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Original research article

Dose distribution verification for GYN brachytherapy using EBT Gafchromic film and TG-43 calculation

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ARTICLE INFO

Article history:
Received 23 October 2015
Received in revised form
20 January 2016
Accepted 26 June 2016
Available online 18 July 2016

Keywords:
QA brachytherapy phantom
Film dosimetry
GZP6 HDR system
Selectron LDR system
TG-43

ABSTRACT

Aim: Verification of dose distributions for gynecological (GYN) brachytherapy implants using EBT Gafchromic film.

Background: One major challenge in brachytherapy is to verify the accuracy of dose distributions calculated by a treatment planning system.

Materials and methods: A new phantom was designed and fabricated using 90 slabs of 18 cm × 16 cm × 0.2 cm Perspex to accommodate a tandem and Ovoid assembly, which is normally used for GYN brachytherapy treatment. This phantom design allows the use of EBT Gafchromic films for dosimetric verification of GYN implants with a cobalt-60 HDR system or a LDR Cs-137 system. Gafchromic films were exposed using a plan that was designed to deliver 1.5 Gy of dose to 0.5 cm distance from the lateral surface of ovoids from a pair of ovoid assembly that was used for treatment vaginal cuff. For a quantitative analysis of the results for both LDR and HDR systems, the measured dose values at several points of interests were compared with the calculated data from a commercially available treatment planning system. This planning system was utilizing the TG-43 formalism and parameters for calculation of dose distributions around a brachytherapy implant.

Results: The results of these investigations indicated that the differences between the calculated and measured data at different points were ranging from 2.4% to 3.8% for the LDR Cs-137 and HDR Co-60 systems, respectively.

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http://dx.doi.org/10.1016/j.rpor.2016.06.005

Conclusion: The EBT Gafchromic films combined with the newly designed phantom could be utilized for verification of the dose distributions around different GYN implants treated with either LDR or HDR brachytherapy procedures.

1. Background

As radiation therapy techniques become more complex, the quality assurance (QA) techniques have to be changed to provide a sound and practical method of verification of treatment delivery in order to reduce errors during radiation therapy.[1] A QA progress needs to be adopted for complex brachytherapy treatment techniques, particularly when it involves treatment with a complex gynecologic (GYN) system.

GYN brachytherapy treatments for the cervix, vaginal and endometrial cancers have been commonly used for over 100 years.[2] Accuracy of dose calculation plays a vital role in the brachytherapy treatment planning. Experimental verification of dose accuracy is one of possible QA procedures for determination of over-dose or under-dose area in the brachytherapy planning volume. However, this technique faces several challenges related to the measurements of dose distributions in a high-gradient region. One of the important criteria for these experimental setups is to have a dosimeter with high spatial resolution such as Gafchromic films. Gafchromic films are being used as 2D dosimeters by several investigators in various types of applications.[3]

Different investigators had demonstrated the usefulness of the EBT Gafchromic films for brachytherapy source dosimetry.[4] These films require no chemical processing and they are insensitive to ambient light. Therefore, they can be cut to the shape of the experimental geometry for the best representation of a dosimetric setup.

2. Aim

Verification of dose distributions for gynecological (GYN) brachytherapy implants using EBT Gafchromic film.

3. Materials and methods

EBT Gafchoromic film dosimetry for two different brachytherapy systems for GYN treatment were considered in this study: the GZP6 high dose rate (HDR) ^{60}Co brachytherapy unit that was introduced by Nuclear Power Institute of China for brachytherapy procedures,[5] and the Selectron low-dose-rate (LDR) ^{137}Cs remote afterloading system distributed by Nucletron (Nucletron BV, Veenendaal, The Netherlands).[6]

3.1. GZP6 HDR system

GZP6 afterloading unit (Nuclear Power Institute of China) with HDR ^{60}Co sources has one stepping source and five non-stepping source-braids.[7] The GZP6 treatment planning system is able to produce dose distributions in the transverse and longitudinal planes. It calculates dose using the superposition dose calculation technique. This system could be used for intracavitary treatment of cervical, vaginal, endometrial, rectal, esophageal and nasopharyngeal malignancies. The sources in this system were consisted of ^{60}Co active pellets (3.5 mm long and 1.5 mm diameter) sealed by titanium capsules and spherical stainless steel inactive pellets (1.5 mm diameter) which were covered by a steel spring.[8] TG-43 recommended dosimetric characteristics of the sources in this system have been evaluated by several different investigators.[7–9]

In this study channels 3 and 4 of GZP6 HDR system were utilized to deliver 1.5 Gy dose to 0.5 cm distance from the lateral surface of ovoids within 4.62 min. Each of the channels 3 and 4 contains one stationary active pellet (they are nearly identical in their source strength and geometry) and they can be used in the ovoids.

3.2. Selectron LDR system

Selectron Cs-137 LDR system has some active pellet spherical sources (supplied by Amersham Corporation, Louisville, CO) and inactive or dummy pellets in an applicator set.[10] Different combinations of active and inactive pellets are used for GYN cancer. The Nucletron PLATO treatment planning system (TPS) calculates the dose delivered by the unit at the point of interest.[10] The TPS determines the dose distribution around different combinations of sources and spacers by assuming each active pellet as a point source, using the superposition dose calculation technique.

The Selectron unit consists of spherical Cs-137 pellets composed of 1.5 mm active source core of ceramic, encapsulated in 0.5 mm steel, with a total diameter of 2.5 mm.[11] In addition, this system contains some non-active pellets as a dummy, with the same dimensions and chemical composition as the active pellets.[6] Liu et al. have published the TG-43 recommended dosimetric characteristics of the sources in this system.[12]

In this study, from a set of 8 pellets, numbers 2–7 are considered active, and the remainders are non-active, in order to deliver 1.5 Gy of dose to 0.5 cm distance from the lateral surface of ovoids within 1.01 h.

3.3. EBT Gafchromic film dosimetry

The new phantom was designed and fabricated from 90 slabs of 18 cm × 16 cm × 0.2 cm Perspex to accommodate GYN applicators (tandem and ovoid). The composition of the Perspex taken to be H, 8%; C, 60%; O, 32%, with a density of 1.18 g/cm^3.[13] This configuration enables us to verify the dose distributions around the applicator with a high spatial resolution. Fig. 1 shows the schematic diagram of this phantom with its layers and the ovoid applicator which is placed in the phantom.

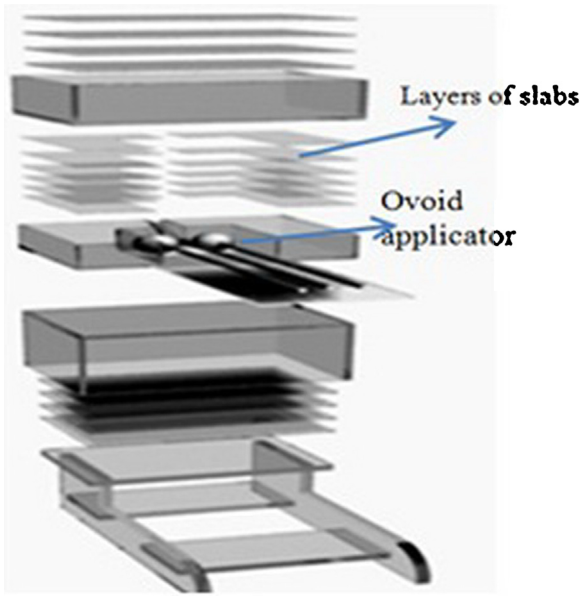

Fig. 1 – Schematics of different layers of the phantom and Oviod applicator.

The thin layer of the slabs was carefully machined to accommodate layers of Gafchromic films in between the slabs for radiation dosimetry. The irradiated films were cut with scissors in various sizes and shape to match the curvature and location of the applicator. Large size (3 cm diameter) ovoids were selected for both GZP6 and Selectron machines. With this assembly, EBT Gafchromic films[14] were exposed using a plan with 1.5 Gy dose deliveries to 0.5 cm distance from the lateral surface of the ovoids for both units.

For a quantitative evaluation, only a pair of the ovoids has been used in order to be able to reproduce the experimental setup and geometry of the assembly for repetition of the measurement, and also for different source types.

Fig. 2 shows the schematic diagram of the points of interest and the applicator. These points of interest include, point "D" representing vaginal mucosa, located at 0.5 cm distance from the lateral surface of the ovoid and "F" that was located at 1 cm distance from the lateral surface of the ovoid.

The differences between the planned and measured data demonstrate the accuracy of the planned dose distribution

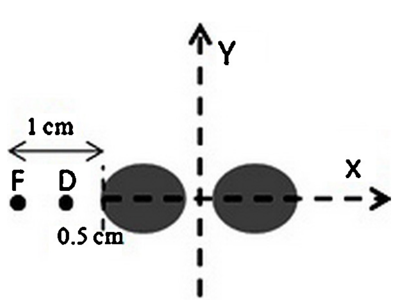

Fig. 2 – Schematic diagram of the Ovoid applicators and calculated points relative to the applicator. D and F show points of interest for dose calculation (graphs are not to the scale).

around applicators. These measurements were repeated at least 3 times to improve the statistical fluctuation of the final data.

Samples of EBT Gafchromic films were calibrated to determine the sensitivity curve (i.e. response vs. dose). A calibrated teletherapy cobalt-60 system was chosen for calibration process of the Gafchromic films. For ^{137}Cs dose calculation because of energy dependence of Gafchromic films,[15] response curve and the energy dependence of Gafchromic film for different radiation energies from Chiu-Tsao study was considered.[16] Calibration curve and its relative energy dependence coefficient were used for the analysis of the irradiated films around the GYN applicator for ^{60}Co and ^{137}Cs sources within the new phantom design. 130 pieces of EBT films with size of 2 cm × 1.5 cm were selected for calibrating samples using a teletherapy cobalt-60 system in the range of 25–800 cGy dose with 25 cGy interval. These films were exposed at 1 cm depth in a 30 cm × 30 cm × 10 cm slab Perspex layers with a 20 cm × 20 cm radiation field size. After 24 h from exposure, films were scanned using a flatbed Microtek scanner (model: ScanMaker 9800XL, Microtek Laboratories, Inc., Dayton, OH). Since the peak absorption of the radiochromic film is in the red region of the visible spectrum (636 nm), extraction of the red channel from the RGB image can improve scanner sensitivity. As suggested in the guideline of the Gafchromic films, the irradiated films for both calibration and measurement process were scanned in the landscape orientation. For film calibration and both Unit experimental measurements, films were used from the same batch.

In addition, we complied with the recommendation on projecting the film orientation on small pieces that were used for radiation dosimetry. Both calibrations and experimental film scanning were performed using 100 dpi resolutions.

The pixel values were obtained from IMAGEJ software (Java-based image processing program, National Institute of Health). The scanners allow the acquisition of transmission scans in up to 16 bits per color. In Eq. (1) net optical density (NOD) was calculated from subtraction of OD_{irr} and OD_{unirr} which represented the optical densities of un-irradiated and irradiated film, respectively:

$$NOD = OD_{irr} - OD_{unirr} = \left[-\log_{10}\frac{(PV_{irr} - PV_{dark})}{(PV_{blank} - PV_{dark})}\right] - \left[-\log_{10}\frac{(PV_{unirr} - PV_{dark})}{(PV_{blank} - PV_{dark})}\right] \quad (1)$$

where the PV_{irr}, PV_{unirr}, PV_{dark} and PV_{blank} represent the pixel values measured in the irradiated film, un-irradiated film, zero-light transmitted images of the opaque sheet scan and blank, respectively.

The selected region of interest was a 2 mm × 2 mm in the center of the film piece to avoid optical density (OD) measurement artifacts near film edges.[17]

3.4. TG-43 calculation

The task group 43 (TG-43) of the American Association of Physicists in Medicine (AAPM) has published a protocol regarding the brachytherapy dose calculation formalism.[18]

TG-43 formalism can also be used for verification of experimental dosimetry. Various investigators have determined the dosimetric characteristics of different brachytherapy sources using this recommendation.[19,20] Dosimetric characteristics of the single pellets from each system have been evaluated using the TG-43 protocols by different investigators.[12,21]

For both Selectron and GZP6 unit film dosimetry with the new phantom at multiple levels relative to the GYN applicators were done. We compared dose calculation of film dosimetry from some interesting points with treatment planning. TG-43 calculation was considered for both sources. The phantom material density ($d = 1.18\,g/cm^3$) was considered for TG-43 calculations of both sources.

TG-43 formalism was employed depending on dosimetric parameters of ^{60}Co and ^{137}Cs sources.

These parameters consist of air kerma strength, dose rate constant, geometry function, radial dose function and anisotropy function. They are indicated in Eq. (2)[18]:

$$D \cdot (r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \cdot g(r) \cdot F(r,\theta) \qquad (2)$$

Dosimetric characterizations of GZP6 ^{60}Co HDR brachytherapy for TG-43 calculation were used from Toosi's study.[22] So, the superposition technique was used. Based on their study, dose rate constant value of GZP6 is $1.04\,cGy\,h^{-1}\,U^{-1}$. Radial dose and 2D anisotropy functions were considered from their Monte Carlo simulation. TG-43 parameters of Cs-137 Selectron LDR brachytherapy sources were considered from Sina's Monte Carlo simulation.[23] So, dose rate constant value for this unit is $1.102\,cGy\,h^{-1}\,U^{-1}$. We used air kerma strength (S_K) from treatment planning for dose calculation in Eq. (3) for Cs-137 Selectron sources. For Cs-137 Selectron, air kerma strength (S_K) from treatment planning system was considered in TG-43 calculation. While, for GZP6 system, air kerma strengths of sources were measured using the ionization chamber dosimeter.

3.5. *GZP6 air kerma strength*

The vendor of GZP6 has provided approximately 600 preplans without providing the algorithms that had been used in these calculations. The only parameter that was given, in addition to the plans, was the source strengths for individual sources. Therefore, it was decided to verify the accuracy of this parameter. To investigate the air kerma strength of GZP6 unit, Monte Carlo simulation and practical measurement were utilized. In our calculation, it is considered that the date of practical S_K measurement, air kerma from Monte Carlo simulation and treatment planning S_K was the same.

For simulation, MCNP4C Code is used based on the technique that was published by Toosi et al. Self-absorption of the source core and its capsule were taken into account at their study.[7] For this part of our work, cylindrical rings with 0.5 cm thickness and 0.5 cm length were simulated in the 1–25 cm transverse distance from the source center, in 1 cm increments. In ring cells, the F6 tally was used to calculate air kerma in unit of MeV/g per photon in the ring cells. Source activity, self-absorption, number of disintegration for ^{60}Co source, decay coefficient based on cobalt-60 half time and date of measurement, square of distance and other appropriate conversion factors were multiplied by the value of the result from Tally F6 to calculate S_K. Photon primary history was 10^7 to reduce statistical error to less than 1%. For both photons and electrons the cutoff energy was defined as 10 keV.

Air kerma strength of GZP6 unit was measured according to the TECDOC-1274 technical document of the International Atomic Energy Agency (IAEA).[24] For measurement of air kerma, available $0.6\,cm^3$ Farmer type ionization chamber (FC65-G TNC/249 Scanditronix Wellhofer) was used with $0.551\,g/cm^3$ build up cap and an electrometer (Scanditronix Wellhofer). The chamber was calibrated by the SSDL laboratory of Atomic Energy Organization of Iran (AEOI) for standard field of a teletherapy cobalt-60 machine with $N_{D,W} = 4.83\,cGy/nc$. We used the multiple distance method and readings of chamber in ampere at specified distances along the perpendicular bisector of the line source were scored. The exact position of the source was well defined by using a millimetric ruler and source autoradiography. Apparent distance between the sensitive volume of the chamber and the center of the source was measured. There is 1 mm offset in distance. Measurements were performed in 1 cm intervals. In each position, we measured 3 times and made the average of values. To approach S_K, chamber reading in ampere was multiplied by the chamber calibration value ($N_{D,W}$), temperature and pressure correction factor ($K_{T,P}$), duration exposure and square of the distance to the center of the source.

3.6. *Film dosimetry uncertainty estimation*

The overall accuracy of EBT film measurements was derived using the method proposed by Devic et al.[25] Statistical uncertainty of film response to the same value of dose is related to some factors such as non-uniformity thickness in the sensitive layer of the films, uncertainties associated with the scanning procedure and output variations of Linac during exposure. In this study, we considered two sources of uncertainties. The first one is related to netOD measurements and the other is related to fitting coefficients in calibration curves. Moreover, a special attention was paid to the distances between the phantom's edge and edge of the film. The distance between the phantom slabs' edge and the applicators is 95 μm. Moreover, there is a 0.1 mm gap between the edge of the machined film and the phantom's edge. Also, there is a 0.5 mm error in determining the position of points of interest.

The total dose uncertainty was calculated through the following equation:

$$\sigma_{Total} = \sqrt{\sigma^2_{netOD} + \sigma^2_{calib\text{-}fit} + \sigma^2_{phantom\text{-}film}} \qquad (3)$$

4. Results

4.1. *EBT Gafchromic film calibration*

Fig. 3 shows the calibration curve of the EBT Gafchromic film response, in terms of net optical density (NOD), as a function of absorbed dose to water in the range of 25–800 cGy. The measured data were correlated using the following polynominal

Table 1 – Comparison between the measured and calculated dose values at different points around a typical applicator in GYN implant of Selectron ^{137}Cs LDR source.

Points	Dose-treatment planning (cGy)	Dose-TG-43 (cGy)	Dose-film (cGy)	Difference between film dosimetry and TG-43 calculation (%)
Point D-L	150	144.3	145.8	+1
Point D-R	150	144.3	144.9	+0.4
Point F-L	100	93.5	95.8	+2.4
Point F-R	100	93.5	95.4	+2

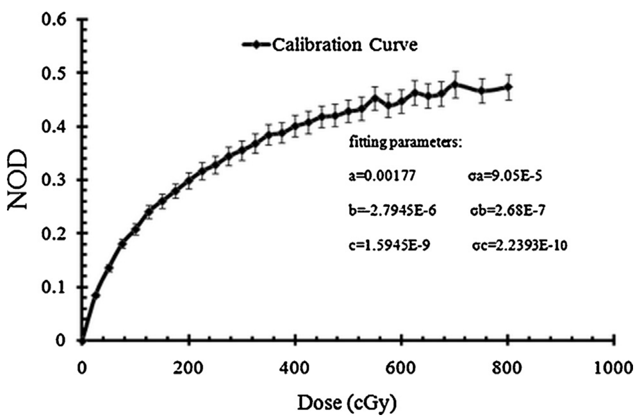

Fig. 3 – Calibration curve for EBT Gafchromic film response (optical density) as function of the absorbed dose (cGy). The error bars in this graph represent ±5%. The solid line on this graph simply connects the data points.

function in Eq. (4) with $R^2 = 0.9837$. Calibration coefficient of ^{137}Cs source was obtained from Chiu-Tsao's study. For scanner with red light relationship between the NOD response of the EBT film and source energy in MeV (parameter x) is considered as Eq. (5).

$$Dose \quad (Gy) = 42.43NOD^2 - 8.14NOD + 5.24 \qquad (4)$$

$$NOD = -0.025x^2 + 0.1165x + 0.869 \qquad (5)$$

So, there is 2% difference between ^{60}Co with mean energy 1.25 MeV and ^{137}Cs with energy 0.662 MeV. This difference is employed for ^{137}Cs film dosimetry. There is a total of 5% uncertainty that was employed for the results of dose measurements.

4.2. *Selectron LDR brachytherapy*

The value of reference air kerma rate for Selectron TG-43 dose calculation is extracted from treatment planning and equal to 8876.74 Gy m^2 h^{-1}. The quantitative analysis of the measured data for Selectron ^{137}Cs LDR source and TG-43 dose calculation is shown in Table 1. Results of Selectron unit show good agreement (total difference is up to 6%) between film dosimetry, TG-43 dose calculation and treatment planning.

4.3. *GZP6 HDR brachytherapy*

Air kerma strength (S_K) for GZP6 HDR brachytherapy system from Monte Carlo code was obtained 4414×10^{-6} and 4077×10^{-6} Gy m^2 h^{-1} for source of CH_3 and CH_4, respectively.

The value of measured air kerma strength was obtained by taking into account the date of measurement $4207 \times 10^{-6} \pm 1\%$ Gym^2 h^{-1} for CH_3 and $3864.5 \times 10^{-6} \pm 1\%$ Gym^2 h^{-1} for CH_4. Fig. 4 shows results of S_K measurement by a multiple distance method. There is about 5.4% difference between the measurement and simulation.

Table 2 indicates the results of TG-43 dose calculations and film dosimetry. Maximum difference between film dosimetry and TG-43 was to 3.8%.

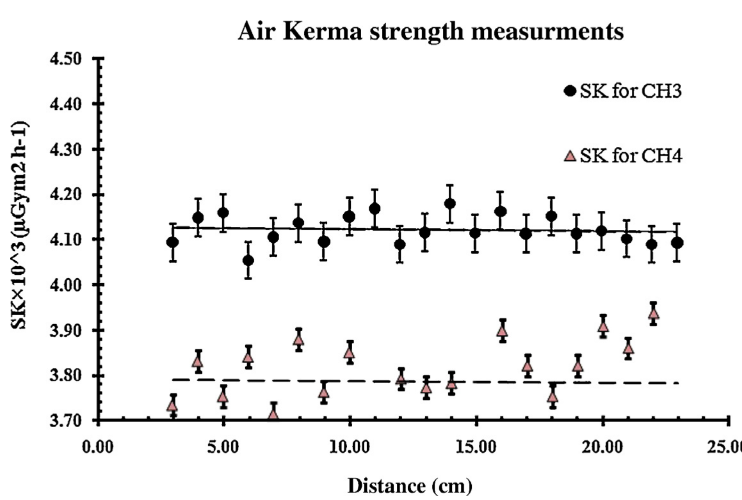

Fig. 4 – Plot of the air kerma rate × d^2 vs. distance *d* (cm) from the source center. The error bars on this data points represent 5% statistical fluctuation of the Farmer dosimetry.

Table 2 – Comparison between the measured and calculated dose values at different points around a typical applicator in GYN implant of GZP6 ^{60}Co HDR source.

Points	Dose-treatment planning (cGy)	Dose-TG-43 (cGy)	Dose-film (cGy)	Difference between film dosimetry and TG-43 calculation (%)
Point D-L	150	148.5	143.6	−3.3
Point D-R	150	148.5	142.8	−3.8
Point F-L	100	98	95	−3
Point F-R	100	98	95.5	−2.5

5. Conclusions

Although the American Association of Physicists in Medicine Task Group reports 56 and 59 provide reasonable guidance on specific process of QA in brachytherapy,[26,27] improved guidance is needed for any treatment delivery system to minimize each individual treatment failure. In this project, the dose distributions around the GYN applicators for two different machines, Selectron LDR source and GZP6 HDR system were measured using EBT Gafchoromic film for a sample GYN setup. The result shows good agreement between our film dosimetry, TG-43 calculation and treatment planning (total difference is up to 6%). In this study, it has been demonstrated that Perspex can be used as phantom material in brachytherapy. The Perspex material is denser than water, so it produces more attenuation of primary radiation but on the other hand, this is compensated by an increase in scatter radiation under full scattering conditions.[28]

These investigations have verified that using the Gafchromic film dosimetry technique together with the new phantom; one could examine the accuracy of dose calculation at different distances to the GYN applicators. This system has shown that in a high dose gradient region around compound applicators, users could verify the accuracy of dose distribution with a technique that is clinically relevant and practical. Recently, there are some studies related to proper phantoms for QA of brachytherapy systems.[29,30] Comparing them with this phantom, different models of Gafchromic films can be used which are very convenient and reliable for routine quality assurance. This assembly can be used at high gradient regions for periodic QA procedures.

Conflict of interest

None.

Financial disclosure

None.

Acknowledgements

I hereby acknowledge Clinical Research Development Unit (CRDU) Shohada Tajrish hospital which was supported this research.

The Radiotherapy Department of Shahid Beheshti University at Shohada hospital sponsored the purchase of the phantom materials and films used in the investigations. The authors would like to present their appreciation for Dr Mehdi Ghorbani for his invaluable contributions at different phases of this project. In addition, the editorial comments and suggestions by Dr Courtney Knaup for enhancing the quality of the manuscript are greatly appreciated.

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