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FULL PAPER

Dosimetric comparison of brachytherapy sources for high-dose-rate treatment of endometrial cancer: ^{192}Ir , ^{60}Co and an electronic brachytherapy source

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Objective: To compare high-dose-rate (HDR) brachytherapy systems with ^{192}Ir , ^{60}Co and electronic brachytherapy source (EBS) for treatment of endometrial cancers.

Methods: Two additional plans were generated per patient fraction using a ^{60}Co source and Xofter-EBS on 10 selected patients, previously treated with a vaginal cylinder applicator using a ^{192}Ir source. Dose coverage of "PTV_CYLD", a 5-mm shell surrounding the cylinder, was evaluated. Doses to the following organs at risk (OARs) the rectum, bladder and sigmoid were evaluated in terms of $V_{35\%}$ and $V_{50\%}$, the percentage volume receiving 35% and 50% of the prescription dose, respectively, and $D_{2\text{cm}^3}$, the highest dose to a 2-cm³ volume of an OAR.

Results: Xofter-EBS reduces doses to all OARs in the lower dose range, but it does not always provide better sparing

of the rectum in higher dose range as does evaluation using $D_{2\text{cm}^3}$. $V_{150\%}$ and $V_{200\%}$ for PTV_CYLD was up to four times greater for Xofter-EBS plans than for plans generated with ^{192}Ir or ^{60}Co . Surface mucosal (vaginal cylinder surface) doses were also 23% higher for Xofter-EBS than for ^{192}Ir or ^{60}Co plans.

Conclusion: Xofter-EBS is a suitable HDR source for vaginal applicator treatment with advantages of reducing radiation exposure to OARs in the lower dose range, while simultaneously increasing the vaginal mucosal dose.

Advances in knowledge: This work presents newer knowledge in dosimetric comparison between ^{192}Ir or ^{60}Co and Xofter-EBS sources for endometrial vaginal cylinder HDR planning.

INTRODUCTION

The standard medical management for local and locally advanced endometrial cancers generally includes a total abdominal hysterectomy that may be followed by vaginal-cuff brachytherapy.¹ Vaginal brachytherapy may either be delivered alone or in conjunction with whole-pelvic irradiation.² Vaginal brachytherapy is generally delivered using a vaginal cylinder (applicator) and high-dose-rate (HDR) iridium-192 (^{192}Ir) radiation-source afterloader. Recently, a cobalt-60 radioactive source (^{60}Co) has become commercially available³ for use in some afterloader systems designed or adapted for its use. The main advantage of a ^{60}Co radioactive source is that it has a much longer half-life of 5.27 years compared with 73.8 days for ^{192}Ir . Using the ^{60}Co radioactive source will therefore reduce the number of radioactive source exchanges significantly and hence could be a more economical alternative to ^{192}Ir HDR source.³ The dosimetry aspect of these two sources has been compared by some investigators like Richter et al,⁴

and their results suggest that both sources provide equivalent doses for both target volume coverage and organs at risk (OARs) (bladder, rectum and sigmoid).

In addition to these, more traditional radioactive sources for brachytherapy, an electronic brachytherapy source (EBS) (Xofter® Electronic Brachytherapy System, iCad-Axxent®; iCad, Inc., Nashua, NH), has also been introduced commercially. It has been successfully used for several applications including accelerated partial-breast brachytherapy and vaginal applicator treatment.⁵⁻⁷ The Bremsstrahlung photon spectrum ranges from 26.7 to 34.5 keV. This EBS needs not be used in a conventional vault because its low-energy photon beams can easily be shielded in a regular room.⁸ The entire system is the size of a typical ultrasound unit and hence is reasonably mobile and therefore can be moved around within the hospital. Another advantage is that the source itself is not inherently radioactive; so, all problems associated with transportation, storing and monitoring of the radioactive sources are eliminated.

The purpose of this study was to dosimetrically compare plans generated by using ^{192}Ir , ^{60}Co and Xofter-EBS for vaginal brachytherapy HDR treatments. We compared the target dose coverage and doses to OARs of radiation damage for 10 patients who were previously planned and treated with HDR ^{192}Ir sources at the University of Mississippi Medical Center.

METHODS AND MATERIALS

All the patients reported in this series were previously treated for endometrial or vaginal cancer with vaginal cylinder ^{192}Ir HDR brachytherapy. Several of the patients had also received 25 fractions of external-beam radiation therapy at 1.8 Gy per fraction to a total dose of 45 Gy to the whole pelvis. External-beam radiation therapy was then followed by weekly administration of vaginal applicator HDR brachytherapy with the ^{192}Ir source. Each patient received HDR brachytherapy of 6 Gy prescribed to a surface located 5 mm away from the vaginal cylinder surface. For each patient plan that had been previously approved and treated using the ^{192}Ir source, we generated another two plans using the ^{60}Co HDR source and Xofter-EBS. In our clinic, each HDR brachytherapy treatment is individually planned with a new CT scan performed after each insertion of the applicator. Each patient received 3 fractions; each fraction is planned individually, consequently resulting in 30 original treatment plans for the 10 selected patients. With the 2 additional plans generated per ^{192}Ir treatment plan, this gave rise to a total of 90 treatment plans (30 plans for ^{192}Ir , 30 plans for ^{60}Co and 30 plans for the Xofter-EBS). The results presented here are based on the evaluation of these 90 plans. This work has been approved by our institutional internal review board.

The Varian® BrachyVision™ treatment planning system (TPS) v. 10.8.9 was used to generate the treatment plans evaluated in this study. We used the TG-43 physics data as published by Rivard et al⁹ for EBS. The TG-43 physics data for HDR ^{60}Co BeBig source were obtained from published work by other investigators.^{10,11} We also commissioned the Xofter-EBS into the Varian BrachyVision TPS. The data entered into the Varian BrachyVision TPS for all the radiation sources included: S_k —air kerma strength, Λ —dose rate constant, $g(r)$ —radial dose function, $G(r, \theta)$ —line-source geometry function and $F(r, \theta)$ —anisotropy function. We also created a Microsoft Excel worksheet that calculated the dose to a specified point using the point-source approximation, which was used to calculate the dose at the prescription point from all the source-dwell positions for all the sources.

As per our departmental HDR policy and procedures, all HDR patients underwent a CT scan of the pelvis generated with 2 mm slice thickness. The bladder was always evacuated, and the patient had a Foley catheter (Medtronic, Minneapolis, MN) inserted in the bladder. The catheter balloon would normally have 7 cm³ of contrast media. We contoured the balloon on the CT scans, and this represented the bladder for the purpose of determining bladder doses. The contouring of the rectum and sigmoid followed the GEC-ESTRO (Groupe Européen de Curiethérapie-European Society for Radiotherapy and Oncology) guidelines.¹² The diameter sizes of the vaginal cylinder used in this study ranged from 2.2 to 4.0 cm. Out of the 10 patients, 2 patients were treated with a 2.2 cm-diameter cylinder,

3 patients with a 2.6 cm-diameter cylinder, 4 patients with a 3.0 cm-diameter cylinder and 1 patient with a 4.0 cm-diameter cylinder. The treatment length ranged from 4.5 to 6.0 cm. The prescription dose was optimized to deliver a uniform dose to a surface 5 mm from the cylinder.

For each plan, the cylinder volume was contoured based on the treatment length selected by the radiation oncologist (SP) as shown in Figure 1. This was then expanded by 5 mm in all directions except inferiorly to obtain a volume, which is cylinder + 5-mm expansion. A volume called PTV_CYLD was then obtained by subtracting the contoured cylinder volume from the cylinder + 5-mm expansion. PTV_CYLD is therefore a shell volume which served as the planning target volume (PTV) for the purpose of dosimetric planning and evaluation. The process of creating PTV_CYLD is similar to the process of creating PTV_EVAL (PTV for evaluation) in accelerated partial breast irradiation treatment planning, except that the PTV_EVAL for the breast is the balloon or cavity plus a 1-cm expansion of the cavity minus the balloon volume.

All the treatment plans generated with any of the sources were then evaluated for several dosimetric parameters: $V_{90\%}$, $V_{150\%}$ and $V_{200\%}$ for the PTV_CYLD ($V_{90\%}$ was the percentage of PTV_CYLD receiving 90% of the prescription dose, while $V_{150\%}$ and $V_{200\%}$ were the percentages of PTV_CYLD getting 150% and 200% of the prescription dose, respectively). We also determined the cylinder surface dose and compared the surface dose to the prescription dose. For OARs (bladder, rectum and sigmoid), we also determined the $D_{2\text{cm}^3}$ (highest dose to a 2-cm³ volume of an OAR), $V_{35\%}$ and $V_{50\%}$ (the percentage volumes receiving 35% and 50% of the prescription dose, respectively). Statistical analysis of the data was performed using the IBM SPSS® v. 22 (IBM Corp., New York, NY; formerly SPSS Inc., Chicago, IL). If the p -value is >0.05 , it indicates no significant difference between the quantities being evaluated.

RESULTS

Evaluation of PTV_CYLD and surface doses

Table 1 shows the dose coverage and dose homogeneity evaluation for the target volume (PTV_CYLD). Evaluation of PTV_CYLD shows that the $V_{90\%}$, the percentage of

Figure 1. Sagittal view of a patient showing the vaginal cylinder, PTV_CYLD, rectum and balloon. A, anterior; F, feet; H, head; P, posterior.

Table 1. Evaluation of PTV_CYLD doses and surface doses for 2.2-, 3.0- and 4.0-cm-diameter vaginal cylinders

Source type	$V_{90\%}$ PTV_CYLD (%)	$V_{150\%}$ PTV_CYLD (%)	$V_{200\%}$ PTV_CYLD (%)	Surface dose (Gy)	Ratio of surface dose to prescription dose
2.2-cm-diameter cylinder					
^{192}Ir	98	17.3	3.5	9.2	1.54
^{60}Co	97	20.2	3.9	9.4	1.57
Xofter-EBS	95	33.8	10.2	11.2	1.87
3.0-cm-diameter cylinder					
^{192}Ir	99	10.7	2.7	8.7	1.45
^{60}Co	98	11.8	3.1	8.8	1.47
Xofter-EBS	98	26.2	9.2	10.4	1.73
4.0 cm diameter cylinder					
^{192}Ir	100	2.4	0	7.9	1.32
^{60}Co	100	2.9	0	8.0	1.34
Xofter-EBS	100	13.9	2.7	9.1	1.52

EBS, electronic brachytherapy source.

PTV_CYLD covered by 90% of the prescription dose, is at least 95% for all the cylinders and for all the sources, although there appears to be a marginal decrease of $V_{90\%}$ for the 2.2 cm-diameter one compared with the other sized cylinders. Thus, from dose coverage perspective, all the sources appear to perform equally well. Table 1 also shows the $V_{150\%}$ and $V_{200\%}$, for PTV_CYLD with different sources and different vaginal cylinder diameters.

It can be summarized from Table 1 that:

- (a) There appeared to be no significant differences between the plans generated by ^{192}Ir and ^{60}Co as far as the PTV is concerned (PTV_CYLD), irrespective of the size of the vaginal cylinder applicator used.
- (b) There was a significant difference for the $V_{150\%}$ between Xofter-EBS and either ^{192}Ir or ^{60}Co . This difference increases as the cylinder diameter increases.

The values for the $V_{200\%}$ and $V_{150\%}$ for Xofter-EBS were up to four times greater than either ^{192}Ir or ^{60}Co radioactive sources. For example, $V_{150\%}$ for 4-cm diameter is 2.4% for ^{192}Ir , while it is 13.9% for Xofter-EBS.

The radiation dose for vaginal cylinder brachytherapy is conventionally prescribed either to the surface of the vaginal cylinder or to a depth of 5 mm from the vaginal surface. When the prescribed dose is to the 5 mm depth from the vaginal cylinder surface, the surface dose of the cylinder would consequently be different, depending on the size of the vaginal cylinder used.

Table 1 also shows the surface doses for all three radiation sources as functions of vaginal cylinder sizes. It can be noted that for the Xofter-EBS, the surface dose for the same prescription dose of 6 Gy ranges from 11.2 Gy for the 2.2 cm-diameter cylinder to 9.1 Gy for the 4.0 cm-diameter one. The ratio of the surface dose to the prescription dose thus varies from 1.52 for the 4.0-cm-diameter cylinder to 1.87 for the 2.2-cm-diameter one, a difference of about 23%. For ^{192}Ir , the surface dose ranges from 9.2 to 7.9 Gy, a difference of only 16% between the 2.2- and 4.0-cm-diameter cylinders. The surface dose differences between ^{60}Co and ^{192}Ir were not significantly different. For all cylinder sizes we examined, the surface dose of the Xofter-EBS was always significantly greater than the surface dose generated with the ^{192}Ir source, irrespective of size. It can also be noted that the well-established axiom that vaginal brachytherapy should be performed with the widest vaginal cylinder tolerated by the patient is confirmed by the fact that the ratio of the surface dose to the prescription dose decreases with increasing vaginal diameter.

Figure 2 shows the sagittal view for one of the 2.2 cm-diameter cylinder plans generated with the Xofter-EBS and ^{192}Ir source. It can be noted that the 200% isodose line (yellow) hugs the cylinder surface throughout the entire treatment length for the Xofter-EBS, while for the ^{192}Ir plan, the surface dose is mostly represented by the 150% isodose line instead.

Doses to organs at risk

Figure 3 depicts the dose-volume histogram (DVH) for the ^{192}Ir (filled square), ^{60}Co (filled circle) and Xofter-EBS (filled triangle)

Figure 2. Comparison of surface dose between ^{192}Ir and Xofter-electronic brachytherapy source (EBS). F, feet; H, head.

all using a 2.6-cm-diameter cylinder. It is noted that the DVH curve for the Xofter-EBS for all of the OARs lies below and to the left of the DVH curves for both ^{192}Ir and ^{60}Co radioactive sources for doses below 5 Gy, whereas for higher doses, DVH curves for these three sources converge, and sometimes, they would cross or overlap each other. Once again, minor differences can be seen between plans generated by ^{192}Ir and ^{60}Co radioactive sources.

Table 2 shows the average of the dose to the maximum 2 cm^3 of the rectum for all the patients in our series ($D_{2\text{cm}^3}$). Also shown in Table 2 are the $V_{35\%}$ and $V_{50\%}$. The data in Table 2 represent the average over three fractions for $D_{2\text{cm}^3}$, $V_{35\%}$ and $V_{50\%}$. The $V_{35\%}$ and $V_{50\%}$ parameters characterize the lower dose region of the DVH curve.

Comparing the $V_{35\%}$ and $V_{50\%}$ for the rectum in Table 2, it can be seen that for all the patients, both $V_{35\%}$ and $V_{50\%}$ are always lower with the Xofter-EBS than for those with the ^{192}Ir or the ^{60}Co radioactive sources. The difference in $V_{35\%}$ and $V_{50\%}$ is at least

30% and perhaps as high as 70% between Xofter-EBS and the ^{192}Ir or ^{60}Co sources. Thus, we can conclude from these results that in the lower dose range, the Xofter-EBS provides better organ sparing than either of the other radioactive sources studied. For the rectum, the $D_{2\text{cm}^3}$ is comparable for all three sources for most of the patients. For three of the patients (Patient numbers 1, 2 and 9), $D_{2\text{cm}^3}$ is actually higher for plans generated with Xofter-EBS than for those with ^{192}Ir or ^{60}Co .

Table 3 shows $D_{2\text{cm}^3}$, $V_{35\%}$ and $V_{50\%}$ values for the bladder for all the patients in our series. These data show that the $D_{2\text{cm}^3}$ can be up to 60% lower for the bladder than for the rectum, irrespective of the source used (refer to Table 2). Moreover, for all the patients, $D_{2\text{cm}^3}$, $V_{35\%}$ and $V_{50\%}$ were always lower for the Xofter-EBS than for either ^{192}Ir or ^{60}Co . In this instance, the Xofter-EBS source provided better sparing of the bladder than either ^{192}Ir or ^{60}Co over the entire dose range. Table 4 shows $D_{2\text{cm}^3}$ for the sigmoid, and results show that there is no significant difference between Xofter-EBS and either ^{192}Ir or ^{60}Co radioactive source.

Figure 3. Dose-volume histogram for the sigmoid, rectum and bladder (balloon).

Table 2. $D_{2\text{cm}3}$, $V_{35\%}$ and $V_{50\%}$ for the rectum for all patients studied in this series

Patient number	$D_{2\text{cm}3}$ (Gy)			$V_{35\%}$			$V_{50\%}$		
	^{192}Ir	^{60}Co	Xofter	^{192}Ir	^{60}Co	Xofter	^{192}Ir	^{60}Co	Xofter
1 ($\varnothing = 2.6$ cm)	6.03	6.02	6.16	55.2	53.0	33.0	31.6	29.8	18.4
2 ($\varnothing = 2.2$ cm)	5.97	5.96	5.98	75.3	73.4	48.0	45.1	42.4	27.6
3 ($\varnothing = 2.2$ cm)	5.38	5.47	5.39	32.7	33.0	17.5	16.7	17.3	10.3
4 ($\varnothing = 4.0$ cm)	5.20	5.30	5.06	52.0	52.1	38.2	33.5	33.7	23.2
5 ($\varnothing = 2.6$ cm)	5.35	5.33	5.24	69.6	66.7	41.5	34.2	32.3	22.2
6 ($\varnothing = 3.0$ cm)	4.48	4.46	4.09	66.7	65.0	36.0	31.0	29.7	15.8
7 ($\varnothing = 3.0$ cm)	3.50	3.44	2.92	36.9	34.3	14.7	11.3	10.2	4.3
8 ($\varnothing = 3.0$ cm)	5.42	5.02	4.92	44.3	49.1	34.1	22.4	24.6	18.3
9 ($\varnothing = 4.0$ cm)	5.92	5.99	6.29	85.8	84.8	65.5	61.7	60.9	42.6
10 ($\varnothing = 3.0$ cm)	5.78	5.78	5.71	70.6	67.7	40.7	39.6	37.4	21.4
Average	5.3 ± 0.8	5.3 ± 0.8	5.2 ± 1.0	58.9 ± 17.5	57.9 ± 16.7	36.9 ± 14.4	32.7 ± 14.1	31.8 ± 13.9	20.4 ± 10.3
p-value ($\alpha < 0.05$)	n/a	0.944	0.76	n/a	0.900	0.007	n/a	0.890	0.041

n/a, not applicable.

DISCUSSION

In this work, we have incorporated the concept of PTV_CYLD (specifically, a 5-mm expanded shell volume around the vaginal cylinder applicator with a length that approximates the treatment length), which is analogous to the PTV_EVAL utilized in accelerated partial-breast radiotherapy, in an attempt to better understand the dosimetric parameters in vaginal HDR plans

generated with three different brachytherapy sources. In Table 1, it can be noted that the value of $V_{150\%}$ for PTV_CYLD calculated using Xofter-EBS is more than double the value achieved with either ^{192}Ir or ^{60}Co for the same patient. Similarly, $V_{200\%}$ for Xofter-EBS generated plans is about three times greater than for plans generated with either ^{192}Ir or ^{60}Co sources. The value of $V_{200\%}$ is up to 10% of PTV_CYLD for the smallest diameter

Table 3. Average $D_{2\text{cm}3}$, $V_{35\%}$ and $V_{50\%}$ for the bladder for all patients studied in our series

Patient number	$D_{2\text{cm}3}$ (Gy)			$V_{35\%}$			$V_{50\%}$		
	^{192}Ir	^{60}Co	Xofter	^{192}Ir	^{60}Co	Xofter	^{192}Ir	^{60}Co	Xofter
1 ($\varnothing = 2.6$ cm)	3.6	3.5	2.8	96.7	93.7	51.5	51.5	47.1	23.1
2 ($\varnothing = 2.2$ cm)	3.5	3.4	2.7	86.1	82.2	43.5	41.7	38.8	19.2
3 ($\varnothing = 2.2$ cm)	2.3	2.2	1.3	22.8	20.6	8.0	3.8	3.3	0.0
4 ($\varnothing = 4.0$ cm)	3.2	3.2	2.5	64.3	63.1	31.7	26.6	26.4	13.1
5 ($\varnothing = 2.6$ cm)	3.4	3.3	3.0	69.0	65.0	43.8	33.1	30.4	23.7
6 ($\varnothing = 3.0$ cm)	3.1	3.1	2.3	66.9	63.2	27.6	24.7	22.9	8.8
7 ($\varnothing = 3.0$ cm)	2.6	2.6	1.9	49.0	45.4	16.7	13.1	11.8	3.6
8 ($\varnothing = 3.0$ cm)	3.8	3.9	3.3	79.8	85.9	54.5	43.4	45.8	28.7
9 ($\varnothing = 4.0$ cm)	3.1	3.1	2.3	89.2	86.5	34.8	33.8	31.6	8.4
10 ($\varnothing = 3.0$ cm)	4.1	4.1	3.4	98.9	98.0	67.1	67.2	63.5	35.0
Average and standard deviation	3.3 ± 0.5	3.2 ± 0.5	2.6 ± 0.7	72.3 ± 23.4	70.3 ± 24	37.9 ± 17.9	33.9 ± 18.4	32.2 ± 17.6	15.6 ± 11.8
p-value ($\alpha < 0.05$)	n/a	0.900	0.014	n/a	0.860	0.002	n/a	0.830	0.021

n/a, not applicable.

Table 4. Average $D_{2\text{cm}^3}$ for the sigmoid for all patients studied in our series

Patient number	$D_{2\text{cm}^3}$ (Gy)		
	^{192}Ir	^{60}Co	Xoft
1 ($\varnothing = 2.6$ cm)	2.10	2.09	1.32
2 ($\varnothing = 2.2$ cm)	3.61	3.66	3.43
3 ($\varnothing = 2.2$ cm)	3.96	4.36	3.80
4 ($\varnothing = 4.0$ cm)	4.30	4.52	4.26
5 ($\varnothing = 2.6$ cm)	4.83	4.81	4.65
6 ($\varnothing = 3.0$ cm)	3.68	3.81	3.54
7 ($\varnothing = 3.0$ cm)	4.01	4.29	4.11
8 ($\varnothing = 3.0$ cm)	3.87	4.15	3.95
9 ($\varnothing = 4.0$ cm)	4.65	4.80	5.29
10 ($\varnothing = 3.0$ cm)	5.07	5.03	5.14
Average and standard deviation	4.01 ± 0.83	4.15 ± 0.85	3.95 ± 1.12
p -value ($\alpha < 0.05$)	n/a	0.706	0.895

n/a, not applicable.

vaginal cylinder (2.2-cm diameter). It has also been shown in Table 1 and Figure 2 that the vaginal surface dose is significantly greater for the Xoft-EBS generated plans than for either the ^{192}Ir or ^{60}Co source. The surface of the cylinder is entirely covered by the 150% isodose line, if the Xoft-EBS brachytherapy system is used, whereas for both ^{192}Ir and ^{60}Co , the 150% isodose line lies within the cylinder applicator itself. The increase in the surface dose of Xoft-EBS-generated plans compared with ^{192}Ir -source-generated plans has also been demonstrated by other investigators, for not only vaginal cylinder treatment but also accelerated partial-breast balloon-type radiation therapy.^{5,7,13,14}

It is commonly agreed that low-energy X-rays and γ rays have a higher relative biological effectiveness (RBE) than the high-energy X-rays or γ rays such as those produced by ^{192}Ir sources or ^{60}Co .^{15,16} Values assumed in the literature for RBE for low-energy X-rays often range from 1.2 to 2. This means that even if the physical dose is the same for Xoft-EBS and ^{192}Ir , the biological effective dose would be significantly higher for Xoft-EBS brachytherapy plans than for plans generated with either ^{192}Ir or ^{60}Co . So, the higher biologically equivalent dose and the higher physical dose delivered by Xoft-EBS to the vaginal mucosa may potentially lead to undesirable local effects. Wazer et al¹⁷ have demonstrated that the volume of the PTV receiving 200% of the prescription dose may be correlated with an increased risk of fat necrosis, when using interstitial multicatheter brachytherapy for accelerated partial-breast irradiation. This concept may also hold true for HDR brachytherapy with higher surface doses as shown here for Xoft-EBS. Although a retrospective study by Dooley et al¹⁴ did not identify any grade 3 or higher morbidity associated with the use of Xoft-EBS for HDR vaginal cancer treatments, longer term follow-up data in this regard are lacking and are certainly needed.

Our studies also show that while the Xoft-EBS source shows significant advantage by having smaller values of $V_{35\%}$ and $V_{50\%}$

for the rectum and bladder than either ^{192}Ir or ^{60}Co radioactive source, the value for $D_{2\text{cm}^3}$ is almost identical for most patients. 3 out of 10 patients in our series (Patient numbers 1, 2 and 9) have average values of $D_{2\text{cm}^3}$ that are higher for plans generated with Xoft-EBS than for those generated with ^{192}Ir or ^{60}Co sources. A detailed examination of the CT data for these patients indicated that the rectum was closer than 5 mm to the vaginal cylinder, especially near the top of the cylinder. Since the relative depth dose curve (normalized to dose at 5-mm depth) for Xoft-EBS source is higher than that of ^{192}Ir radioactive source for distances < 5 mm, this leads to higher vaginal mucosa doses and higher doses to the OARs, if an appreciative volume of these organs lies < 5 mm from the vaginal cylinder. Given the fact that the Xoft-EBS has a higher RBE than the other two sources, as we had previously discussed, the biologically equivalent dose to the rectum would be higher, despite a similar physical dose or even a higher dose in the case of these three patients. This high dose to a small volume may potentially be mitigated by the lower volumes exposed in the low-dose range than if ^{192}Ir or ^{60}Co were the source of radiation. Increasing the number of treatment fractions and decreasing the dose per fraction using the Xoft-EBS could also conceivably alleviate any short- and long-term side effects of radiotherapy.

CONCLUSION

From our modelling of these three radiation sources using a standard TG-43 formalism, all of them appear to be suitable for use in vaginal cylinder brachytherapy. The Xoft-EBS appears to have the advantage of reducing radiation exposure to OARs (rectum and bladder) in the lower dose range, while simultaneously achieving comparable dose coverage in the target volume (PTV_CYLD). However, in the higher dose range (closer to the prescription dose), Xoft-EBS does not always provide better sparing of the rectum and sometimes performs worse than either ^{192}Ir or ^{60}Co , as indicated with the evaluation of $D_{2\text{cm}^3}$. The

vaginal surface doses for plans generated with Xofter-EBS were between 15% and 23% greater than those for comparable plans generated with ^{192}Ir or ^{60}Co sources. Using the concept of a PTV_CYLD, a 5-mm expanded shell region around the vaginal applicator, our data indicate that $V_{150\%}$ and $V_{200\%}$ were between two and four times greater in Xofter-EBS-generated plans than in plans generated with ^{192}Ir or ^{60}Co radioactive sources. The

surface dose can be up to 87% higher than the prescription dose for a 2.2-cm diameter using the Xofter-EBS, while this value is only 54% higher for ^{192}Ir . Given the higher biological effective dose for Xofter-EBS than that for either ^{192}Ir or ^{60}Co sources, practitioners using Xofter-EBS may consider increasing the number of fractions and reducing the dose per fraction and the total dose per treatment course.

REFERENCES

- Small W Jr, Beriwal S, Demanes DJ, Dusenbery KE, Eifel P, Erickson B, et al; American Brachytherapy Society. American Brachytherapy Society consensus guidelines for adjuvant vaginal cuff brachytherapy after hysterectomy. *Brachytherapy* 2012; **11**: 58–67. doi: [10.1016/j.brachy.2011.08.005](https://doi.org/10.1016/j.brachy.2011.08.005)
- Nout RA, Smit VT, Putter H, Jürgenliemk-Schulz IM, Jobsen JJ, Lutgens LC, et al; PORTEC Study Group. Vaginal brachytherapy versus pelvic external beam radiotherapy for patients with endometrial cancer of high-intermediate risk (PORTEC-2): an open-label, non-inferiority, randomized trial. *Lancet* 2010; **375**: 816–23. doi: [10.1016/S0140-6736\(09\)62163-2](https://doi.org/10.1016/S0140-6736(09)62163-2)
- Ntekim A, Adenipekun A, Akinlade B, Campbell O. High dose rate brachytherapy in the treatment of cervical cancer: preliminary experience with cobalt 60 Radionuclide source-A Prospective Study. *Clin Med Insights Oncol* 2010; **19**: 89–94. doi: [10.4137/CMO.S5269](https://doi.org/10.4137/CMO.S5269)
- Richter J, Baier K, Flentje M. Comparison of cobalt-60 and iridium-192 sources in high dose rate afterloading brachytherapy. *Strahlenther Onkol* 2008; **184**: 187–92. doi: [10.1007/s00066-008-1684-y](https://doi.org/10.1007/s00066-008-1684-y)
- Dickler A, Kirk MC, Coon A, Bernard D, Zusag T, Rotmensch J, et al. A dosimetric comparison of Xofter Axxent electronic brachytherapy and iridium-192 high-dose-rate brachytherapy in the treatment of endometrial cancer. *Brachytherapy* 2008; **7**: 351–4. doi: [10.1016/j.brachy.2008.05.003](https://doi.org/10.1016/j.brachy.2008.05.003)
- Dickler A, Kirk MC, Seif N, Greim K, Dowlathshahi K, Franscatt D, et al. A dosimetric comparison of MammoSite high-dose-rate brachytherapy and Xofter Axxent electronic brachytherapy. *Brachytherapy* 2007; **6**: 164–8. doi: [10.1016/j.brachy.2007.01.005](https://doi.org/10.1016/j.brachy.2007.01.005)
- Smitt MC, Kirby R. Dose-volume characteristics of a 50-kV electronic brachytherapy source for intracavitary accelerated partial breast irradiation. *Brachytherapy* 2007; **6**: 207–11. doi: [10.1016/j.brachy.2007.03.002](https://doi.org/10.1016/j.brachy.2007.03.002)
- Mobit PN, Rajaguru P, Brewer M, Baird M, Packianathan S, Yang CC. Radiation safety consideration during intraoperative radiation therapy. *Radiat Prot Dosimetry* 2015; **164**: 376–82. doi: [10.1093/rpd/ncu292](https://doi.org/10.1093/rpd/ncu292)
- Rivard MJ, Davis SD, DeWerd LA, Rusch TW, Axelrod S. Calculated and measured brachytherapy dosimetry parameters in water for the Xofter Axxent X-Ray Source: an electronic brachytherapy source. *Med Phys* 2006; **33**: 4020–32. doi: [10.1118/1.2357021](https://doi.org/10.1118/1.2357021)
- Ballester F, Granero D, Pérez-Calatayud J, Casal E, Agramunt S, Cases R. Monte Carlo dosimetric study of the BEBIG ^{60}Co HDR source. *Phys Med Biol* 2005; **50**: N309–16. doi: [10.1088/0031-9155/50/21/N03](https://doi.org/10.1088/0031-9155/50/21/N03)
- Granero D, Pérez-Calatayud J, Ballester F. Technical note: dosimetric study of a new ^{60}Co source used in brachytherapy. *Med Phys* 2007; **34**: 3485–8. doi: [10.1118/1.2759602](https://doi.org/10.1118/1.2759602)
- Pötter R, Haie-Meder C, Van Limbergen E, Barillot I, De Brabandere M, Dimopoulos J, et al; GEC ESTRO Working Group. Recommendations from gynecological (GYN) GEC ESTRO working group (II): concepts and terms in 3D image-based treatment planning in cervix cancer brachytherapy-3D dose volume parameters and aspects of 3D image-based anatomy, radiation physics, radiobiology. *Radiother Oncol* 2006; **78**: 67–77. doi: [10.1016/j.radonc.2005.11.014](https://doi.org/10.1016/j.radonc.2005.11.014)
- Kamrava M, Chung MP, Demarco J, Kayode O, Park SJ, Borja L, et al. Electronic brachytherapy for postsurgical adjuvant vaginal cuff irradiation therapy in endometrial and cervical cancer: a retrospective study. *Brachytherapy* 2013; **12**: 141–7. doi: [10.1016/j.brachy.2012.04.003](https://doi.org/10.1016/j.brachy.2012.04.003)
- Dooley WC, Thropay JP, Schreiber GJ, Puthawala MY, Lane SC, Wurzer JC, et al. Use of electronic brachytherapy to deliver postsurgical adjuvant radiation therapy for endometrial cancer: a retrospective multicenter study. *Oncol Targets Ther* 2010; **3**: 197–203. doi: [10.2147/OTT.S13593](https://doi.org/10.2147/OTT.S13593)
- Rava P, Dvorak T, Markelewicz RJ Jr, Hiatt JR, Sternick ES, MacAusland SG, et al. A comparison of the biological effective dose of 50-kV electronic brachytherapy with ^{192}Ir high-dose-rate brachytherapy for vaginal cuff irradiation. *Brachytherapy* 2012; **11**: 402–7. doi: [10.1016/j.brachy.2011.08.004](https://doi.org/10.1016/j.brachy.2011.08.004)
- Wuu CS, Kliauga P, Zaider M, Amols HI. Microdosimetric evaluation of relative biological effectiveness for ^{103}Pd , ^{125}I , ^{241}Am , and ^{192}Ir brachytherapy sources. *Int J Radiat Oncol Biol Phys* 1996; **36**: 689–97. doi: [10.1016/S0360-3016\(96\)00374-4](https://doi.org/10.1016/S0360-3016(96)00374-4)
- Wazer DE, Kaufman S, Cuttino L, DiPetrillo T, Arthur DW. Accelerated partial breast irradiation: an analysis of variables associated with late toxicity and long-term cosmetic outcome after high-dose-rate interstitial brachytherapy. *Int J Radiat Oncol Biol Phys* 2006; **64**: 489–95. doi: [10.1016/j.ijrobp.2005.06.028](https://doi.org/10.1016/j.ijrobp.2005.06.028)