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Original research article

A Monte Carlo study on dose distribution validation of GZP6 ^{60}Co stepping source

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ARTICLE INFO

Article history:
Received 30 April 2012
Received in revised form
22 August 2012
Accepted 22 October 2012

Keywords:
High dose rate
GZP6 brachytherapy system
Stepping source
Monte Carlo

ABSTRACT

Aim: Stepping source in brachytherapy systems is used to treat a target lesion longer than the effective treatment length of the source. Cancerous lesions in the cervix, esophagus and rectum are examples of such a target lesion.

Background: In this study, the stepping source of a GZP6 afterloading intracavitary brachytherapy unit was simulated using Monte Carlo (MC) simulation and the results were used for the validation of the GZP6 treatment planning system (TPS).

Materials and methods: The stepping source was simulated using MCNPX Monte Carlo code. Dose distributions in the longitudinal plane were obtained by using a matrix shift method for esophageal tumor lengths of 8 and 10 cm. A mesh tally has been employed for the absorbed dose calculation in a cylindrical water phantom. A total of 5×10^8 photon histories were scored and the MC statistical error obtained was at the range of 0.008–3.5%, an average of 0.2%.

Results: The acquired MC and TPS isodose curves were compared and it was shown that the dose distributions in the longitudinal plane were relatively coincidental. In the transverse direction, a maximum dose difference of 7% and 5% was observed for tumor lengths of 8 and 10 cm, respectively.

Conclusion: Considering that the certified source activity is given with ±10% uncertainty, the obtained difference is reasonable. It can be concluded that the accuracy of the dose distributions produced by GZP6 TPS for the stepping source is acceptable for its clinical applications.

1. Background

Brachytherapy is a method of treatment in which sealed radioactive sources are used to deliver radiation to tumor at a short distance through interstitial, intracavitary or surface applications.[1] Although not as widespread as ^{192}Ir sources, ^{60}Co is also available on afterloading equipment dedicated to high dose rate (HDR) brachytherapy.[2] In modern brachytherapy, treatment planning is performed to define a planning

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http://dx.doi.org/10.1016/j.rpor.2012.10.004

target volume (PTV) and to spare adjacent critical structures. Optimization procedure in the determination of the treatment parameters is usually to minimize the variations of the dose values on the surface of the PTV. This aim is achieved by defining a number of points on the PTV surface and determining dwell times (dwell weights) for the source dwell positions within the applicators. For this purpose, stepping sources are used as an option and are loaded in the applicator.[3] Several Monte Carlo methods have been employed to assess the absorbed dose near brachytherapy stepping sources.[4–7] Also there are other Monte Carlo based studies in which dose distributions were calculated around non stepping brachytherapy sources.[8,9] Since the treatment planning process is very important in assuring an optimum treatment in brachytherapy the determination of dose distribution becomes an important task. Therefore, it is necessary to know the extent of dosimetric errors including over- or under-dosage of the target volume.[7] The quality control of treatment planning has been the subject of several studies, and was reviewed in the report by task group (TG) number 59 of the American Association of Physicists in Medicine (AAPM).[10] There are different studies which have already been performed on the GZP6 unit. Bahreyni et al. evaluated air kerma strength for the GZP6 source no. 3 certified by GZP6 unit through in-air measurements and Monte Carlo simulations of this source.[11] Mesbahi performed a Monte Carlo study on calculation of radial dose function for the GZP6 sources nos. 1, 2 and 5.[12] Naseri and Mesbahi in another study simulated the three mentioned GZP6 sources and verified dose distributions for the three sources based on comparisons of the dose distributions obtained from Monte Carlo method by those from GZP6 treatment planning system.[13] As another study, they measured air kerma strength for the three mentioned GZP6 sources.[14] In a previous work by Bahreyni et al. a matrix shift method was developed toward simulation of stepping movement of the GZP6 source no. 6.[15]

2. Aim

As far as we are aware, at the current time there is no published report on the verification of dose distributions using the GZP6 treatment planning system for the stepping source (source no. 6). In this study, the dose distributions calculated by the GZP6 treatment planning system for the stepping source were evaluated using Monte Carlo simulation and the application of a matrix shift method.

3. Materials and methods

3.1. GZP6 stepping source

GZP6 afterloading unit (manufactured by the Nuclear Power Institute of China) has six ^{60}Co source braids including one stepping and five non-stepping source braids. It is used for intracavitary treatments such as brachytherapy of cervix, rectum, esophagus and nasopharynx malignancies. The GZP6 stepping source consists of a ^{60}Co active cylinder with diameters of 2 mm and 1 mm. The source has a very thin nickel plating which is covered by a titanium capsule. The overall length of the titanium capsule is 3.5 mm and its outer diameter is 1.5 mm. There are a number of inactive steel pellets in the source braid with a diameter of 1.5 mm. The active and non-active pellets are covered by a steel spring. A schematic representation of the GZP6 stepping source is illustrated in Fig. 1.

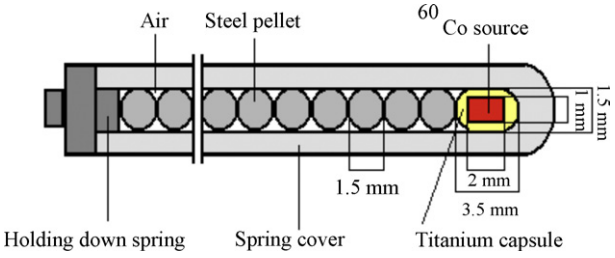

Fig. 1 – A schematic diagram illustrating the stepping source of the GZP6 brachytherapy unit.

3.2. Treatment planning

GZP6 unit is composed of an afterloading system as well as a treatment planning system. The name of the TPS is GZP6 treatment planning system. This planning system displays dose distribution in the form of isodose curves for the GZP6 sources. The treatment planning system uses Sievert integral for its dose calculations. In the Sievert integral method, a linear source is divided into several segments. Each segment is small enough to be assumed as a point source. Using point source approximation, the integration of the exposure rate contributions from each segment to a given point is then calculated. The following equation represents a classical Sievert integral:

$$I(x,y)=\frac{\mathrm{Meq}\cdot\Gamma_{\mathrm{Ra}}}{Ly}e^{\mu t'}\int_{\theta_1}^{\theta_2}e^{-\mu t\sec\theta'}d\theta' \quad (1)$$

In which, Meq is total source strength (mg Ra Eq); Γ_{Ra} is exposure rate constant of ^{226}Ra source, with 0.5 mm of platinum filter. L is the active length of the source; μ' is effective attenuation coefficient of the source capsule; and t is thickness of the source capsule.

When the source strength is specified in terms of air kerma strength (S_K), Eq. (1) will be changed to the following one[16]:

$$I(x,y)=\frac{S_K}{Ly(W/e)}e^{\mu t'}\int_{\theta_1}^{\theta_2}e^{-\mu t\sec\theta'}d\theta' \quad (2)$$

Esophagus and cervical cancer treatments are being performed in our center using the GZP6 stepping source. The main difference between the dose distributions used in the treatment of esophagus and cervical cancer is related to the difference in the material used in their applicators. The applicator used for treating esophageal cancer is made of plastic while the one used for cervical cancer is of stainless steel. In the present study, the dose distributions were only obtained in the longitudinal plane for the treatment of esophageal cancer by GZP6 treatment planning system. The obtained dose distributions from the GZP6 treatment planning system are based on a dose value of 5 Gy prescribed to the point 0, 0, 1 cm

Table 1 – Mass density and composition of the materials used in the Monte Carlo simulations.

Material: description	Mass density (g/cm^3)	Composition (element/weight fraction)
Cobalt: source core	8.85	Co/1
Nickel: source plating	8.902	Ni/1
Titanium: source capsule	4.54	Ti/1
Steel pellets: spacers in the source braid	7.9	Fe/0.71994, C/0.0005, Si/0.0072, Mn/0.0137, S/0.00011, P/0.00025, Cr/0.17, Ni/0.0822, Mo/0.0013, V/0.0006, Ti/0.0042
Steel: spring cover	6.999	Fe/0.7416, Ni/0.069, S/0.0001, Cr/0.167, C/0.0006, Mn/0.0062, Cu/0.0026, Al/0.0062, Mo/0.0015, Si/0.0052
Air	0.001205	C/0.000124, N/0.7555267, O/0.231781, Ar/0.012827
Water: phantom material	1	H/0.111894, O/0.888106

relative to the central step. The related number of steps, the time interval between the steps and the source activity were recorded and applied to our Monte Carlo simulations.

3.3. *Monte Carlo simulations*

To calculate dose distributions for the GZP6 stepping source, the GZP6 stepping source was simulated using MCNPX (version 2.4.0) Monte Carlo code.[17] MCNPX is a general purpose Monte Carlo code for transporting neutrons, photons, electrons, and other particles in various geometries. It includes a geometry modeling tool and various tallies related to energy deposition, particle current, and particle flux.[18] This code uses the MCPLIB02 cross section library for transport of photons. A cylindrical water phantom with a length of 80 cm and a diameter of 50 cm was also simulated. The source was located at the center of the simulated water phantom. To describe the photon spectrum of ^{60}Co source, two photons with 1.17 and 1.33 MeV energies and equal emission probabilities were defined in the source definition card. Mass density and composition of various components of the GZP6 source, air and water phantom used in our Monte Carlo simulations are listed in Table 1.

The simulations were performed in both photon and electron modes. The absorbed dose in the mesh pixels was calculated for photons using a type 1 mesh tally with a "pedep" option (photon energy deposition). The pedep option in a mesh tally (type 1) scores the average energy deposited per unit volume for the particle type P (photon) (MeV/cm^3/source particle). This tally is different from other tallies in MCNP code. In contrast to the 3rd type of mesh tally, energy deposition can be obtained in this option for any particular particle. At the points in which charged particle equilibrium exists, absorbed dose for photons can be approximated by kerma. In MCNP code, F6 tally is used to score kerma. Therefore, at the points with a charged particle equilibrium, photon dose values can be obtained by scoring F6 tally the tally cells. However for calculation of dose in mesh tally cells the F6 tally cannot be used and instead, as mentioned in the MCNPX manual, the pedep option in a type 1 mesh tally allows one to score the equivalent of an F6:P heating tally for the particle type P (photon).[17] The energy cut off of 1 keV was used for photons and electrons and no other variance reduction techniques were used. This mesh tally type with pedep option has been used in a previous study by Gifford et al. to calculate dose values around a brachytherapy tandem applicator.[18] The dimensions of a rectangular mesh were 280 pixels × 280 pixels × 1 pixel. The resolution of the rectangular mesh was 0.05 cm. The used rectangular mesh corresponds to a 14 cm × 14 cm × 0.05 cm space. The conversion program, "gridconv", was used for the conversion of the mesh tally output file to a text file. The pedep option in a mesh tally scores the average energy deposited per unit volume for a source particle (MeV/cm^3/source particle). The outputs were converted to dose in Gy by multiplying it by the corresponding conversion coefficients. The coefficients include the source activity, a number of coefficients for conversion of units, radiation fractional yield of ^{60}Co (number of photons emitted per disintegration), etc. A total of 5×10^8 photon histories were scored and the obtained MC statistical error of the calculations was in the range of 0.008–3.5% with an average of 0.2%. A service pack 2 of Microsoft Windows XP (professional) software, a Pentium III CPU, 2 GB RAM memory, was used for our MC simulation. Except for energy cut off, we did not use any other variance reduction technique. The computation time needed to complete 5×10^8 photon histories was about 20 days.

In this study, matrix shift method was applied to obtain the isodose curves in the longitudinal plane for the treatment of esophageal tumor length of 8 and 10 cm. According to this method for considering the stepping movement of the source in the longitudinal plane, it is assumed that the source is stationary and, instead, the data matrix is shifted. The number of shifts is equal to the number of steps. Dose distribution data matrix is obtained using a mesh tally which can be defined in MCNP Monte Carlo code. Following various shifts in the dose data matrix, the final dose data matrix is obtained by summing up the matrices from various shifts. The summation and plotting the isodose contours can be performed in MATLAB software environment. More details on this method can be found in the study by Bahreyni et al.[15] In our applications, the data matrix was shifted 31 and 38 steps to obtain the isodose curves related to 8 and 10 cm tumor lengths, respectively. Finally, all matrices were summed up and the isodoses for dose contours of 1.25, 2.5, 3.75, 5, 6.25 and 7.5 Gy were plotted. Matrix shifting was performed in MATLAB (version 7.2.0.232, MathWorks, Inc., Natwick, MA, USA) environment.

4. Results

The dose distributions related to the treatment length of 8 cm of esophageal tumor in the longitudinal plane for the GZP6 stepping source, obtained by Monte Carlo simulation and GZP6 treatment planning system are illustrated in Fig. 2. In this

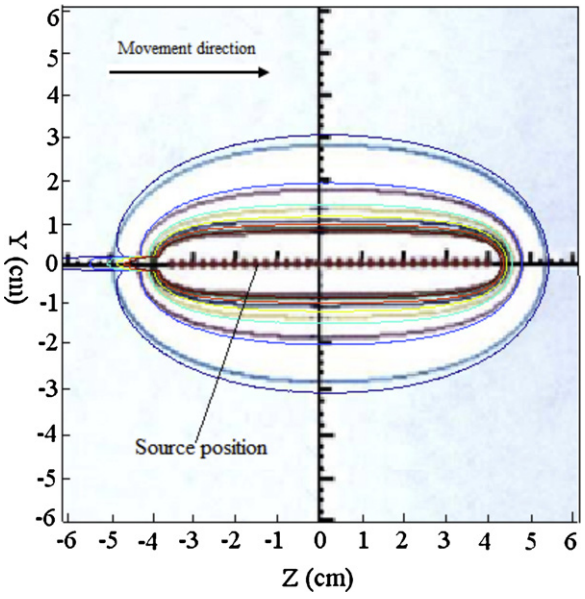

Fig. 2 – Dose distributions for the GZP6 stepping source obtained by MC simulation and the GZP6 TPS for esophageal cancer tumor length of 8 cm. MC contours are shown by sharp clear curves and TPS contours by the blunt unclear curves.

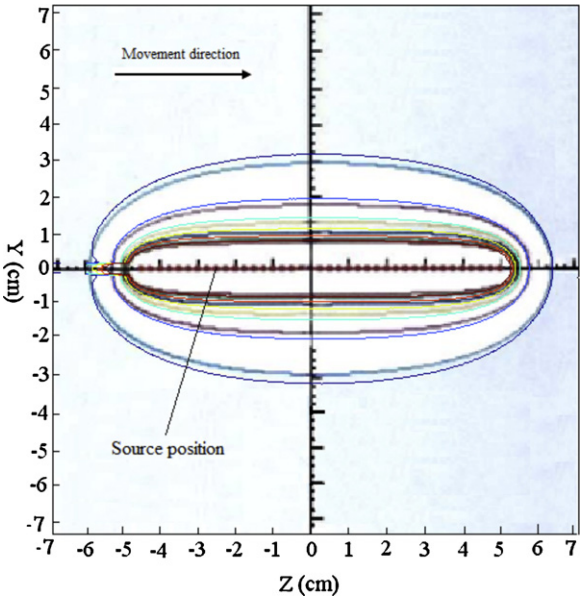

Fig. 3 – Dose distributions for the GZP6 stepping source obtained by MC simulation and the GZP6 TPS for esophageal cancer tumor length of 10 cm. MC contours are shown by sharp clear curves and TPS contours by the blunt unclear curves.

figure, the dose contours corresponding to 1.25, 2.5, 3.75, 5, 6.25 and 7.5 Gy dose values are plotted from peripheral to central regions and the solid fine points on the horizontal axis illustrate the source positions.

The comparison of MC and TPS dose distributions shows that the isodose curves are coincidental in the longitudinal direction, however in the transverse direction (Y-axis direction on the Y–Z plane as shown in Figs. 2 and 3), a maximum dose difference of 7% is observed between the dose distributions obtained by the two mentioned methods.

The dose distributions related to the treatment length of 10 cm of esophageal tumor in the longitudinal plane for the GZP6 stepping source, obtained by Monte Carlo simulation and GZP6 treatment planning system are illustrated in Fig. 3. In this figure, the dose contours corresponding to 1.25, 2.5, 3.75, 5, 6.25 and 7.5 Gy dose values are plotted from peripheral to central regions and the solid fine points on the horizontal axis illustrate the source positions.

The comparison of MC and TPS dose distributions shows that the isodose curves are coincidental in the longitudinal direction. However in the transverse direction (Y-axis direction on the Y–Z plane as shown in Figs. 2 and 3), a maximum dose difference of 5% is observed between the dose distributions obtained by the two mentioned methods.

5. Discussion and conclusions

In the present study, the GZP6 stepping source was simulated and the results were used toward validation of dose distributions certified by the GZP6 treatment planning system. Although the obtained results show that the maximum difference between MC and TPS calculations is about 7%, considering that the certified source activity (which was used in our MC calculations) is given with ±10% uncertainty, the difference is reasonable. Generally speaking, by keeping in mind this level of uncertainty in source activity, the accuracy of the dose distributions produced by GZP6 TPS for the stepping source is acceptable for its clinical application. However, in both Monte Carlo and TPS methods the theoretical activity, with ±10% uncertainty, is used as an input in dose distribution calculations. Performing a precise measurement of GZP6 stepping source's activity can lead to a lower uncertainty in the source activity. Then, inputting the measured activity in Monte Carlo calculations may result in a lower level of difference between the MC and GZP6 TPS dose distributions.

Conflict of interest

There is no relationship that might lead to a conflict of interest.

Financial disclosure

None declared.

Acknowledgements

The authors would like to thank the Reza Radiotherapy and Oncology Center (Mashhad, Iran) for providing the treatment planning data. The authors also would like to thank Dr. Ali Asghar Mowlavi, Dr. Ali Soleimani Meigooni and Dr. Reza Hashemian for their assistance. This work was fully funded by the Mashhad University of Medical Sciences (MUMS).

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