Dose distribution verification for GZP6 sources: a comparison of Monte Carlo, radiochromic film, and GZP6 treatment planning system

Mohammad Taghi Bahreyni Toossi[1], Mahdi Ghorbani[2,*], Ali Asghar Mowlavi[3], Abdolreza Hashemian[1], Ali Soleimani Meigooni[4]

SUMMARY

Background: *Treatment planning systems (TPSs) are used for dose calculations in dose delivery by afterloading brachytherapy machines. Such planning systems usually use simplified algorithms in their dose calculations. Verification of dose distributions produced by TPS is of clinical importance and is part of a quality assurance program. In this study, the dose distributions generated by GZP6 TPS for two GZP6 sources were verified.*

Methods: *The evaluation was based on the inter comparisons between the isodose curves obtained through Monte Carlo simulations, radiochromic film measurements, and GZP6 treatment planning system. MCNPX Monte Carlo code was used to simulate the sources. Dose measurements were performed in a perspex phantom using Gafchromic® EBT radiochromic films. Comparisons between the results obtained from MC, RCF, and TPS were performed by gamma function calculations with 5% dose/2 mm distance criterion.*

Results: *Based on gamma calculations our results showed that there was good agreement between the dose distributions obtained by the three aforementioned methods in both transverse and longitudinal planes for the GZP6 source No.2. However, for source No. 5, the agreement was good in the transverse plane but it was low in the longitudinal plane.*

Conclusion: *The results showed that dose distributions certified by the GZP6 TPS for the GZP6 source No. 2 were validated. However, for source No. 5 some discrepancies were observed. Accurate knowledge of the activity of each active pellet in the source No. 5 can clarify the cause of the discrepancies.*

Key words: *Brachytherapy; Radiotherapy Planning, Computer-Assisted; Radiotherapy Dosage, Monte Carlo Method; Film Dosimetry*

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[1]Medical Physics Research Center, Mashhad University of Medical Sciences, Mashhad, Iran
[2]North Khorasan University of Medical Sciences, Bojnurd, Iran, [3]Physics Department, School of Sciences, Hakim Sabzevari University, Sabzevar, Iran, [4]Comprehensive Cancer Center of Nevada, Las Vegas, Nevada, USA

Correspondence to:
Mahdi Ghorbani, Vice Chancellery of Research and Technology, North Khorasan University of Medical Sciences, South Shariati No. 7, Bojnurd, North Khorasan, Iran
mhdghorbani@gmail.com

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INTRODUCTION

The GZP6 high dose rate (HDR) afterloading brachytherapy unit (Nuclear Power Institute of China) (1) has recently been introduced in the Iranian radiation oncology centers. The unit has six different cobalt-60 source braids being loaded in tandem and ovoid applicators. The sources are used in the treatment of cervix, vagina, rectum, esophagus, and a number of other cancers. The unit has a treatment planning system, which presents dose distributions for different insertions in terms of isodose curves (2).

In dose delivery by brachytherapy systems, the delivered dose to the target volume and the dose received by the adjacent critical organs are calculated using dose distributions presented by treatment planning system (3). The treatment planning systems commonly calculate the dose distributions by assuming each source as a point source. The source capsule, inter-pellet attenuation, and scattering are not also incorporated in the algorithms used in the treatment planning system for dose calculations (4). Since the treatment planning systems use simplified algorithms in their dose calculations, verification of the dose distributions presented by the systems may be of clinical importance (5). Evaluation of the treatment planning systems in terms of their presented dose distribution can be a part of quality assurance in the clinical practice of brachytherapy (6).

There are scarce studies conducted on GZP6 unit focusing on the calculation and measurement of task group number 43 (TG-43) (7) parameters for different sources of the GZP6 unit (8, 9). In our previous study, an evaluation verifying the dose distribution around the first source of GZP6 unit was performed (10). Naseri *et al*. have studied dose distribution around the source number one, two, and five of the unit but their study was for a vaginal applicator and was based on relative dose evaluations (2). To our knowledge there is no other study verifying dose distributions around source braids of this unit. In this study, the dose distributions presented by GZP6 treatment planning system for the source braids No. 2 and No. 5 were evaluated based on Monte Carlo simulations and in-phantom radiochromic film measurements.

MATERIALS AND METHODS

GZP6 sources and GZP6 straight tandem applicator

GZP6 afterloading HDR unit has 6 sources. The sources 1 to 5 are non-stepping and the source 6 is a stepping source. In this study, we evaluated the sources number two and five of the unit. The source braids No. 2 and 5 contain respectively four and three active cylindrical cobalt-60 pellets (with a radius of 0.5 mm and length of 2 mm). A number of non-active

spherical pellets (with radius of 1.5 mm) exist in the source braids and are as intervals between the active ones (Figure 1). Each active pellet has a thin nickel platting and it is covered by a titanium capsule. The active and non-active pellets are covered by a spring cover.

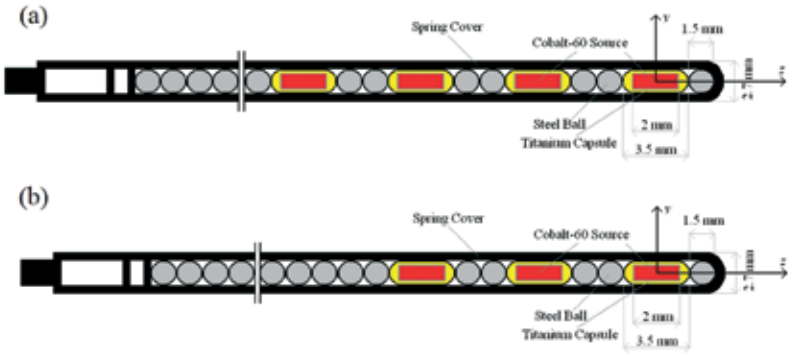

Figure 1. A schematic figure illustrating the GZP6 source braid number two (a) and five (b). The source braids consist of a number of active ^{60}Co pellets, non-active spherical stainless steel pellets, and spring cover

The UT0 tandem applicator is a hollow cylindrical with an inner diameter of 4.3 mm and wall thickness of 0.6 mm. The applicator was chemically analyzed by Esfahan Steel Company and the announced composition was incorporated in our Monte Carlo simulations. As the results of the chemical analysis the main components were: Fe (71.99%), Cr (17.00%), Ni (8.22%), Mn (1.37%), Si (0.72%), Ti (0.42%), Mo (0.13%), V (0.06%), C (0.05%), P (0.025%), S (0.011%). In this study, the source braids were inserted in the tandem applicator in our Monte Carlo simulations and in-phantom measurements.

Monte Carlo simulations

The MCNPX Monte Carlo code (11) was used as the tool for the simulation of the source braid and the tandem applicator. The source braid, when being inside the straight tandem applicator, was centered in a cylindrical Perspex phantom with a 25 cm radius and length of 50 cm. The phantom was also located in a 1.5 m air filled sphere, simulating the air content. Two transverse and longitudinal meshes were overlaid on the geometry to obtain dose distributions in the transverse and longitudinal planes relative to the applicator respectively. To be consistent with the GZP6 TPS dose distribution, the transverse mesh was crossing the point 0, 0, -2.45 cm and 0, 0, -1.8 from the origin of the *x-y-z* coordination respectively for the sources No. 2 and 5 (on the center of the first active pellet (Figure 1)). The pedep mesh tally type 1 in the MCNPX code was used for photons, giving the energy deposition in terms of $\mathrm{MeV/cm^3 \cdot photon}$. The pedep mesh tally was used to score the dose in terms of MeV/cm^3.particle. The tally values can be converted to dose in Gy by applying the appropriate conversion factors like the source activity, source decay factor, mass density etc. (12). The number of source particle histories followed in the code was equal to 0.5×10^9. The resulted value of the mean error was 1.66 and 1.87% in the mesh cells in the transverse and longitudinal directions for source No.2. The obtained statistical errors for source No 5 in the transverse and longitudinal directions were obtained 1.63, and 1.86% respectively. More details on the simulation were the same as our previous study on the GZP6 source number one (13).

Radiochromic film measurements

Film calibrations

GafChromic EBT radiochromic film sheets (lot number 34351-05, ISP Corp., Wayne, NJ, USA (14)) from a single batch were used for calibration and in phantom measurements. For the purpose of calibration, the film pieces of 2×3 cm^2 size were used. Film calibration was performed in a $32\times32\times31$ cm^3 water phantom in a 20×20 cm^2 field of a Theratron 780C Cobalt unit at the depth of 5 cm. Prior to film calibration the output of the unit was calibrated using a Farmer type 2581 ionization chamber. The film pieces were irradiated in the dose range of 0.5-35 Gy. Three pieces of films were irradiated in each calibration dose and the average pixel value was used in the calculation of optical density. The irradiated films were scanned by a Microtek ScanMaker Pro 1000XL color scanner (Microtek International Inc., Hsinchu, Taiwan (15)) 24 hours after the film irradiation. The characteristics of the scanner as a radiochromic film reader were evaluated in our previous work (13). An image of the Microtek 1000XL scanner is illustrated in Figure 2.

Figure 2. The Microtek 1000XL scanner used in this study for RCF readings

The net optical density (the difference of the average optical densities on irradiated and non irradiated films) was plotted versus the dose and the fitted formula was used for further extraction of dose from the net optical density in the measurement films. The film handling, scanning protocol was according to the recommendations of task group 55 (TG-55) of the American Association of Physicists in Medicine (AAPM) report (16).

In-phantom measurements

The measurements were performed in a 50×50×50 cm^3 Perspex phantom containing 1 cm Perspex slabs. A hole was drilled in between two slabs to house the applicator. The radiochromic film was inserted between the Perspex slabs in such a way that the dose can be measured in a longitudinal plane relative to the long axis of the applicator.

The measurement set-up including the GZP6 afterloading unit and the Perspex phantom is shown in Figure 3.

Figure 3. In phantom measurement set-up showing the GZP6 afterloading unit and the perspex phantom

Film scanning

A Microtek color scanner (model: ScanMaker Pro 1000XL, Microtek International Inc., Hsinchu, Taiwan) was used for film digitization. The films were scanned 24 hours after irradiation. The films were positioned in the central portion of the scanning bed in the landscape direction. Each film, calibration and measurement films, was scanned 3 times to overcome the scanner noise effects. Scanning was performed three times for each piece of film with 100 ppi (points per inches) resolution and 48-bit RGB color mode. The film images were saved as unzipped TIFF format files. Averaged image between three scans for each film was used for the purpose of noise reduction. The red color channel was used for the extraction of optical density values. The net optical density was calculated as the difference of the optical density for each film pixel before and after the film irradiation. The room temperature during the film calibration, measurement, and reading was as normal room temperature to avoid the effect of film heating in the measurement of optical density. The net optical density was plotted versus the delivered dose for the calibration films and the fitted curve was used in the reading of measurement film for conversion of net optical value to the dose value. The detailed scanning procedure is the same as that used in our previous study (13).

GZP6 treatment planning system

The GZP6 treatment planning system presents two dimensional dose distributions for six GZP6 sources as well as a number of source combinations. It uses Sievert integral for calculation of dose distributions. The GZP6 treatment planning system is able to produce dose distributions in the transverse and longitudinal planes.

Dose distribution comparisons

Dose distributions obtained by the MC, RCF and TPS were compared. For this purpose, the film dosimetry results were considered as reference and the results of MC and GZP6 TPS were compared with the film dosimetry results. Comparisons were based on one dimensional gamma function calculations. Specially written software named *gamma_index.exe* by DOSISoft Company was provided. The software is working in the environment of Gnuplot software (version 4.4 patch level 3, Geeknet Inc., USA). As recommended by IAEA TRS 430 report for commissioning of brachytherapy treatment planning system (17), a 5% dose/2 mm distance criterion was established for our gamma index calculations.

As it will be mentioned in the results section, some discrepancies were observed for the source No. 5 between the dose distributions obtained by MC, GZP6, and RCF methods. It is believed that the discrepancies may be related to the uncertainty of total activity of the source No. 5 or partial activity of each three active pellets contained in this source. Two new experiments were arranged on the source No. 5 to illuminate the cause of the discrepancies: (1) Estimation of air kerma strength by MC and in air measurements since the total activity and air kerma strength are dependent; (2) Measurement of the activity of the active pellets in this source by placing a radiochromic film under the source braid. Air kerma rates for source No. 5 were measured using a Farmer type ionization chamber (NE 2581, #1106) following multiple distance method. Air kerma strength was then calculated using the measured air kerma rates and the result was compared by the value of air kerma strength obtained by MC simulations and that ascertained by the GZP6 TPS. The details for air kerma strength estimations in this study were as described in our previous study for the GZP6 source No. 3 (10). As it has already been mentioned the activities of active pellets in the source was measured by placing a sheet of radiochromic film under the source. The sheet was selected from the same batch used in our radiochromic film calibration and in phantom measurements in this study and the calibration fitting was used to convert net optical density map to dose map for the sheet of film.

RESULTS AND DISCUSSION

The isodose curves obtained through Monte Carlo simulation and those presented by the GZP6 treatment planning system in the transverse plane relative to the applicator long axis for the GZP6 sources No. 2 and 5 are contoured in Figure 4. The contours of 1.25, 2.5, 3.75, 5, 6.25, and 7.5 Gy are plotted in the Figure 4.

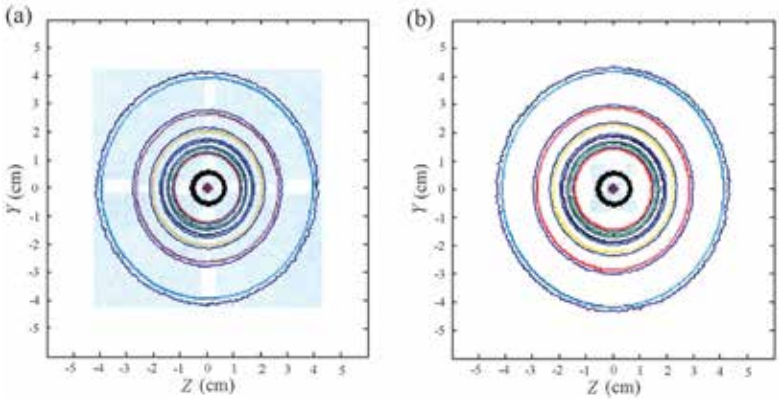

Figure 4. Isodose curves in the transverse plane obtained through Monte Carlo simulations (blue lines) and GZP6 treatment planning system (color lines): parts (a) and (b) are related to the GZP6 source braids number 2 and 5 respectively. The dose contours of 1.25-7.5 Gy are illustrated from the peripheral to central region in the figure

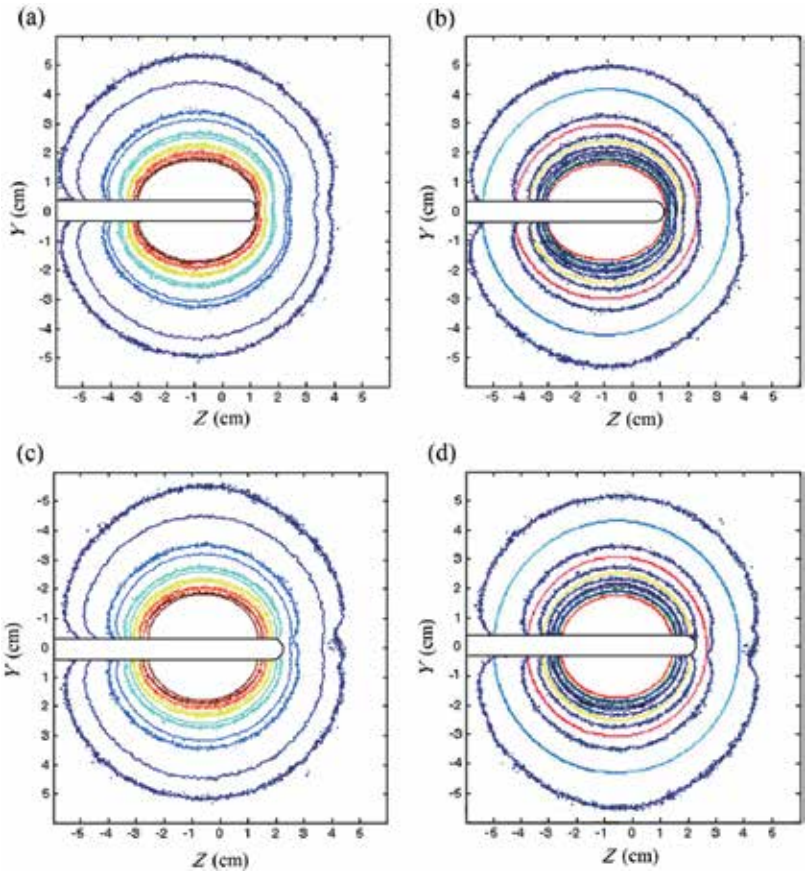

Figure 5. Isodose curves in the longitudinal plane for the GZP6 sources: (a) and (c) are related to Monte Carlo (color lines) versus RCF (blue lines). While (b) and (d) are related to RCF measurements (blue lines) versus GZP6 treatment planning system (color lines). Parts (a) and (b) are related to the source No two while parts (c) and (d) are related to the source No 5. Dose contours of 1.25-7.5 Gy are illustrated in the figure

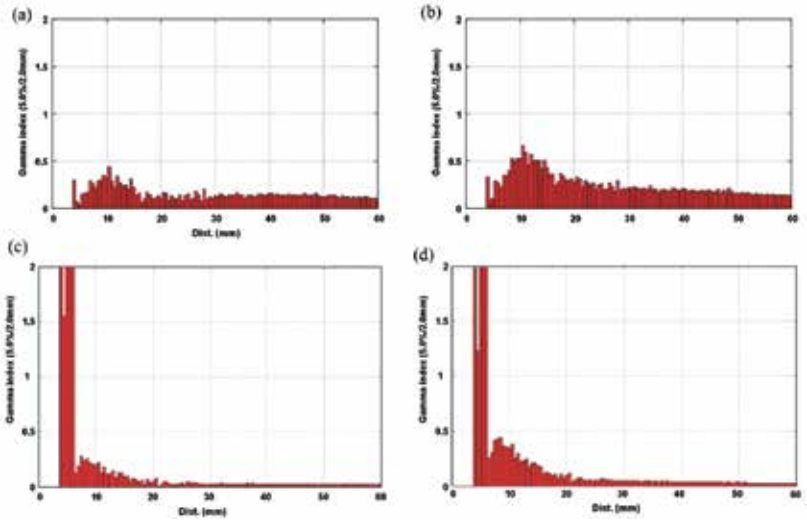

Figure 6. The gamma values related to the transverse dose data used for comparison of MC and GZP6 TPS dose distributions with RCF data: (a) MC versus RCF for source No. 2; (b) GZP6 TPS versus RCF for source No. 2; (c) MC versus RCF for source No. 5; (d) GZP6 TPS versus RCF for source No. 5

A dose difference of 6% exists between the Monte Carlo and treatment planning dose contours for both sources.

The NOD data were extracted from the data related to red channel of scanned RGB images. The following equation was fitted to the data for the dose and NOD:

$$NOD = 0.8859\,e^{0.00996\,D} - 0.8176e^{-0.1834\,D} \quad (1)$$

The R^2 value for this fitting was equal to 0.9988.

The dose distributions in the plane parallel to the long axis of the GZP6 source No. 2 presented by the GZP6 planning system and the Monte Carlo simulation are illustrated in Figure 5. The dose contours correspond to the dose values of 1.25-7.5 Gy.

One dimensional gamma index values related to the data in the transverse plane are plotted in Fig. 6. These gamma data were used for the comparison between the MC and RCF dose distributions as well as GZP6 TPS and RCF dose distributions for GZP6 sources No. 2 and 5. Gamma indices of 1 or less are considered a "pass" and gamma values exceeding the unity are considered a "fail" (18). Gamma calculations were performed with 5% dose/2 mm distance criterion.

As it is evident from Figure 6, gamma values are less than unity in almost most points. There are only some limited points in the high dose gradient region for the source No. 5, which have gamma values more than unity. The gamma data indicate that GZP6 TPS dose data are validated for the source No. 2. However, isodose contours in the longitudinal plane for source No. 5 (Figure 5) indicate that the agreement becomes less for the source No. 5 since dose differences of up to 16% are observed between the isodose lines.

Table 1. Air kerma strength values (μGym^2h^{-1}) for the GZP6 source No. 5 obtained by Monte Carlo, measurement and GZP6 TPS.

	MC	Measurement	GZP6 TPS
Air kerma strength	26885.81	26365.08	19279

As it is evident from Table 1, there is a good agreement between the Monte Carlo and measured value of air kerma strength (difference: 1.98%) but a major discrepancy is observed between the Monte Carlo and GZP6 treatment planning system value of air kerma strength (difference: 28.29%). Based on the aforementioned points, the value of Monte Carlo calculated air kerma strength was validated. Since the activity ascertained by the GZP6 manufacture was used in our Monte Carlo calculations of air kerma strength for the source No. 5, thus the corresponded value of activity ascertained by the GZP6 manufacturer for this source braid is verified. It could also be concluded that the discrepancy between the Monte Carlo calculated and measured dose distributions for the source braid No. 5 (Figure 5) was not originated from the activity of the source. When considering that the source No. 5 consists of three cobalt-60 pellets and observing that the dose discrepancy is more considered in the points outside the transverse plane (Figure 5), the discrepancy could be related to the uncertainty of each active pellet in the source, not the sum (total) activity that was validated here. So having more information about the accurate activity in each active pellet in this source braid can illuminate the cause of the discrepancies. Since the source braid is packed, direct measurement of activity of each pellet separately was not feasible. As it is mentioned in the methods section, a small experiment was performed by placing a sheet of Gafchromic EBT film under the source No. 5 for quantification of activity of the pellets in the source braid. The result of the experiment is plotted in Figure 7.

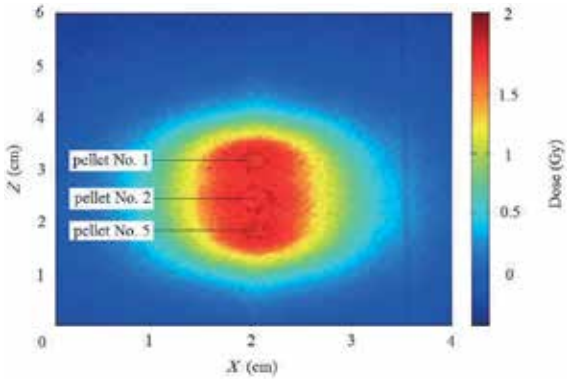

Figure 7. Dose map under the GZP6 source No. 5 to quantify the activity of each active pellet in this source braid

The details are not mentioned here but our results of the radiochromic film dosimetry under the source No. 5 showed that the sensitivity and accuracy of the experiment was not enough to accurately determine the activity of the active pellets in source No. 5.

CONCLUSIONS

The dose distribution in the transverse and longitudinal planes relative to the GZP6 source No. two and five when loaded in the GZP6 straight tandem applicator presented by the GZP6 treatment planning system was verified through Monte Carlo simulations and radiochromic film measurements. Our results show that there are acceptable dose difference between the Monte Carlo simulation, radiochromic film measurements, and the GZP6 treatment planning dose distributions for source No. two. However, the GZP6 treatment planning system presents a simplified dose distribution in the regions near the tip and base of the applicator in the longitudinal directions for both sources. It can be concluded that the GZP6 treatment planning system presents accurate dose distributions in both transverse and longitudinal directions from the applicator when is used with the source number 2 of the unit. Dose distributions certified by the GZP6 TPS for the source No. 5 are not validated thoroughly in all points and there are some discrepancies between the results by the three mentioned methods for this source. The results of air kerma strength and radiochromic film dosimetry for source No. 5 (Table 1 and Figure 7) indicated that while the total activity for the source used in our Monte Carlo calculations was accurate, the main cause of discrepancy between dose distribution estimation by MC and RCF dosimetry and GZP6 TPS for source No. 5 might be the inaccuracy of activities of active pellets in source No. 5 that were certified by GZP6 manufacturer. Therefore, accurate knowledge of the activity of each active pellet in source No. 5 can illuminate the cause of the discrepancies for this source dosimetry.

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Conflict of interest

We declare no conflicts of interest.

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