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DOSIMETRIC EVALUATION OF RECTAL DOSE IN HDR INTRACAVITARY BRACHYTHERAPY OF CERVIX

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Abstract – *Objective:* *In the majority of commercially available treatment planning systems used for high-dose rate brachytherapy have TG-43 formalism for dose calculation. This formalism overlooks the heterogeneities present in the patient for dose calculation. The current study used Gafchromic EBT3 film dosimetry and Monte Carlo simulations to evaluate their impact on the dose received by the rectum during HDR brachytherapy of the cervix.*

Materials and Methods: *In this study, a straight stainless-steel central tandem with a 35 mm polyetheretherketone vaginal cylinder was placed in a cylindrical phantom made of Elasto-gel. In this cylindrical phantom, EBT3 Gafchromic films were placed for dose measurements at 1.9 cm from the central tandem. The results were ascertained using Monte Carlo simulations.*

Results: *The treatment planning systems overestimated the dose for the straight central metallic tandem when used with a 35 mm vaginal cylinder. The overestimation of dose was all along the vertical axis of the applicator at 1.9 cm from the central tandem. The maximum overestimation dose values obtained using Gafchromic EBT3 film dosimetry and Monte Carlo simulations were 6.36% and 6.18%, respectively.*

Conclusions: *The difference between the practical dose and the dose calculated by the treatment planning system should be considered for the proper estimation of the dose to the rectum. These findings suggest that cervical applicator effects should be considered for better rectal dose estimation.*

KEYWORDS: *Polyetheretherketone, Stainless steel central tandem, HDR Brachytherapy, TG-43, Treatment planning system.*

INTRODUCTION

According to the World Health Organization, cervical cancer is the second most common cancer in women after breast cancer[1]. The common treatment methods for this type of cancer include chemotherapy, external beam radiotherapy (EBRT), and brachytherapy. Radiation therapy now has a higher cure rate and better post-treatment quality of life owing to ongoing technological advancements in medical instrumentation[2-4]. The focus is on delivering higher doses of radiation to the tumor while minimizing damage to the surrounding healthy tissue. According to the American Brachytherapy Society, EBRT followed by high-dose-rate (HDR) intracavitary brachytherapy is the current benchmark therapeutic strategy for patients with cervical cancer receiving radiotherapy.

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A typical EBRT treatment involves delivering 40-50 Gy over 4-5 weeks to the whole pelvis. After EBRT, intracavitary brachytherapy is given in 3-10 fractions, with a prescribed dose of 4-8 Gy per fraction[5]. The Manchester technique is the most widely used intracavitary brachytherapy treatment for cervical cancer[6-11]. In the Manchester system, the dose is prescribed at point A, which is 2 cm superior to the cervical os and 2 cm lateral to the cervical canal. The organ reference dose defined by the International Commission of Radiation Units and Measurement Report 38 has been used to assess the probability of late sequelae[12]. The treatment planning system (TPS) in HDR brachytherapy is used to calculate the prescribed dose at the intended region and performs dose optimization to minimize the radiation dose to the surrounding organs. In HDR brachytherapy, the applicator is inserted into the patient and a computed tomography (CT) scan is taken with the applicator in place. The CT scan is then transferred to the TPS. The TPS uses this information to create a customized treatment plan for the patient. The most commonly used algorithm for dose calculations in HDR brachytherapy TPSs is Task Group No. 43 (TG-43), proposed by the American Association of Physicists in Medicine (AAPM). The TG-43 formalism used for dose calculations in brachytherapy doesn't account for tissue heterogeneity within the human body and assumes a radioactive source in the center of the water for calculations[13]. However, in reality, different metallic tandems and vaginal cylinders are used in brachytherapy for gynaecological cancers, and the TG-43 formalism does not consider the impact of these applicators on the dose distribution. As a result, it is uncertain to guarantee the precision of the doses at various points given by the TPS, having the TG-43 algorithm for calculations. This study is aimed to evaluate the impact of the cervical applicator material on the dose received by the rectal wall during HDR brachytherapy. The cervix applicator studied in this article included a vaginal cylinder and a straight central metallic tandem, as shown in Figure 1. The cervix applicator is made up of polyetheretherketone (PEEK) of density 1.32 g/cm^3, length of 14 cm, and diameter of 35 mm. The central metallic tandem was made up of stainless steel of density 7.8 g/cm^3 having a total length of 25 cm. The core part of the tandem is 19 cm long and has a diameter of 6 mm, while the remaining 9 cm has a 3 mm diameter for easy insertion. Overdose to the rectum is the primary limiting factor for enhancing the target dose in cervical HDR brachytherapy. Therefore, this study focuses on the attenuation offered to the rectal wall by a stainless-steel central tandem when used with a 35 mm PEEK vaginal cylinder. This type of applicator has not yet been studied for its dosimetric effects on the rectum during cervical HDR brachytherapy. In this study, the dose distribution in water was simulated using the Monte Carlo EGSnrc code and measurements were taken using EBT3 Gafchromic films. EBT3 Gafchromic films are energy-independent, tissue-equivalent, and can be used for a wide range of doses. The experimental results obtained by using EBT3 Gafchromic films were verified using Monte Carlo simulations and both were compared with the TPS-calculated dose values.

MATERIALS AND METHODS

This study was carried out at a tertiary care facility equipped with advanced radiotherapy equipment. In this study, Varian made GammaMedplus IX has been used, which is a fifth-generation afterloader with 24 channels and can deliver HDR brachytherapy to the patients. The HDR unit is completely integrated with the BrachyVision version 11 TPS, which calculates dosage using the AAPM TG-43 formalism. The Ir-192 radioactive source is housed in the GammaMedplus iX afterloader HDR unit. The Ir-192 source has an active length of 3.6 mm, a diameter of 0.65 mm, and a density of 22.42 g/cm^3. It is enclosed in a stainless steel outer cover with an outer diameter of 0.9 mm that was welded to a steel wire for connection to a remote afterloading device.

Measurement of dose using Gafchromic films

The vaginal cylinder and tandem assembly were placed in a cylindrical phantom made up of Elasto-Gel (water-based gels with acrylic polymer) of density 1.02 g/cm^3, 28 cm length and diameter of 12.3 cm as shown in Figure 2. EBT3 Gafchromic film sheets, 1x1 cm^2 in size, wrapped in thin, transparent polythene, were taped on Elasto-Gel phantom. The Gafchromic films were placed all along the circumference of the applicator at 1.9 cm from the central tandem, as shown in Figure 3. (In Figure 3, film placement is shown only along the x- and y-axes). For this study, the distance of 1.9 cm was chosen for dose measurements because it was observed from a sample of randomly selected 20 patients that the average distance between the central tandem to the anterior rectal

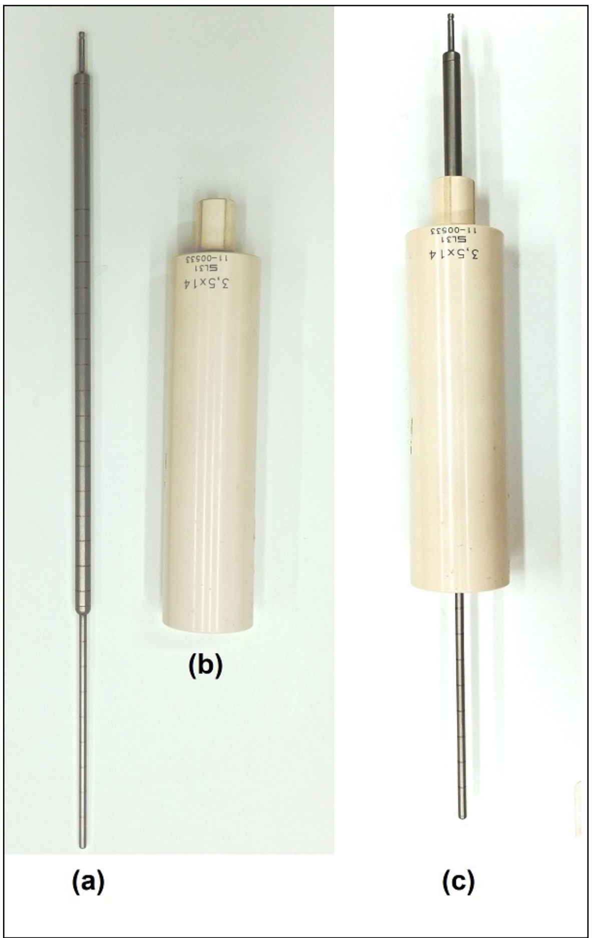

Fig. 1. (a) Central metallic tandem; (b) Vaginal cylinder; (c) Cervix applicator assembly with both central tandem and vaginal cylinder.

Fig. 2. Vaginal cylinder with central tandem wrapped in Elasto-Gel.

wall was 1.9 cm. The Gafchromic films were positioned on the surface of Elasto-Gel at predefined intervals from the distal end of the cylinder so that the same can be easily reproduced on the TPS. To imitate the backscatter within the patient, 6 cm thick Elasto-gel was used beyond the point of measurements. A CT scan of the phantom was taken, and the plan was created on Brachyvision version 11 TPS. A dose of 7 Gy was given at a point, 2 cm above the distal end of the vaginal cylinder and 2 cm later to the central tandem, as shown in Figure 4. The distal end of the vaginal cylinder along the center of the metallic tandem was taken as the origin for the dose measurements along various axes, as shown in Figure 3. The accepted protocol was adapted for precise film-dose measurements [13]. EBT3 films were first exposed to known doses and then scanned using an Epson scanner. The input data collected was fed to the Omnipro software, allowing the calibration curve to be generated and thus the dose recorded on the exposed EBT3 films placed within the phantom was measured.

Monte Carlo simulation

The aforementioned experimental setup used for the dose measurement was compared using Monte Carlo simulations. For the Monte Carlo simulations, the EGSnrc code was used, which is a modified version of the EGS4 code. This code allows users to define parameters, such as dose, energy deposition, and interaction while tracking the history of primary and secondary photons, electrons, and positrons.

The geometry modelled for this code was the GammaMedPlus IX HDR Ir-192 source located in the center of a water-equivalent cylinder with a length of 80 cm and radius of 20 cm. The components of the Varian GammaMed HDR Plus source were adapted from previous research[14-16], as shown in Figure 5.

The simulation contained a source of a 0.9 mm diameter AISI 316 L stainless steel capsule enclosing a 3.5 mm long Ir-192 core with a 0.6 mm diameter. The simulation also contained a 6 cm long AISI 304 stainless steel cylinder to replicate the proximal end of the cable.

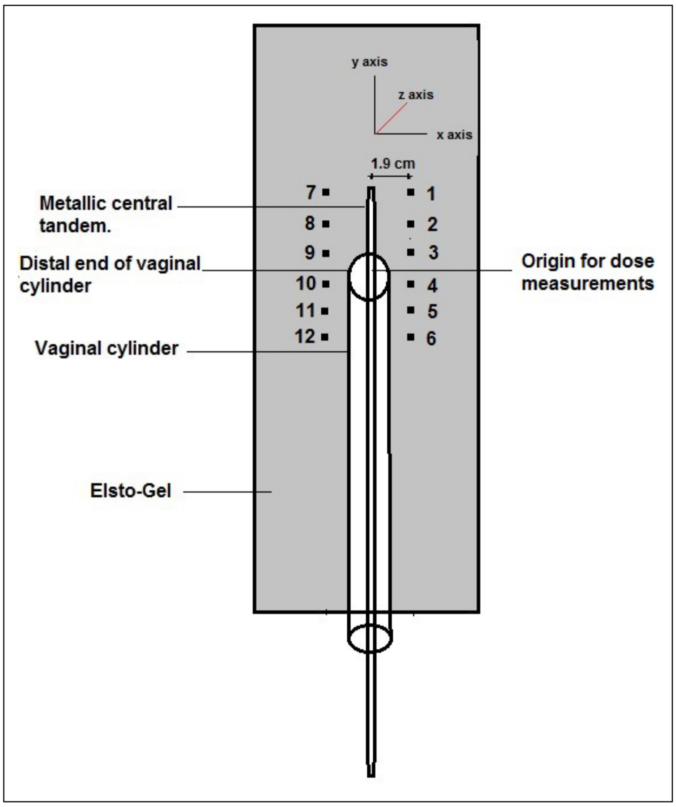

Fig. 3. Schematic diagram of setup used for film measurement.

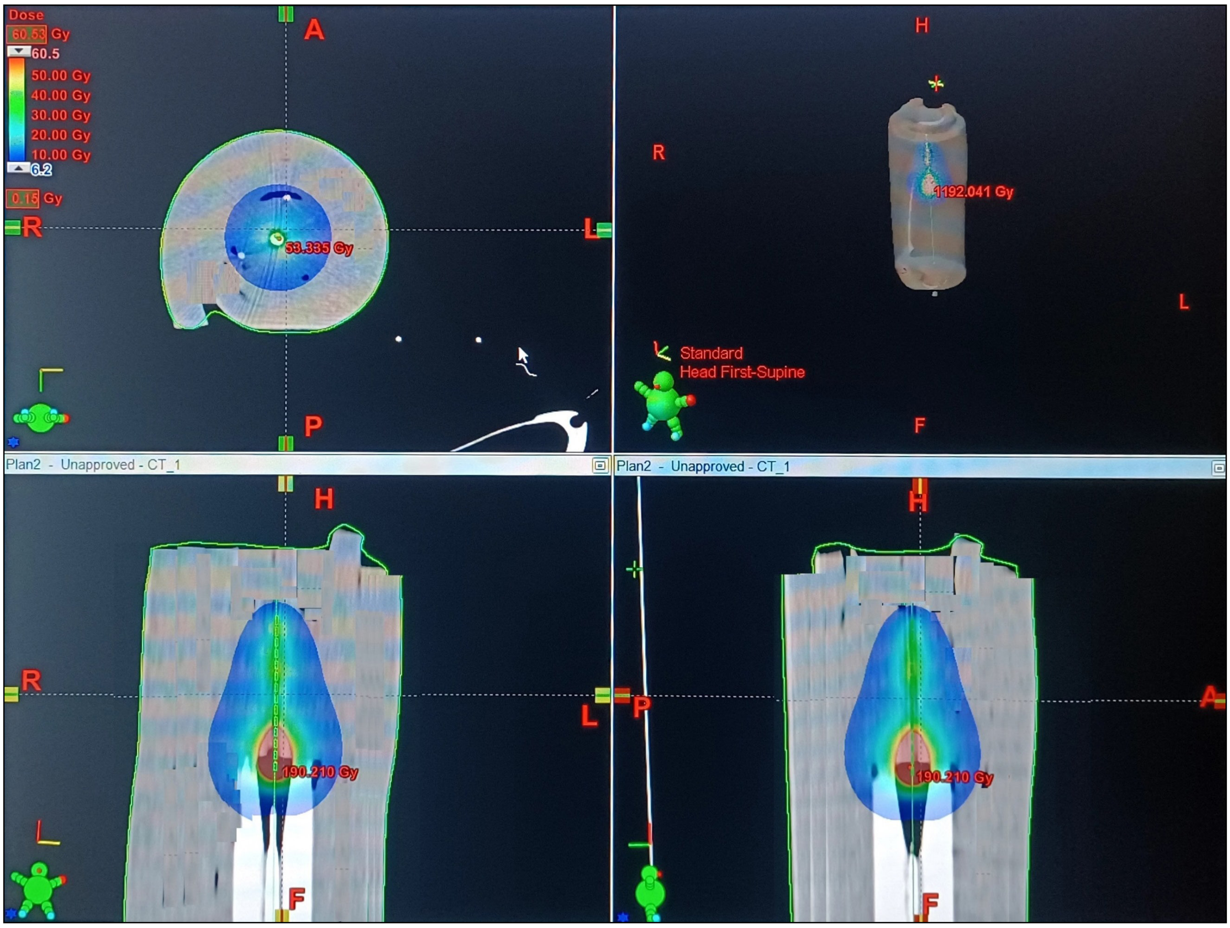

Fig. 4. Dose colour wash in multiplanar and three-dimensional views for 7 Gy prescription at point A.

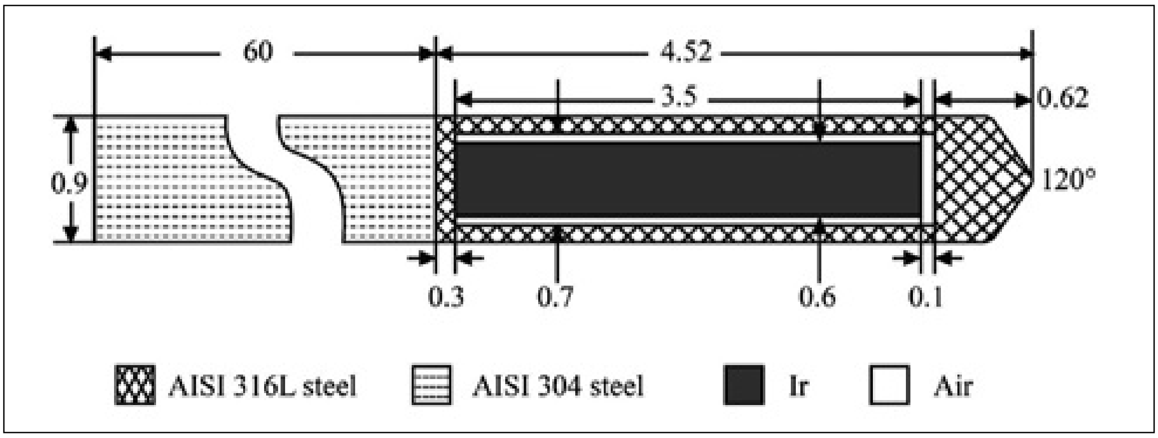

Fig. 5. GammaMed HDR Plus source's components.

The components, proportions, and densities of the materials used in the simulations are given in Table 1.

The laser-welded stainless steel wire has a diameter of 0.7 mm and is attached to the source at one end. In this simulation the cable length assumed was 5 cm so the cable's contribution to the backscatter can be also accounted for. Although the HDR Ir-192 source emits both beta particles and gamma photons, the majority of the beta particles are attenuated by the stainless steel enclosure of the source and the remaining beta particles are attenuated by the medium, reducing the chances of beta particles entering the rectal cavity. Therefore, only the interaction of gamma-ray photons generated from the source has been studied in this simulation[17]. The simulated photon interactions included pair production, photoelectric absorption, Compton and Rayleigh scattering, and the production of K-edge characteristic X-rays. The cross-sectional tables and photon energy spectra for the source used for the Monte Carlo calculations were derived from EPDL 97[18]. The energy deposited by the Ir-192 source was determined by tracing 10^9 histories.

For the Monte Carlo simulation, a central tandem and a vaginal cylinder were also simulated. A cylinder of density 1.32 g/cm^3, having a total length of 14 cm was considered; within its central axis, a central tandem of density 7.8 g/cm^3 and length of 25 cm was considered. The diameter of the central tandem used for this simulation was 6 mm up to the length of 16 cm, and 3 mm for the remaining 9 cm.

For this simulation, we also considered a cylindrical water phantom within which the above applicator was placed. The length of the cylindrical water phantom taken was 80 cm and the radius was 20 cm, approximating the dimension of the patient's pelvis. Furthermore, the density of water taken was 0.998 g/cm^3 at 22°C, as recommended by TG-43U1 to house an Ir-192 source[19]. Dose scoring cells of dimensions 0.5 X 0.5 mm^2 were assumed within this phantom for dose calculation. The deposited energy at the points of interest was determined by tracing 10^9 histories.

The air kerma strength was also calculated by individually simulating the Ir-192 source at the center of a cubical phantom with dimensions of 5 × 5 × 5 m^3 and air with a density of 0.1293 ×10^{-2} g/cm^3.

TABLE 1. The material used in Monte Carlo (MC) simulations.

Material	***Elements and percentages***	***Density (g.cm^{-3})***
Ir	Ir(100)	22.42
AISI	C(0.03), N(11.5), Si(0.75), P(0.045), S(0.03), Cr(17.5),	7.8
316L steel[a]	Cr(17), Mn(2), Fe(65.545), Ni(12), Mo(2.5)	7.93
AISI 304 steel[b]	C(0.08), N(0.1), Si(0.75), P(0.045), S(0.03), Cr(19), Mn(2), Fe(67.995), Ni(10)	5.6
Liquid water[c]	H(11.1), O(88.9)	0.998
Dry airc	C(0.012), N(75.527), O(23.178), Ar(1.283)	1.197 x 10^{-3}

[a]AK Steel Corporation. *Product datasheet 316/316L stainless steel*.
[b]AK Steel Corporation. *Product datasheet 304/304L stainless steel*.
[c]Recommended parameters by TG-43U1S2 report[12].

Air-kerma strengths per unit activity were scored in small voxels of dimensions 0.5 × 0.5 × 1.0 mm^3 at transverse distances of 1-100 cm from the source. Our calculation outcomes were compared with those of earlier studies that employed various Monte Carlo codes[20-22]. The absorbed dose measurements were carried out at the points of interest mentioned in the rectal wall EBT3 film measurements. Three simulations were performed to reduce the statistical uncertainty in the dose calculation.

Statistical analysis

The measured dose recorded by the Gafchromic films and the TPS calculated dose were compared using paired *t*-test, and analyzed on the data editor of SPSS version 20 (IBM Corp., Armonk, NY, USA). Also, the values obtained by using Monte Carlo simulations were compared with TPS calculated dose using the same test. A *p*-value less than 0.05 were considered significant.

RESULTS

The Gafchromic films were placed 1.9 cm along the transverse plane from the central tandem, as shown in Figure 3. The mean dose recorded on Gafchromic films vs. the TPS-calculated doses at various points along the positive Y-axis from the origin is given in Table 2. From Table 2, it can be observed that the TPS overestimated the dose at 1.9 cm from the central tandem, all along the circumference of the tandem. However, a maximum overestimation of 3.02% was found along the positive X-axis as shown in Table 2.

The mean dose recorded on Gafchromic films vs. the TPS-calculated doses at various points along the negative Y-axis from the origin is given in Table 3. From Table 3, it can be observed that along the negative Y-axis, there is more overestimation of the dose compared to the positive Y-axis, and the maximum overestimation of the dose along the negative Y-axis at 1.9 cm from the central tandem is 6.36%.

The percentage mean attenuation values obtained by using Monte Carlo simulation at the same points were also calculated and were compared with the experimental results obtained by using Gafchromic films and are given in Table 4.

The experimental and Monte Carlo results were in close agreement with each other. However, the results obtained using the Monte Carlo simulation showed that the maximum overestimation of dose by TPS along the positive Y-axis was 2.96% and along the negative y-axis, the maximum overestimation of the dose was 6.18% as shown in Table 4.

Paired *t*-test was used to determine whether the TPS-calculated dose is significantly less than

TABLE 2. Mean dose recorded on Gafchromic films vs. the TPS calculated doses along the positive Y-axis.

S No.	*Axis of Measurement*	*Measured dose (Gy) recorded on Gafchromic films at 1.9 cm from central tandem at various locations*	*TPS calculated dose (Gy) at 1.9 cm from the central tandem*	*Percentage attenuation**
1	**+X-axis**	6.61	6.80	2.79
		7.64	7.90	3.29
		10.77	11.10	2.97
		Mean Percentage attenuation		**3.02**
2	**-X-axis**	6.62	6.80	2.64
		7.61	7.90	3.67
		10.81	11.10	2.61
		Mean Percentage attenuation		**2.97**
3	**+Z-axis**	6.61	6.80	2.79
		7.68	7.90	2.78
		10.72	11.10	3.42
		Mean Percentage attenuation		**2.99**
4	**-Z-axis**	6.63	6.80	2.50
		7.63	7.90	3.42
		10.82	11.10	2.52
		Mean Percentage attenuation		**2.81**

$$* \; 100 - \frac{\textit{Measured dose}}{\textit{Calculated dose}} \times 100$$

TABLE 3. Mean dose recorded on Gafchromic films vs. the TPS calculated doses along the negative Y-axis.

S No.	Axis of Measurement	Measured dose (Gy) recorded on Gafchromic films at 1.9 cm from central tandem at various locations	TPS calculated dose (Gy) at 1.9 cm from the central tandem	Percentage attenuation*
1	+X-axis	15.40	16.40	6.10
		11.81	12.60	6.27
		4.50	4.80	6.25
		Mean Percentage attenuation		**6.21**
2	-X-axis	15.42	16.40	5.98
		11.84	12.60	6.03
		4.53	4.80	5.63
		Mean Percentage attenuation		**5.88**
3	+Z-axis	15.36	16.40	6.34
		11.81	12.60	6.27
		4.49	4.80	6.46
		Mean Percentage attenuation		**6.36**
4	-Z-axis	15.39	16.40	6.16
		11.79	12.60	6.43
		4.51	4.80	6.04
		Mean Percentage attenuation		**6.21**

$$* \; 100 - \frac{Measured\ dose}{Calculated\ dose} \times 100$$

the dose measured on Gafchromic films along the Positive Y-axis and Negative Y-axis. The *p*-value in both cases was <0.05. Since the *p*-value is less than the usual significance level of 0.05, we can thus reject the null hypothesis and it was concluded that the dose calculated by the TPS was significantly less than the dose measured by using Gafchromic films. Paired *t*-test was also used to determine whether the TPS-calculated dose is significantly less than the dose calculated by using Monte Carlo simulations. Here again, it was concluded that the dose calculated by the TPS was significantly less than the dose calculated by using Monte Carlo simulations as the *p*-value was less than 0.05.

DISCUSSION

This study examined the attenuation offered by the stainless-steel central tandem when used with polyetheretherketone vaginal cylinders for HDR brachytherapy of the cervix. The EBT3 Gafchromic films and Monte Carlo simulations were used to determine the dosimetric impact of this applicator in brachytherapy. In most brachytherapy TPSs, the TG-43 algorithm is used for dose calculations. However, such TPSs do not consider the applicator material when calculating the dose at various points. As a result, TPS overestimates the dose to the target and organs at risk. In this study, attenuation of the dose was measured at 1.9 cm which

TABLE 4. Comparison of Percentage mean attenuation values obtained by using Gafchromic Films *vs.* Monte Carlo simulation.

S No.	Axis of Measurement	At 1.9 cm from cental tandem along various axes.	Percentage mean attenuation by using Gafchromic Films	Percentage mean attenuation by using Monte Carlo Simulation
1	Along +Y-axis	+X-axis	3.02%	2.92%
2		-X-axis	2.98%	2.96%
3		+Z-axis	3.00%	2.95%
4		-Z-axis	2.81%	2.91%
5	Along -Y-axis	+X-axis	6.21%	6.11%
6		-X-axis	5.88%	6.18%
7		+Z-axis	6.36%	6.14%
8		-Z-axis	6.21%	6.11%

imitates the anterior rectal wall dose in patients receiving HDR brachytherapy for the cervix. In some regions, that is, along the positive Y-axis (depicted by points 1,2,3,7,8,9 in Figure 3), the dose contribution is mainly due to the photons that pass through the central tandem only, whereas along the negative Y-axis (depicted by points 4,5,6,10,11,12 in Figure 3), the main dose contributor is the photons that had to pass through the central tandem as well as vaginal cylinder. This is the reason that TPS overestimation at 1.9 cm from the central tandem is greater along the negative Y-axis than the positive Y-axis.

In HDR intracavitary brachytherapy of the cervix, the dose to the cervix is specified in terms of doses at a few designated points. A uniform system was advocated by the International Commission on Radiation Units and Measurements (ICRU), and it was recommended that the rectal dose in HDR brachytherapy of the cervix needs to be evaluated by employing specific reference points in dose reporting to assess rectal complications[12].

The anterior region of the rectum with the highest dose value is referred to as the ICRU rectal point. According to the GEC ESTRO recommendations, the dose to small rectal volumes (0.1 cc, 1 cc, 2 cc) assesses late rectal toxicity. In HDR brachytherapy, these small volumes located near the anterior rectal wall are primarily affected, as the dose in those regions is very large. However, as investigated in this study, the TPS overestimates the dose there and close by, and thus a slightly higher dose can be given because the real dose to the anterior rectal wall under consideration is slightly low. This may lead to improved tumor control without worsening late rectal problems.

Using Monte Carlo simulations, Parsai et al[22] investigated the dosage attenuation around Fletcher-Suit-Delclos caused by stainless steel tube for HDR brachytherapy. The authors concluded that metallic applicators may cause patients to receive a lower dose. The authors further concluded that the radial dosage function does not change significantly as a result of attenuation; however, the anisotropy function has a substantial influence on dose reduction [22]. According to the research conducted by Oyekunle et al[23] and Gholami et al[24], the TPS overestimates the dose because the non-water equivalence of the applicator and the same should be considered for more accurate dose estimations to the target and organs at risk.

To properly achieve overestimation of the TPS dose in this study, we adapted two different methods, and the findings show that both methods are almost in sync with one another. Therefore, it is anticipated that accounting for dose attenuation by these applicators will increase HDR dose delivery accuracy.

CONCLUSIONS

The current study evaluated the impact of the cervical applicator on dose distribution to the rectum. The goal of the current study was to use the Gafchromic EBT3 film dosimeter and Monte Carlo simulations to measure the impact of treatment heterogeneities caused by the applicator material in HDR brachytherapy for cervical cancer. The AAPM TG-43 formalism of dose calculation, which assumes that the medium is homogeneous and water-equivalent, is the foundation for the TPS employed in this study. The Monte Carlo simulation and EBT3 Gafchromic films were used in this study and both were in agreement with the conclusion that the TPS ignored the applicator's effect and the dose calculated by the TPS is significantly less than the actual dose received by the rectum. By considering the above findings it is suggested that the material of the cervical applicator should be considered for better rectal dose estimation in HDR brachytherapy of the cervix.

Ethics Committee Approval:

The study was approved by the Sher I Kashmir Institute of Medical Sciences Institutional Ethics Committee (no: SIMS 131/IEC-SKIMS/2022-196, date: 10/05/2022).

Consent to participate:

Consent from patients was not required as datasets were not for clinical use of patients.

Consent for publication:

We, the authors of this manuscript, give our consent for the publication of this manuscript to be published in the World Cancer Research Journal.

Availability of data and material:

All data generated or analysed during this study are included in this article. Further enquiries can be directed to the corresponding author.

Conflict of interest:

The authors declare that they have no affiliations or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript.

Authors Contributions:

The study plan was charted out by Aijaz Ahmad Khan in coordination with Tovseef Ahmad Tali and Misba Hamid Baba. Aijaz Ahmad Khan, Tovseef Ahmad Tali and Misba Hamid Baba collected and analyzed the data under the direct supervision of Anuj Vijay and Sajad Ahmad Rather. The first draft of this manuscript was prepared by Aijaz Ahmad Khan, Mushtaq Ahmad Sofi and revised by Sajad Ahmad Rather. Anuj Vijay reviewed the final draft of this

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REFERENCES

1. Allen D, Narayan K. Managing advanced-stage cervical cancer. Best Practice Res Clin Obstetr Gynaecol 2005; 19: 591-609.
2. Tanderup K, Georg D, Pötter R, Kirisits C, Grau C, Lindegaard JC. Adaptive management of cervical cancer radiotherapy. Semin Radiat Oncol 2010; 20: 121-9.
3. Macdonald DM, Lin LL, Biehl K, Mutic S, Nantz R, Grigsby PW. Combined intensity-modulated radiation therapy and brachytherapy in the treatment of cervical cancer. Int J Radiat Oncol Biol Phys 2008; 71: 618-624.
4. Gadda IR, Khan NA, Wani SQ, Baba MH. To evaluate the use of tandem and cylinder as an intracavitary brachytherapy device for carcinoma of the cervix with regard to local control and toxicities. J Cancer Res Ther 2022; 18: 740-746.
5. Wu CH, Liao YJ, Shiau AC, Lin HY, Hsueh Liu YW, Hsu SM. HDR Brachytherapy Dose Distribution is Influenced by the Metal Material of the Applicator. Sci Rep 2015; 5: 17863.
6. Roy S, Subramani V, Singh K, Rathi AK, Savita A, Aditi A. Study of the effects of dwell time deviation constraints on inverse planning simulated annealing optimized plans of intracavitary brachytherapy of cancer cervix. J Cancer Res Ther 2019; 15: 1370-1376.
7. Fellner C, Pötter R, Knocke TH, Wambersie A. Comparison of radiography- and computed tomography-based treatment planning in cervix cancer in brachytherapy with specific attention to some quality assurance aspects. Radiother Oncol 2001; 58: 53-62.
8. Schoeppel SL, LaVigne ML, Martel MK, McShan DL, Fraass BA, Roberts JA. Three-dimensional treatment planning of intracavitary gynecologic implants: analysis of ten cases and implications for dose specification. Int J Radiat Oncol Biol Phys 1994; 28: 277-283.
9. Kapp KS, Stuecklschweiger GF, Kapp DS, Hackl AG. Dosimetry of intracavitary placements for uterine and cervical carcinoma: results of orthogonal film, TLD, and CT-assisted techniques. Radiother Oncol 1992; 24: 137-146.
10. Khan AA, Vijay A, Wani SQ, Haq MM. Dosimetric analysis of intracavitary brachytherapy applicators: a practical study. Radiat Oncol J 2022; 40: 180-191.
11. Ling CC, Schell MC, Working KR, Jentzsch K, Harisiadis L, Carabell S, Rogers CC. CT-assisted assessment of bladder and rectum dose in gynecological implants. Int J Radiat Oncol Biol Phys 1987; 13: 1577-1582.
12. ICRU Report 38, Dose and Volume Specification for Reporting Intracavitary Therapy in Gynecology – ICRU [Internet]. [cited 2023 Apr 2]. Available from: https://www.icru.org/report/dose-and-volume-specification-for-reporting-intracavitary-therapy-in-gynecology-report-38/.
13. Garchromic EBT Films - GAFchromicTM [Internet]. [cited 2023 Apr 2]. Available from: http://www.gafchromic.com/gafchromic-film/radiotherapy-films/EBT/index.asp.
14. Taylor REP, Rogers DWO. EGSnrc Monte Carlo calculated dosimetry parameters for 192Ir and 169Yb brachytherapy sources. Med Phys 2008; 35: 4933-4944.
15. Ballester F, Puchades V, Lluch JL, Serrano-Andrés MA, Limami Y, Pérez-Calatayud J, Casal E. Technical note: Monte-Carlo dosimetry of the HDR 12i and Plus 192Ir sources. Med Phys 2001; 28: 2586-2591.
16. Perez-Calatayud J, Ballester F, Das RK, Dewerd LA, Ibbott GS, Meigooni AS, Ouhib Z, Rivard MJ, Sloboda RS, Williamson JF. Dose calculation for photon-emitting brachytherapy sources with average energy higher than 50 keV: report of the AAPM and ESTRO. Med Phys 2012; 39: 2904-2929.
17. Baltas D, Karaiskos P, Papagiannis P, Sakelliou L, Loeffler E, Zamboglou N. Beta versus gamma dosimetry close to Ir-192 brachytherapy sources. Med Phys 2001; 28: 1875-1882.
18. EPICS2017-Status.pdf [Internet]. [cited 2023 Apr 2]. Available from: http://redcullen1.net/HOMEPAGE.NEW/Papers/EPICS2017/EPICS2017-Status.pdf.
19. Rivard MJ, Coursey BM, DeWerd LA, Hanson WF, Huq MS, Ibbott GS, Mitch MG, Nath R, Williamson JF. Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations. Med Phys 2004; 31: 633-674.
20. Russell KR, Ahnesjö A. Dose calculation in brachytherapy for a 192Ir source using a primary and scatter dose separation technique. Phys Med Biol 1996; 41: 1007-1024.
21. Borg J, Rogers DW. Spectra and air-kerma strength for encapsulated 192Ir sources. Med Phys 1999; 26: 2441-2444.
22. Parsai EI, Zhang Z, Feldmeier JJ. A quantitative three-dimensional dose attenuation analysis around Fletcher-Suit-Delclos due to stainless steel tube for high-dose-rate brachytherapy by Monte Carlo calculations. Brachytherapy 2009; 8: 318-323.
23. Oyekunle EO, Obed RI, Akinlade BI, Ntekim A. Comparison of doses to the rectum derived from treatment planning system with in-vivo dose values in vaginal vault brachytherapy using cylinder applicators. J Contemp Brachytherapy 2015; 7: 485-491.
24. M H G, M S, F BM, M M. Comparison of the 2-D Dose Distribution Calculated by Planning System and Measured by Gafchromic Film Physical Dosimetry for 60Co and 192Ir Brachytherapy Sources. J Biomed Phys Eng 2020; 10: 299-306.