Determination of Dose in HDR Brachytherapy by using Treatment Planning System, Manual Calculation and Film Measurement

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ABSTRACT: The performance of treatment planning system (TPS) nowadays is a key component in order to deliver an accurate treatment towards target volume in any radiation therapy process. Thus, the purpose of this study is to verify the point doses calculated by Oncentra Brachytherapy Treatment Planning Software 4.1 (Nucletron, Netherlands). Three different simple geometric catheter configurations were planned in TPS, and point doses of TPS calculation were compared with manual calculation and measured point doses using Gafchromic EBT2 films. For manual calculation of three simple geometric catheter configurations planned, 68% of calculated dose agreed with TPS calculation within 10%. This is because the TPS and manual calculations are based on the similar AAPM TG-43 formalism. Meanwhile, 11% of the measured point doses agreed with the TPS calculation within 10%. The films had high spatial resolution, which was highly sensitive for measuring doses in high dose gradient but it also led to overestimation of the dose. It was also inaccurate in detecting the lower dose region due to energy dependence. In conclusion, manually calculated point doses gave the most reliable point dose results compared to the measured point doses in this study. The method used in this study can be used as a procedure for evaluating the accuracy of calculated point doses prior installing and commissioning a new TPS.

Keywords: AAPM TG-43 formalism, brachytherapy treatment planning system, point doses measurements

Introduction

In Greek, “brachy” means “short-range”. Jayaraman and Lanzl (1996) stated that brachytherapy is a method of radiation treatment in which discrete radiation sources are placed in close proximity to or within the tissues to be treated. This can be done by inserting sources either into the tissues (interstitial therapy) or into a natural body cavity (intracavitary), which involves placement of a radioactive material whether temporarily or permanently directs into the body. The sources used may be removed after a few minutes (for high dose rate), days (for low dose rate) or remained in the patient (permanently), depending on the half-life and activity of the sources used. Besides that, it is also known as an internal radiation therapy that allows a physician to use a higher total dose of radiation to treat a smaller area and in a shorter time than is possible in external beam radiotherapy.

Gafchromic film is an established dosimeter for radiotherapy measurements (Butson *et al.*, 2003; Devic 2011; Palmer *et al.*, 2013). It is primarily used to verify the external beam dosimetry, and it has also been widely used in brachytherapy applications (Aldelaijan *et al.*, 2011; Hira *et al.*, 2011; Ghorbani *et al.*, 2012; Uniyal *et al.*, 2012b; Palmer *et al.*, 2013). EBT2 Gafchromic film is also known as radiochromic film, and it is a type of detector used to measure the dose in brachytherapy. This radiochromic film is a self-developing film with a dye as its sensitive component that will undergo polymerization when exposed to ionizing radiation. This yellow marker dye is intended to improve the films dosimetric accuracy by reducing its sensitivity to light and facilitating a correction algorithm for differences in film thickness with previous EBT film. A visible colour change of the film is due to polymerization and measured as the energy absorbed. Niroomand-Rad *et al.* (1998) and Fuss *et al.* (2007) stated that radiochromic films are relatively insensitive to light and may be handled without the need for darkroom, and the artifacts associated with chemical processing of a radiographic film are eliminated. The dose range recommended for EBT2 film is up to 40 Gy.

Dixon and O’Sullivan (2003) emphasized the importance of dosimetry audits or quality assurance processes that help to enable confirmation of the dosimetric, geometric and precision of dose delivery that is conducted by a physicist. Accurate dosimetry is required in brachytherapy to increase the likelihood of desired treatment outcomes by increasing tumour control and reducing toxicity to surrounding healthy tissues, and at the same time minimizing the risk of error and guaranteeing the validity of treatment delivery. Thus, it is desirable to verify the values of point dose of computed treatment planning system (TPS) calculation and compare with manual calculation and measurement using EBT2 Gafchromic films in the dosimetry of HDR ^{192}Ir sources for a quality control test of the TPS performance.

Materials and Methods

Calibration of EBT2 films and point dose measurements

Measurement of point dose was carried out with µSelectron ^{192}Ir HDR version 2 source. ^{192}Ir source strength of 24415.45 cGy.cm^2/ h was used for film calibration and point dose measurement. The source has an active length of 0.36 cm and active diameter of 0.065 cm. It is enclosed in a 0.090 cm outer diameter of AISI 316 stainless steel with 0.0125 cm thickness, 0.5 cm length and 8.06 g/cm^3 density. It has one end welded to a stainless steel drive cable, which is connected to stepping motors that can precisely position the source into the required applicator.

EBT2 Gafchromic film (ISP Technologies lot number A052810-02AB) used in our work is recently introduced as high spatial resolution and high sensitive dosimetry film. It is made up of the same layers as older versions of EBT film but with the addition of a pressure-sensitive adhesive layer as shown in **Figure 1**.

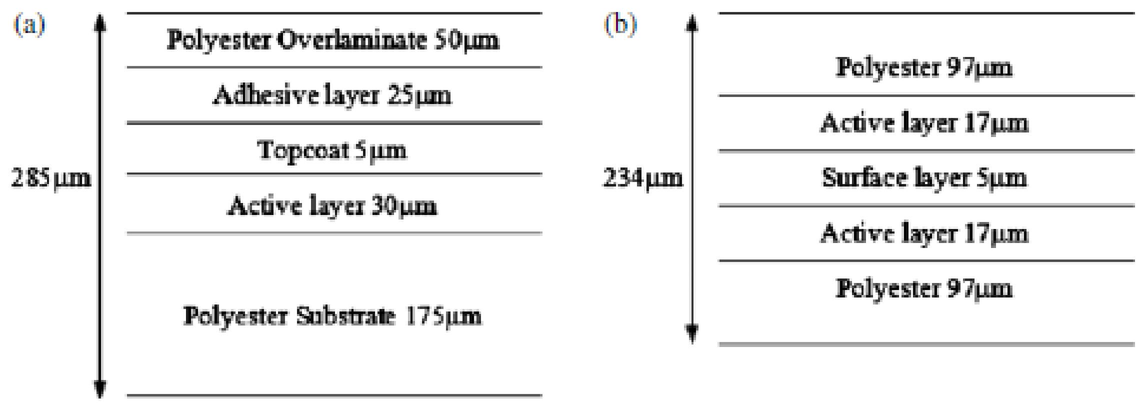


Figure 1: The structures of (a) EBT2 and (b) EBT Gafchromic films.

In addition, the overall atomic composition of this film are H (40.85%), C (42.37%), O (16.59%), N (0.01%), Li (0.1%), K (0.01%), Br (0.01%), and Cl (0.04%). EBT2 film consists of 175 µm thick clear polyester substrate and is coated with 30 µm thick of an active layer film over a 5 µm topcoat. Then, it is layered with 25 µm thick of adhesive layer and 50 µm thick of polyester over laminate. Richley *et al*. (2010) mentioned that the active component of EBT2 is now contained within a single layer, and the radiosensitive monomer is dispersed within a synthetic binding polymer rather than gelatin, which is used as the binding agent in the original film. The nominal thickness of the film has been increased to 285 µm and its effective atomic number, Z_{eff} has been reduced to 6.84 due to the greater proportion of polyester in the EBT2 film.

For film calibration and point dose measurement, the solid water phantom used was composed of 30 x 30 x 14 cm^3 slab. The 5 x 5 cm^2 dimension of Gafchromic EBT2 film was placed on top of the 10 cm solid water phantom and covered with a 0.5 cm bolus. Then, the Freiburg flap applicator was placed above it and covered again with another 0.5 cm bolus and 4 cm of solid water phantom. The top solid water is needed for dose buildup, and the bottom solid water is needed for backscatter. The dose range of 50-1250 cGy was used in irradiating the EBT2 films.

After 24 hours of irradiation, each sample was scanned in landscape orientation in a flatbed scanner Epson Expression 10000XL. The optical density (OD) of each pixel in central 1 cm x 1 cm region of calibration film was measured from the corresponding scan value and the film background scan value. Mean optical density (MOD) for each calibration film was then calculated. A curve between MOD and corresponding dose for EBT2 film was plotted (**Figure 2**) and a fit equation (Eq. (1)) was obtained for determination of the dose from the measured optical density in the subsequent experiment.

$$y = -1426.7x^2 + 4477.8x \quad \text{………………..} \text{ (Eq. 1)}$$

Where x is the optical density and y is the dose in cGy. The MOD values of measured EBT2 films in this study were converted to dose using the Equation (1) obtained from EBT2 calibration curve (**Figure 2**).

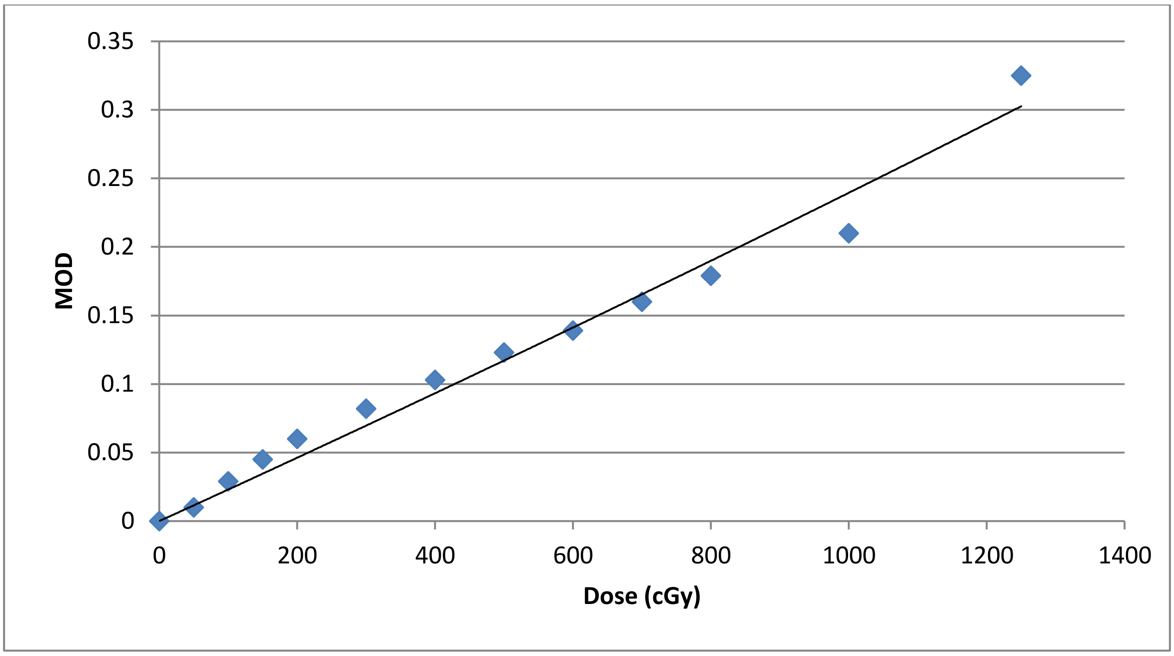


Figure 2: Calibration curve of Gafchromic EBT2 film to ^{192}Ir γ-ray quality

Experimental setup and treatment planning

The two-dimensional (2D) simulation procedure was used to define the exact position of each source or dwell position inside the Freiburg flap applicator. For source localization, the orthogonal radiographs were used, where two films were taken at 90° angle to each other. The image of Freiburg flap applicator with the x-ray dummy inside it was taken using exposure parameter of 50 kV and 1.6 mAs. For the anterior-posterior (AP) view, the gantry angle was set at 20° and 11.1 x 23.3 cm^2 field size was used for collimation of the Freiburg flap applicator . The same exposure parameters were used for lateral view, except that the gantry angle was moved to 290° position. After that, both AP and lateral images were exported to treatment planning workstation through local area network (LAN) for the applicator reconstruction procedure.

Then, simple geometric catheter configurations were planned with Oncentra Brachytherapy Planning Software 4.1 (Nucletron, Netherlands) based on the orthogonal radiographs. For the first simple geometric catheter configuration, one catheter was defined along the Y axis and centered with the XYZ system. The dwell position was activated at (0, 0, 0) coordinate and normalized at A6 with the coordinate of (-0.5, 0, 0). Other points were also defined, which were A1, A2, A3, A4 and A5, with the following coordinates of (-1.0, 0, 0), (-3, 0, 0), (-0.5, 0.5, 0), (-0.5, 1.0, 0) and (-0.5, -0.5, 0), respectively. The coordinates for the first simple geometric catheter configuration are shown in **Figure 3**.

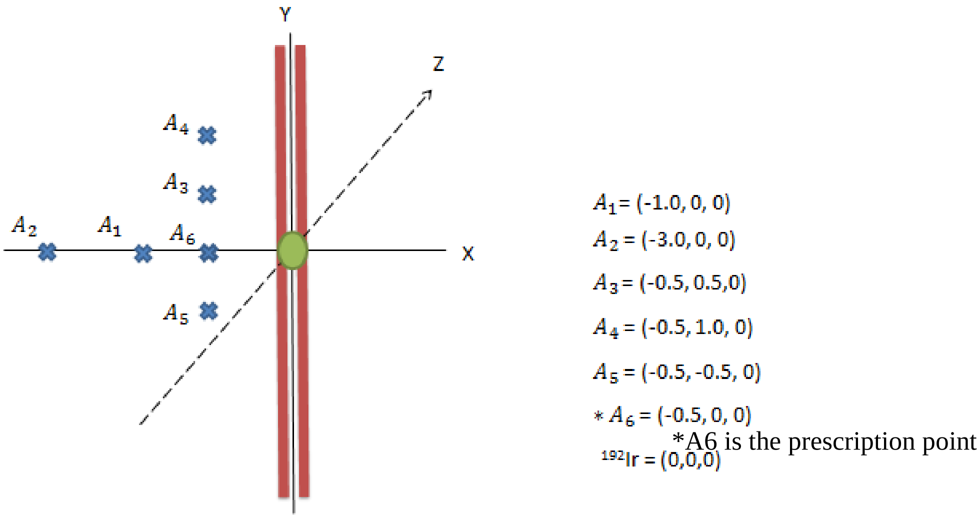


Figure 3: The coordinates for the first simple geometric catheter configuration.

Meanwhile, the second simple geometric catheter configuration was also defined with one catheter aligned through Y axis and centered with the XYZ system as illustrated in **Figure 4**. Two dwell positions were activated at the coordinate of (0, 1.0, 0) and at the coordinate of (0, -1.0, 0). Point A2 with the coordinate of (-0.5, 0, 0) was the normalization point. Points A1, A3, A4 and A5 were also defined, with the following coordinates (-1.0, 0, 0), (-0.5, 0, 0), (0.5, -1.0, 0) and (-0.5, 1.0, 0) respectively.

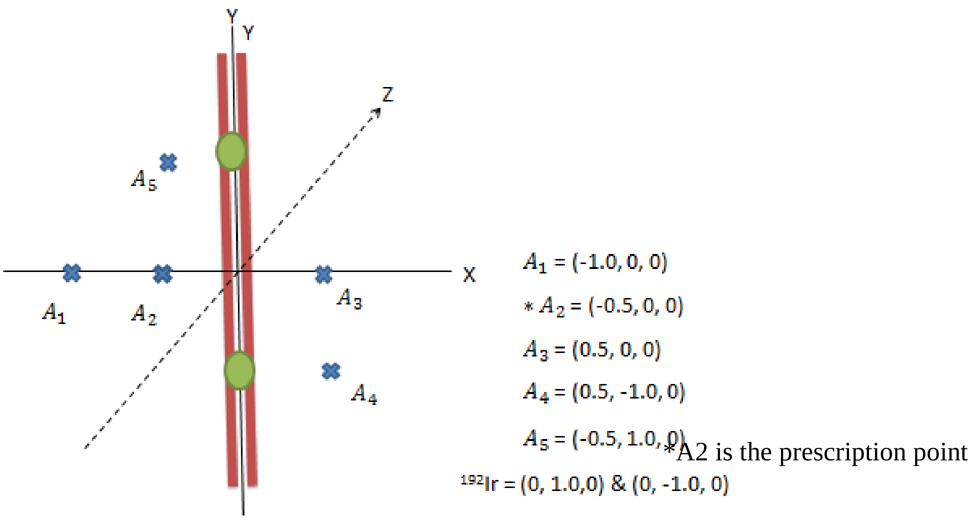
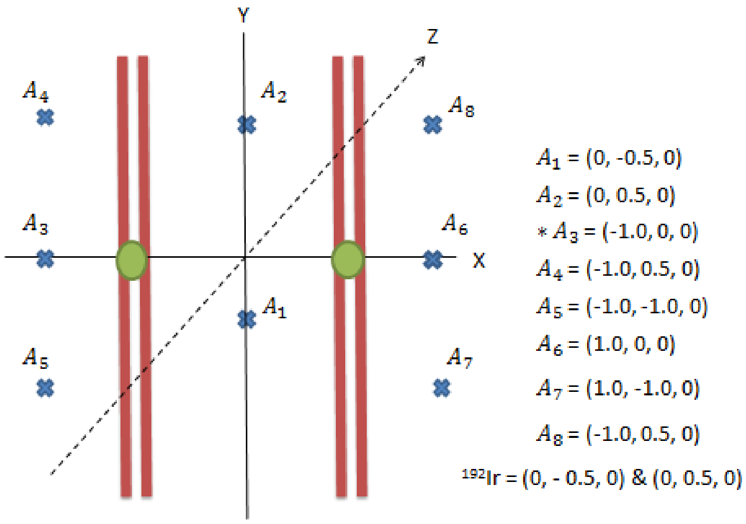


Figure 4: The coordinates for the second simple geometric catheter configuration

Lastly, two catheters were aligned parallel to the Y axis with 1 cm separation for the third simple geometric catheter configuration as shown in **Figure 5**. Two dwell positions were activated. For the first catheter, the dwell position was activated at position 33 with (-0.5, 0, 0) coordinate. The other dwell position was activated at position 34 with (0.5, 0, 0) coordinate for the second catheter. Point A3 with coordinate of (-1.0, 0, 0) was the normalization point. Points A1, A2, A4, A5, A6, A7 and A8 had the following coordinates (0, -0.5, 0), (0, 0.5, 0), (-1.0, 0.5, 0), (-1.0, -1.0, 0), (1.0, 0, 0), (1.0, -1.0, 0) and (1.0, 0.5, 0), respectively.

For each simple geometric configuration catheters, 500 cGy was prescribed to the normalization points. The outputs of these plans were calculated by the TPS which include the total time, source position and dwell time. The outputs were then exported to (HDR) μSelectron brachytherapy treatment unit (Nucletron, Netherlands). ^{192}Ir source strength of 24415.45 cGy. cm^2/ h was used for all calculations.



*A3 is the prescription point

Figure 5: The coordinates of third simple geometric catheter configuration.

Manual calculation based on AAPM TG-43 formalism

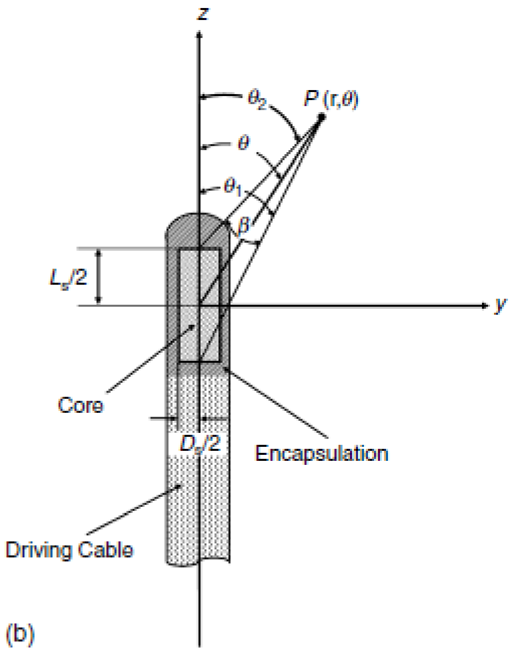


Figure 6: Geometry and parameters as used by the TG-43 protocol for HDR brachytherapy remote-afterloader systems.

According to the AAPM Task Group 43 protocol(refer to **Figure 6**), the dose rate to water in water medium *D (r,θ)* at a point *P (r,θ)* from a source, where *r* is the distance in centimetres from the active source center and θ is the polar angle relative to the positive direction of the source's longitudinal axis is calculated as :

$D\ (r,\theta) = S_K$ □ $g_L(r)\ F(r,\theta)$ ……….. (Equation 2)

where,

S_K = the air kerma strength of the source.

□ = the dose rate constant or dose rate to water in water at a reference point, namely at the distance of *r*□ equal to 1 cm on the transverse axis (*θ* = 90°) per unit air kerma strength, S_K.

$G_L\ (r,\theta)$ = the geometry function at radial distance, r and polar angle, θ.

G_L(*r*□,*θ*□) = the geometry function at the reference point (*r*□,*θ*□) with r□=1.0 cm and θ□= 90°.

$g_L\ (r)$ = the radial dose function that considers the distance dependence of absorption and scatter of the photon rays in the water medium along the transversal axis, which is y-axis or equivalently for *θ* = 90°.

$F(r,\theta)$ = the anisotropy function that considers the effect of absorption and scatter of the photons within the source active core and encapsulation material ,as well as part of the driving cable.
The line source approximation was used to calculate the dose in this study.

$$G_L(r,\theta) = B/L.r \sin\theta \text{............} \quad \text{(Equation 3)}$$

$G_L(r,\theta)$, $g_L(r)$ and $F(r,\theta)$ are also known as the dimensionless quantity. The values of $g_L(r)$, $F(r,\theta)$ and dose rate per unit source strength follows the Monte Carlo calculation that was studied by Daskalov *et al*. (1998). S_K expressed in unit U (1 U = 1 µGy m^2 h^{-1} = 1 cGy cm^2 h^{-1}. Meanwhile, □ is the dose rate constant in water in the unit of cGy h^{-1} U^{-1}. The relationship between S_K and □ is:

□ = ——— …………… (Equation 4)

The dose rate constant depends on both radionuclide and source model and is influenced by both source designs (radioactive core and encapsulation), as well as the experiment methodology used by the primary standard to determine S_K.

Results and Discussion

Point dose calculations were performed in order to test the adequate used of published dosimetric data for ^{192}Ir of the high dose rate (HDR) µSelectron treatment unit and to simultaneously check the correct implementation of the TG 43 dosimetry protocol in Oncentra Brachytherapy treatment planning system (Oliveira et al., 2009). **Table 1** shows the results of percentage differences between the calculated doses from TPS with the measured doses using EBT2 film and manually calculated doses by using AAPM TG-43 formalism for the first simple geometric configuration catheter respectively. The percentage differences (R) were calculated using the formula from Equation 5:

Percentage difference (R) (%) = A – B / ((A + B)/2) x 100 % ………… (Equation 5)

where, A = Measured point doses, and B = Point doses calculated by TPS.

The percentage differences were in the range of -25.42% to 58.29% for measured point doses compared with TPS calculation. Meanwhile, the percentage differences of point dose for manual calculation compared with TPS calculation were in the range of -24.92% to 6.91%. Point A6 that was located at the distance of 0.5 cm was the dose prescription point. Point A3 and A5 were located 0.71 cm apart from the ^{192}Ir source. The maximum percentage difference (58.29%) between the measured doses and TPS calculation was determined at point A2, which was located 3.0 cm away from the ^{192}Ir source. Meanwhile, the percentage differences of dose between manual and TPS calculations were only 6.91% at the same A2 point.

The second simple geometric catheter configuration consisted of a catheter with two activated source positions at coordinates of (0, 1.0, 0) and (0, 1.0, 0) in a single catheter. A2 was the prescription point of 1.12 cm apart from both ^{192}Ir sources. The differences were in the range of -32.24% to 34.64% for measured dose, meanwhile the percentage differences of dose between TPS and manual calculations were in the range of –8.89% to 20.72% as tabulated in **Table 2**. The maximum percentage difference (34.64%) was measured at point A1, which was 1.40 cm radial distance apart from the center source. The measured dose decreased as the distance between the source and measuring point increased. For the comparison of manual and TPS calculations, the maximum percentage difference (20.72%) of dose occurred at point A4, and the radial distance of this point was 2.06 cm.

The third simple geometric configuration catheter composed of two catheters and it was activated with two dwell positions at (0.5, 0, 0) and (-0.5, 0, 0). Point A3 was the normalization point, where it was 1.0 cm away from the first source and 1.5 cm away from the second source. The percentage differences between dose from TPS and manually calculated dose were between -9.48% and 19.99% as tabulated in **Table 3**. The percentage differences of measured doses compared to doses of TPS were from 4.81% to 49.56%.

From the study, the percentage difference was higher at radial distance less than 0.71 cm due to build-up of dose coming from scattered radiation measured by the films. This overestimated the dose measured compared with the dose calculated by TPS. For point dose at a distance more than 2.06 cm, the percentage difference increased due to less contribution of primary photon from the source but more contribution of lower energy scattered photon. The maximum percentage difference between dose calculated by TPS and manual calculation for the simple geometric catheter configuration was -24.92%, while the maximum percentage difference of TPS calculated doses and measured doses was 58.29%. This is due to the film characteristic that is energy dependence. At low energy of photon, the response of the films is underestimated and less accurate. There were fewer variations of the percentage differences for TPS calculation and manual calculation as both calculations obeyed similar formalism for dose calculation. For manual calculation, these values were nearly close to each other due to geometric dependence on dose fall-off that only depended on radial distance and the angle.

This allows users a robust dose calculation with a limited data set and less time consuming. Measured point dose using EBT2 film obeyed the inverse square law where the dose decreased as square distance increased. The doses measured were higher for second and third catheter configurations due to dose contribution from more source positions compared to the first simple configuration catheter. However, there were large percentage differences of measured dose compared to TPS calculation. Furthermore, the brachytherapy TPS implemented AAPM TG 43 dosimetry protocol for dose calculation. The AAPM TG 43 dosimetry protocol assumes that the medium is water equivalent. Meanwhile, the presence of EBT2 film during the measurement generates an inhomogeneous condition. This is because the effective atomic number (Z_{eff}) for EBT2 film is 6.84 while Z_{eff} of water is 7.42. Thus, it implies a mismatch between the dose from TPS and doses delivered to the films. Besides, Uniyal *et al.* (2011) mentioned that the commercially available treatment planning systems (TPS) employ dose calculation algorithms that do not account for the effect of heterogeneities present in patient or film and the shielding effect posed by applicators used in treatment. Further study could also be carried out to measure the effect of heterogeneities condition and mass energy-absorption coefficient produced by the EBT2 film or any medium with different density to the water in ^{192}Ir γ-ray quality in order to correct the uncertainties and apply in TPS algorithm.

As it is an indirect method, a calibration curve is needed to convert the OD values or response of the films to doses. There are many related issues and may affect the accuracy and precision in obtaining reliable OD values such as scanning orientation and scanner uniformity. Therefore, it gives a higher percentage difference in measuring point doses. The effects of film orientation have been discussed by Rink *et al.* (2005), Saur and Frengen (2008), Zeidan *et al.* (2006) and Martisikova *et al.* (2008). All films were scanned in portrait orientation consistently to reduce the effect of orientation. Richley *et al.* (2010) stated that manufacturer recommends to scan the film in portrait, such that the coating direction of the film, which corresponds to the short side of the film is parallel to the scanning direction. Scanner uniformity has also been reported dependent on the orientation of the film due to the different light scatter conditions created by the structure of the film active component (Saur and Frengen 2008; Martisikova *et al.*, 2008; Richley *et al.*, 2010). Thus, all films were kept at the same location during scanning, and the regions of interest close to the center area of the scan bed were selected in order to achieve the most uniform response and also to eliminate the effect of light scattering.

Table 1: The percentage difference of point dose calculated by TPS compared with manual calculation and measured for the first simple geometric catheter configuration

Points	Radial distance (r) (cm)	TPS calculation (cGy)	Measured (cGy)	R (%)	Manual calculation (cGy)	R (%)
A_1	1.00	113.39	163.73	36.33	113.08	- 0.27
A_2	3.00	11.73	21.38	58.29	12.57	6.91
A_3	0.71	251.14	241.96	-3.72	195.49	- 24.92
A_4	1.12	81.69	111.45	30.82	66.43	- 20.60
A_5	0.71	198.41	228.99	14.31	196.10	- 1.17
A_6	0.50	500.00	387.22	-25.42	396.77	-23.03

Table 2: The percentage difference of point dose calculated by TPS compared with manual calculation and measured for the second simple geometric catheter configuration

Points	Radial distance (r) (cm)	TPS calculation (cGy)	Measured (cGy)	R (%)	Manual calculation (cGy)	R (%)
A_1	1.40	314.36	446.08	34.64	301.92	- 4.04
A_2	1.12	500.00	607.08	19.34	457.44	- 8.89
A_3	1.15	489.01	679.92	32.66	457.44	- 6.67
A_4	2.06	1021.67	919.91	-10.48	1257.80	20.72
A_5	2.06	1111.93	803.21	-32.24	1258.49	12.37

Table 3: The percentage difference of point dose calculated by TPS compared with manual calculation and measured for the third simple geometric catheter configuration

Points	Radial distance (r) (cm)	TPS calculation (cGy)	Measured (cGy)	R (%)	Manual calculation (cGy)	R (%)
A_1	0.71	492.54	516.80	4.81	542.56	9.66
A_2	0.71	586.33	755.81	25.26	542.56	-7.75
A_3	1.50	500.00	623.35	21.96	611.06	19.99
A_4	1.58	323.96	537.43	30.52	328.4	1.37
A_5	1.80	134.18	202.96	49.56	150.43	11.42
A_6	1.50	601.99	700.00	15.06	611.06	1.50
A_7	1.80	139.44	198.61	35.00	150.03	7.32
A_8	1.58	364.05	578.50	45.50	331.09	-9.48

Conclusion

For manual point dose calculation of each simple geometric catheter configuration, 68% of point dose agreed with TPS within 10%. This is due to the similar formalism (TG-43 dosimetry protocol) that was applied in both calculations. Meanwhile, 11% of the measured point doses agreed with the TPS calculation within 10%. The films had high spatial resolution, which had higher sensitivity for measuring doses in high dose gradient located very near to the source. However, at the same time, it was inaccurate in detecting the lower dose region located away from the source. It is proven in our study that the maximum percentage difference (58.29 %) was observed at point A2 for the first geometric configuration, where the point was located 3 cm away from the source. Although the dose response for this film is non-linear, it has a low energy dependence within calibration and measuring source energies. In our study, there was a slight error present at the lower dose region range from 0 – 200 cGy. Another factor that might affect the difference of measured point doses compared with TPS calculation is the tissue heterogeneity correction for creating full scatter condition, which is not available in the TPS. In conclusion, manually calculated point doses gave the most reliable point dose results compared with measured point doses using EBT2 films. The method used in this study can be used as a procedure for evaluating the accuracy of calculated point doses prior installing and commissioning a new TPS.

Acknowledgments

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References

Aldelaijan, S., Mohammed, H., Tomic, N., Liang, L. H., Beblois, F., Sarfehnia, A., Abdel-Rahman, W., Seuntjens, J. and Devic, S. (2011). Radiochromic film dosimetry of HDR ^{192}Ir source radiation fields. *Medical Physics*. 38(11): 6074-6083.

Butson, M. J., Yu P. K. N., Cheung, T. and Metcalfe, P. (2003). Radiochromic film for medical radiation dosimetry. *Material Science and Engineering: R*. 41(90): 61-120.

Daskalov, G. M. and Erratum (1998). Monte Carlo aided dosimetry of a new high dose rate brachytherapy source. *Medical Physics*. 25(11): 2200-2208.

Devic, S. (2011). Radiochromic film dosimetry: Past, present and future. *Physica Medica*. 27(3):122-134

Dixon, P. and O'Sullivan, B. (2003). Radiotherapy quality assurance: Time for everyone to take it seriously. *European Journal of Cancer*. 39(4): 423-429.

Fuss, M., Sturtewagon, E., De Wagter, C. and Georg, D. (2007). Dosimetric characterization on Gafchromic EBT film and its implication on film dosimetry quality assurance. *Physics in Medicine and Biology*. 52(14): 4211-4225.

Ghorbani, M., Toossi, M. T. B., Mowlavi, A. A., Rood,i S. B. and Meigooni, A. S. (2012). Application of a color scanner for ^{60}Co high dose rate brachytherapy dosimetry with EBT radiochromic film. *Radiology and Oncology*. 46(4): 369-369.

Hira, M., Podgorsak, M. B., Jaggernuth, W. and Malhotra, H. K. (2011). Measurement of dose perturbation around shielded ovoids in high dose rate brachytherapy. *Brachytherapy* 10(3): 232-241.

Jayamaran, S. and lanzl, L.H. (1996). *Clinical Radiotherapy Physics: Basic Physics and Radiation Dosimetry*. Texas: CRC Press.

Martisikova, M., Ackermann, B. and Jakel, O. (2008). Analysis of uncertainties in Gafchromic film dosimetry of photon beams. *Physics in Medicine and Biology*. 53(24): 7013-7027.

Niroomand-Rad, A., Blackwel,l C. R., Coursey, B. M., Gall, K. P., Galvin, J. M., McLaughlin, W. L., Meigooni, A. S., Nath, R., Rodger, J. E. and Soares, C. G. (1998). Radiochromic film dosimetry: recommendations of AAPM Radiation Therapy Committee Task Group 55. *Medical Physics*. 25(11): 2093-2115.

Oliveira. C. A. D., Lopes, M. D. C. and Mato,s A, (2009). Commissioning of brachytherapy module of Oncentra Masterplan treatment planning system. *Journal of Contemporary Brachytherapy*. 1(4): 224-230.

Palmer, A. L., Lee, C., Ratcliffe, A. J., Bradley, D. and Nisbet, A. (2013). Design and implementation of a film dosimetry audit tool for comparison of planned and delivered dose distributions in high dose rate (HDR) brachytherapy. *Physics in Medicine and Biology*. 58(19): 6623-6640.

Richley, L., John, A. C., Coomber, H. and Fletcher, S. (2012). Evaluation and optimization of the new EBT2 radiochromic film dosimetric system for patient dose verification in radiotherapy. *Physics in Medicine and Biology*. 55(9): 2601.

Rink, A., Vitkin, I. A., and Jaffray, D. A., (2005). Characterisation and real time optical measurements of the ionising radiation dose response for a new radiochromic medium. *Medical Physics*. 32(8):2510-2516.

Saur, S. and Frengen, J. (2008). Gafchromic EBT film dosimetry with flatbed CCD scanner:a novel background correction method and full dose uncertainty analysis. *Medical Physics*. 35(7): 3094-3101.

Uniyal, S C, Sharma, S. D. and Naithani, U. C. (2011). Evaluation of Gafchromic EBT2 film for the measurement of anisotropy function for HDR ^{192}Ir brachytherapy source with respect to thermoluminescent dosimetry. *Reports of Practical Oncology and Radiotherapy*. 16(1): 14-20.

Uniyal, S. C., Sharma, S. D. and Naithani, U. C. (2012b). A dosimetry method in the transverse plane of HDR 192Ir brachytherapy source using Gafchromic EBT2 film. *Physica Medica*. 28(2): 129-133.

Zeidan, O., Stephen, S., Meeks, S., Wagner, T., Willoughby, T., Kupelian, P. and Langen, K. (2006). Characterization and use of EBT radiochromic film for IMRT dose verification. *Medical Physics*. 33(11): 4064-4072.