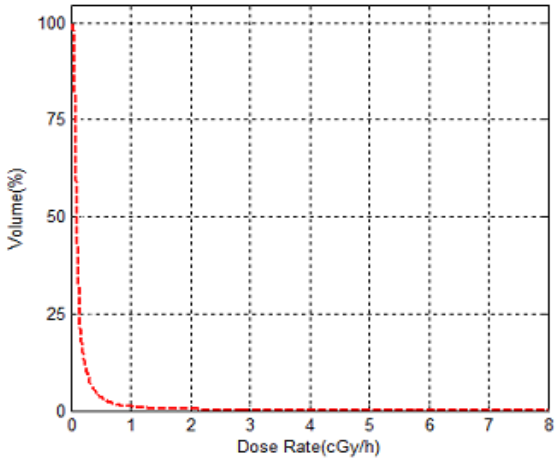

Fig. 5. DVH of single source implant in tumour

The isodose curves for a single source implant with 3 mCi activity were generated and subsequently imported into the CT and MR image. Figure visually represents these isodose curves. Based on the information gleaned from the isodose curves and simulation data, it was determined that the necessary duration to deliver a 60 Gy dose to the tumour would be approximately 550 days (Figure 6).

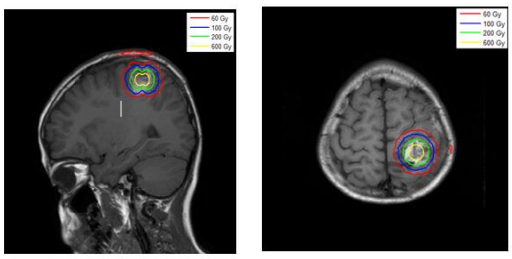

Fig. 6. isodose curves of one source implant in tumour by Scan2MCNP program

Figure 7 illustrates the isodose curves resulting from the implantation of two sources within the tumour, as determined through simulation in the MCNPX code (Figure 7). Comparable to the treatment with a single source implant, each source had an activity of 3 mCi, and the calculated duration for the source implantation was 132 days. Table provides an overview of the dose delivery to various volumes over the course of the entire treatment (Table 4). Additionally, Figure depicts the DVH (Dose-Volume Histogram) corresponding to the two-source implantation (Figure 8).

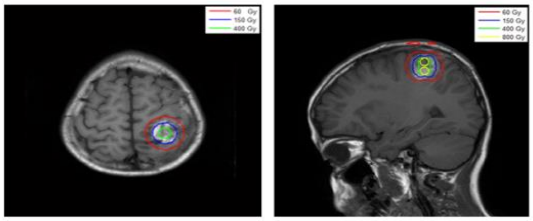

Fig. 7. Isodose curves of two sources implant in tumour by Scan2MCNP program

Tab. 4. Dose delivery to tumour in two sources implant

Treatment time (Day)	Dose (Gy) calculate MCNP	Volume Dose (cm^3)	Tumor Volume (cm^3)
132	800	0.51	17.2
132	400	1.77	17.2
132	150	7.3	17.2
132	60	26.82	17.2

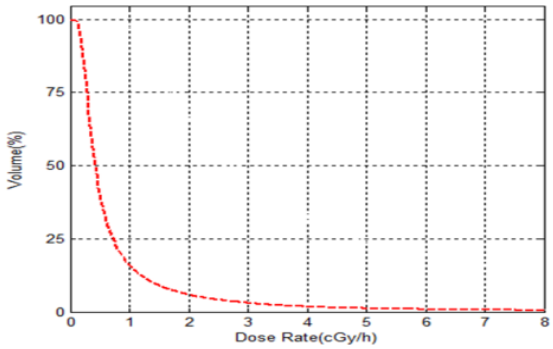

Fig. 8. DVH of two sources implant in tumour

In the case of implanting four sources within the tumour, the source implantation time was determined to be 52 days. Table provides an overview of the dose delivery to various volumes throughout the entire treatment duration (Table 5). Figure displays the isodose curves resulting from the implantation of four sources within the tumour (Figure 9). Additionally, Figure presents the DVH corresponding to the four-source implantation (Figure 10).

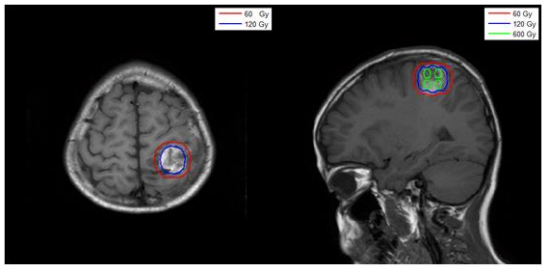

Fig. 9. Isodose curves of four sources implant in tumour by Scan2MCNP program

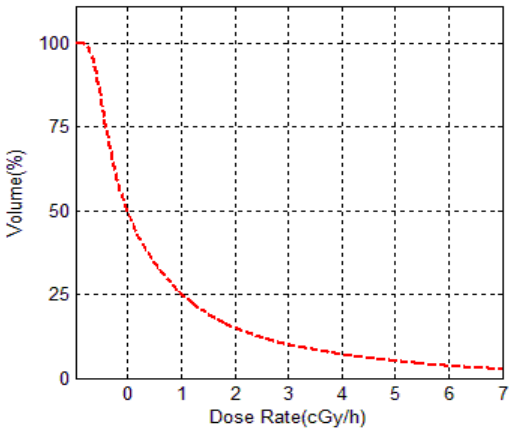

Fig. 10. DVH of two sources implant in tumour

DISCUSSION

Comparing the results of TLD dosimetry and Monte-Carlo simulation using the third type Mesh Tally in MCNPX revealed an acceptable level of agreement between these datasets. While the use of Mesh Tally does increase the computational time, it proves to be a valuable approach for brachytherapy source dosimetry, significantly reducing the code's input file volume due to the small size of simulated cells in brachytherapy.

When comparing different source implantation strategies, it became evident that a single-source implant within the tumour, mainly due to the non-uniformity of dose distribution at the source's ends, resulted in damage to a considerable volume of tissues (44.2 cm^3), which is three times the size of the treatment volume (17.2 cm^3). If we consider the 300% isodose curve as the threshold for causing necrosis, a single-source implant would lead to approximately 9 cm^3 of brain tissue necrosis.

However, the most promising approach was the implantation of four sources within the tumour. This method not only significantly reduced the source implantation time but also achieved a more uniform dose distribution compared to one- and two-source implants. In this scenario, only 22 cm^3 of brain tissues were affected by cell killing, with a mere 1.7 cm^3 experiencing severe necrosis, and this occurred in tissues very close to the source.

Considering that the head contains critical organs responsible for controlling other parts of the body, it becomes evident that a single-source implant within the tumour is not ideal due to the significant damage inflicted on normal tissues and the risk of severe necrosis. While two-source implantation delivers a more uniform dose to the tumour's surface and affects a smaller volume of normal tissues, it still falls short of being an entirely appropriate method due to the risk of necrosis.

Among the methods examined, the implantation of four sources within the tumour stands out as the most suitable approach for brain tumour treatment. This method not only ensures the delivery of a consistent dose to the tumour but also minimizes damage to critical organs, all while avoiding severe necrosis within the head.

On the other hand, a linear implantation of the source within the tumour reduced the dose to the surrounding tissues but still caused damage to 26.82 cm^3 of brain tissue. In the case of two sources implanted, the necrotic region was reduced to 5.3 cm^3, significantly lower than that caused by a single-source implant.

CONCLUSION

The study demonstrates that the choice of the number of I-125 sources implanted in brain tumours significantly impacts treatment outcomes. While a single source implantation may lead to non-uniform dose distribution and damage to healthy tissues, the implantation of four sources offers improved dose distribution, reduced damage

to normal brain tissue, and shorter treatment times. This approach shows promise as a viable method for brain tumour brachytherapy and warrants further investigation and clinical application. Ultimately, the goal of such research is to improve the quality of care and outcomes for patients with brain tumours, providing them with a more effective and less damaging treatment option.

CONFLICTS OF INTEREST

There are no conflicts of interest. The authors report no proprietary or commercial interest in any product mentioned or concept discussed in this article.

REFERENCES

1. Zacharaki, EI., Wang, S., Chawla, S., Soo, Y. D., Wolf, R., et al. Classification of brain tumor type and grade using MRI texture and shape in a machine learning scheme. Magn Reson Med: Off J Int Soc Magn Reson Med. 2009;62:1609-1618.
2. Yadollahpour, A., Nasrollahi, H. Quantitative electroencephalography for objective and differential diagnosis of depression: a comprehensive review. Glob. J Health Sci. 2016;8:249.
3. Khan, FM., Gibbons, JP. Khan's the physics of radiation therapy. Lippincott Williams Wilkins. 2014. [Google Scholar]
4. Poher, A., Berumen, F., Ma, Y., Perl, J., Beaulieu, L. Validation of the TOPAS Monte Carlo toolkit for LDR brachytherapy simulations. Physica Medica. 2023;107.
5. Sheikholeslami, S., Nedaie, HA., Sadeghi, M., Pourbeigy, H., Shahzadi, S., et al. Monte Carlo calculations and experimental measurements of the TG-43U1-recommended dosimetric parameters of 125I (Model IR-Seed2) brachytherapy source. J Appl Clin Med Phys. 2016;17:430-441.
6. Furetta, C. Handbook of thermoluminescence. World Sci. 2010.
7. Graham, R.N., Perriss, R.W., Scarsbrook, A.F. DICOM demystified: a review of digital file formats and their use in radiological practice. Clin radiol. 2005;60:1133-1140.
8. Smyth, J.M., Sutton, D.G., Houston, J.G. Evaluation of the quality of CT-like images obtained using a commercial flat panel detector system. Biomed imaging interv j. 2006;2.
9. Newhauser, W. International commission on radiation units and measurements report 78: Prescribing, recording and reporting proton-beam therapy.
10. Popescu, C.C., Wise, J., Sowards, K., Meigooni, A.S., Ibbott, G.S. Dosimetric characteristics of the Pharma Seed™ model BT-125-I source. Med phys. 2000;27:2174-2181.
11. Saidi, P., Sadeghi, M., Shirazi, A., Tenreiro, C. Monte Carlo calculation of dosimetry parameters for the IR08-brachytherapy source. Med phys. 2010;37:2509-2515.
12. Bushberg, J.T., Boone, J.M. The essential physics of medical imaging. Lippincott Williams Wilkins. 2011.