RESEARCH ARTICLE

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Dosimetric Study to Estimate Deviations in Delivered Radiation Dose due to Occluded Air Spaces in Vaginal Vault Brachytherapy Applications

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Abstract

Background: To develop a dosimetric tool to estimate the dose delivered in the presence of air pockets with EBT3 film while simulating the conditions of vaginal vault brachytherapy (VVBT) with 3.0 diameter cylindrical applicator at a prescription dose distance of 5mm from the surface of it. **Materials and Method:** Six acrylic plates (10 cm x 10 cm, 0.5 cm thick) with four different types of slots were designed and produced locally. They can hold a cylindrical vaginal brachytherapy applicator in the centre, air equivalent material from the applicator's surface [(sizes 4.5 mm (A), 3.0 mm (B), and 2.0 mm (C)], EBT3 film at the prescribed dose distance, and holder rods. Plates were layered together with acrylic rods and assembled in a holding box in a water phantom. Three treatment plans done in TPS with prescription doses of 2 Gy, 3 Gy, and 4 Gy at 5.0 mm with a treatment length of 6 cm, and were executed in Co-60-based HDR brachytherapy unit (M/s SagiNova, Germany) with & without the placement of air equivalent material, and the dose received at slot locations A, B, & C were noted. **Results:** The mean percentage deviation of measured dose without and with presence of air pocket at A, B and C was 13.9%, 11.0% and 6.4% respectively for all dose prescriptions. As the air pocket size expanded radially from 2.0 mm to 4.5 mm, the increase in dosage ranged from 6.4% to 13.9% which was due to the fact that the film was held at dosage prescription distance and the lack of attenuation of photons radially through air pocket. **Conclusions:** The present study can be carried out with a 3D printed phantom that simulates VVBT application having air pockets of different dimensions at different locations and also can be analyzed with Monte Carlo simulations.

Keywords: Air pockets- vaginal vault brachytherapy- high dose-rate- dose deviations

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Introduction

The purpose of vaginal vault brachytherapy (VVBT) is to eliminate a tiny tumour from the vaginal vault lymphatics. Although the applicator utilized for high-dose-rate (HDR) brachytherapy of the vagina varies, the most widely used one is a segmental cylinder (Horowitz et al., 2002). More than 90% of lymphatics were found to be within 2-3 mm of the surface of stretched vaginal mucosa (Choo et al., 2005); it is recommended that vaginal cylinder contact with the vaginal surface be maintained in order to provide adequate doses to the submucosal lymphatics. According to the Group Europeen de Curietherapie and the European Society for Radiotherapy and Oncology (GEC-ESTRO), VVBT dosages should be administered to 5.0 mm from the applicator surface with a 2-mm tolerance (Haie-Meder et al., 2005; Potter et al., 2006). It is reported that air pockets around the applicator are encountered during the administration of VVBT (Richardson et al., 2010). This may cause the vaginal mucosa to shift away from the cylinder's surface, resulting in under-dosing of the vaginal mucosa as well as inability to destroy all microscopic cancer cells, increasing the chance of recurrence (Maxwell et al., 2016). Sapienza et al., (2019) described the length and diameter of the vaginal cylinder utilized, as well as the location and size of air pockets detected from post-insertion computed tomography (CT) in VVBT applications. Figure 1 depicts a CT scan image of one of our patient treated with a vaginal cylinder applicator having 3.0 cm diameter. The dose prescription

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was at 5.0 mm from the surface of the applicator, for a treatment length of 5.0 cm. In the transverse section, two air spaces could be observed along the periphery of the vaginal applicator.

Despite the recent popularity of three-dimensional computed tomography (CT)-based treatment planning systems (TPS) for brachytherapy applications, currently commercially available planning systems do not include heterogeneity adjustments for brachytherapy dosimetry, implying that the tumour and its surrounding tissues were treated as a water equivalent homogeneous medium.

Maxwell et al., (2016) addressed two aspects of VVBT uncertainty to address dosage fluctuations owing to heterogeneity. The first examines the effects of air gaps at the dosage prescribed depth retrospectively. The second is how air gaps affect the American Association of Physicists in Medicine TG-43 formalism (Nath et al., 1995) since it assumes complete scatter and attenuation, which is incorrect when there is an air gap. Efforts to develop acceptable dosimetric methods to estimate dosage differences when air pockets are encountered, employing phantom methods, are required in this area.

The current study attempts a novel phantom design to imitate air pockets surrounding the vaginal cylinder and to quantify dosage changes in the presence of air pockets using radiochromic EBT3 film.

Materials and Methods

HDR Brachytherapy unit

HDR brachytherapy unit (M/s Bebig SagiNova® HDR Model SN-050 Eckert & Ziegler, Germany) is available for clinical applications at our centre. This treatment unit is managed by SagiPlan® operating system provided in the control panel. Co-60 high intensity radioactive stepping source (Model Co0.A86) is used for treatment delivery incorporating certified source strength in reference air kerma rate (RAKR). The source has a central cylindrical active core length of 3.5 mm, with an active core diameter of 0.5 mm. A cylindrical stainless-steel capsule with an exterior diameter of 1.0 mm surrounds the active core. After source loading, source strength was determined using a well type ionization chamber/electrometer with a certificate from a secondary standard dosimetry laboratory (SSDL) for calibration. Measured source strength and TPS indicated activity based on decay table agreed with stated value within 3%.

Gafchromic EBT3 film, calibration and its response

In this study, all dosimetric measurements were carried out with GafChromic EBT3 self-developing dosimetry film (International Specialty Products, Wayne, New Jersey, USA; Lot No. 09071703) which has been demonstrated to be a good tool for mega voltage (MV) radiation dosimetry (Casanova et al., 2013; Chiu-Tsao et al., 2012). This is considered suitable for ‘in vivo’ dose measurements because of its thin configuration (thickness ~ 0.278 mm) and near-tissue equivalence (Chiu-Tsao et al., 2012).

GafChromic (EBT3) film pieces of size 2.0 cm x 2.0 cm, cut from a single sheet were exposed to radiation at a depth of 5.0 cm in a slab phantom of dimensions 30.0 cm × 30.0 cm × 10.0 cm (ρ = 1.045 g/cm3, SP34, IBA Dosimetry GmbH, Germany) having thickness of 1.0 cm of individual sheets. These films were irradiated to the doses of 0.1, 0.3, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, and 6.0 Gy under 80.0 cm isocentric Tele-Cobalt unit (Theratron® Equinox™, M/s.Theratronics, Canada). This unit is calibrated in accordance with TRS-398 IAEA protocol (IAEA, 2000), with a vertical beam of 10.0 cm × 10.0 cm field size, at source to phantom surface distance of 75.0 cm. A calibrated farmer type ionization chamber (IC) model FC65 (IBA Dosimetry GmbH, Schwarzenbruck, Germany) was placed in slab phantom in a separate setup similar to that of film irradiation one and kept adjacent it, to find dose delivered to the film. Unexposed film was taken as control.

Irradiated films were scanned using an Epson 11000XL (Epson America Inc., Long Beach, CA, USA) 24 hours after exposure to radiation. Tagged Image File format (TIFF) was used to store RGB-positive photos with a resolution of 72 dpi and a pixel size of 0.35 mm at 16 bits per color channel. ImageJ v1.42q (National Institute of Health, Bethesda, MA, USA) and MS Excel were used for the image analysis. An area of interest of 2.0 cm × 2.0 cm in size and centered on the red channel yielded the mean pixel value. In comparison to control film, the net optical density (OD) was represented as a logarithmic value of the ratio of the mean pixel value of exposed to unexposed film. A calibration curve plot with radiation dose (Gy) versus net OD using a third-order polynomial is drawn to know about the dose received by any exposed film.

Design and fabrication of a phantom for simulating air pockets around VVBT applicator

The study was carried out with cylindrical VVBT applicator having 3.0 cm diameter. The dose was prescribed at 0.5 cm from the applicator’s surface, with a treatment length of 6.0 cm. To simulate the air pockets around VVBT applicator, as well as dose measurements with EBT3 film, six acrylic plates, each having dimensions of 10.0 cm (length)× 10.0 cm (width)× 0.5 cm (thickness) were taken. Each plate has four different types of slots, which are described below.

1) First type

A central slot to accommodate the placement of a VVBT applicator having 3.0 cm diameter.

2) Second type

To simulate air pockets around the VVBT applicator, three slots (A, B and C) on the circumference of the first slot at 0^o, 120^o, and 240^o angulations were created. Sizes of these three slots were 5.0 mm × 6.0 mm; 3.5 mm ×4.0 mm; and 2.0 mm × 4.0 mm at locations A, B and C respectively. The slot sizes were chosen based on the radial dimensions of the most likely air pockets observed in the literature (Sapienza et al., 2019). An air equivalent material was placed in these slots during the irradiation procedure for dose measurements with air pocket; otherwise, the dose measured will be considered as without an air pocket.

3) Third type

A slot in the shape of an arc with a diameter of 4.0 cm, a thickness of 0.5 mm, and a length of 11.0 cm was made for the placement of the EBT3 film, which is concentric to the first type. The film starting and ending points were noted as P & Q respectively. The distances of slot locations of A, B and C from film starting point 'P' were 2.1 cm, 6.1 cm and 9.4 cm respectively.

4) Fourth type

Four circular slots for placement of an acrylic rods having 0.6 cm diameter were created around the corner of the plate.

Figures 2a and 2b shows the schematic diagram of an acrylic plate having the dimensions of all four types of slots along with their corresponding legends. Figure 2c depicts a photograph of the fabricated plate showing legends of four slots.

All plates (6 Nos) having slots were stacked together with an acrylic rods and were mounted in an acrylic stand. Figures 3a and 3b show top views of constructed plates with air pocket slots without and with air equivalent material placed in the slots, respectively. Cylindrical VVBT applicator (diameter 3.0 cm and length 8.0 cm) and EBT3 film (of size 3.5 cm × 11.0 cm) were placed at respective slots. Figure 3c shows the lateral view of assembled portion of plates, applicator, air equivalent pieces and EBT3 film in respective slots in place mounted in an acrylic stand. As shown in Figure 3c, the complete assembly is supported by a solid acrylic plate that serves as a stopper plate (at the frontal area of the applicator).

The acrylic stand having the assembly was placed in a water phantom having dimensions 30.0 cm × 30.0 cm × 30.0 cm. Figure 4a shows the lateral view of schematic diagram of assembled device having dimensions and water phantom. Figure 4b shows the irradiation setup of assembled device in water phantom.

The CT image of the water phantom was taken using M/s Wipro GE CT Scanner. The serial images were transferred to TPS (M/s SagiPlan, Bebig, Germany). Three treatment plans were generated with a prescription dose of 200 cGy, 300 cGy and 400 cGy at 5.0 mm from the applicator's surface with a treatment length of 6.0 cm (having 5.0 mm dwell separation). Interest points at prescription dose distance along the treatment length were generated and the dose was normalized to these points. The inverse planning optimization was used for calculating the auto dwell time and dwell position was used. Figure 5 shows the iso-dose distribution in TPS around the applicator and location of three air pockets (A, B and C) around the cylinder in the transverse image. All treatment plans were carried out under HDR brachytherapy unit placing the assembled devise in a water phantom without and with placement of air equivalent material (thermocole pieces) and EBT3 film in respective slots.

Results

Figure 7a shows the schematic diagram showing the locations of A, B, and C slot locations on EBT3 film having size 3.5 cm x 11.0 cm, from the film's starting point 'P'. Figure 6a & 6b represents the scanned image of irradiated film in absence and presence of air equivalent material in place of respective slots. The doses measured at the slot locations are tabulated. Percentage deviation of measured vs prescription dose is calculated as per the following formula 1:

$$\%\ \text{deviation of dose} = \frac{Measured\ \ dose - Prescribed\ \ dose}{Prescribed\ \ dose} \times 100 \quad (1)$$

Percentage deviation of measured dose with and without presence of air equivalent material (air pocket) is calculated as per the following formula 2:

$$\%\ \text{deviation of dose} = \frac{Measured\ \ dose\ with\ air\ pocket - Measured\ \ dose\ without\ air\ pocket}{Measured\ \ dose\ with\ air\ pocket} \times 100 \quad (2)$$

Table 1 and Figure 7 shows the comparison of measure doses by EBT3 film without and with air pockets at slots A, B and C for 200, 300 and 400 cGy prescription. As observed from the table 1, the mean percentage deviation of measured dose for the prescription doses of 200 cGy, 300 cGy, and 400 cGy was -3.1%, -0.6%, and -1.4%;

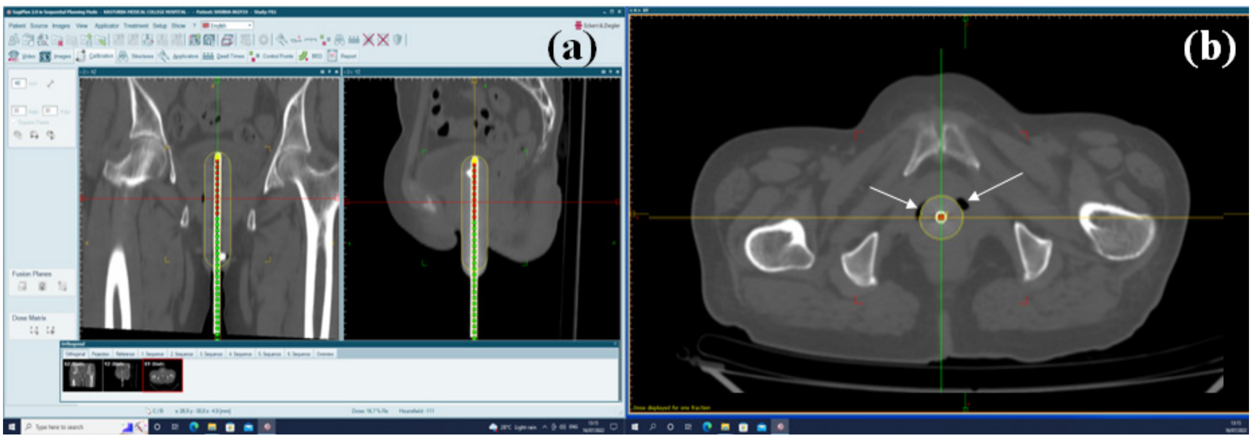

Figure 1. (a) DRR images (coronal & sagittal section of one of patient treated with a vaginal cylinder applicator having 3.0 cm diameter in brachytherapy TPS. (b) In the transverse section, two air spaces (shown in white arrow) could be observed along the periphery of the vaginal applicator. The dose prescription was at 5.0 mm from the surface of the applicator, for a treatment length of 5.0 cm.

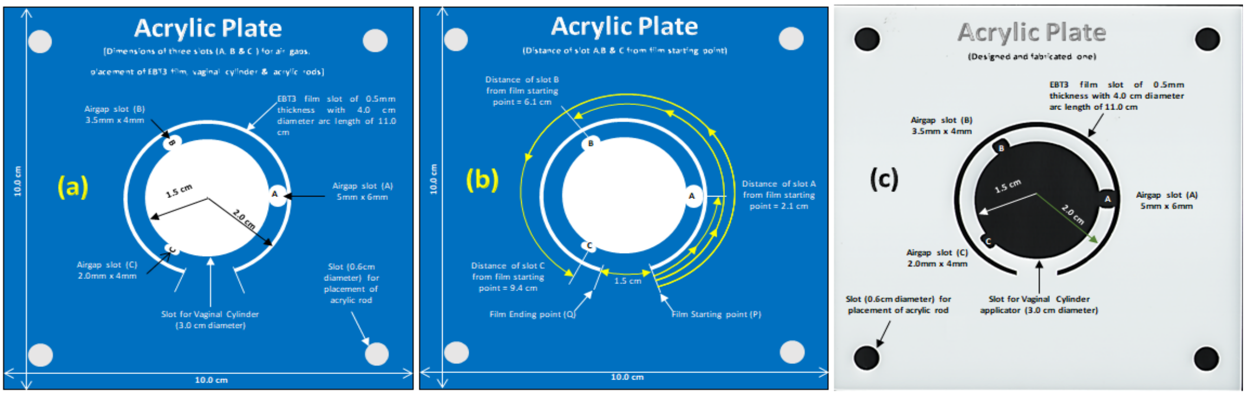

Figure 2. (a) and (b) shows the schematic diagram of an acrylic plate having the dimensions of all four types of slots along with their corresponding legends. (c) photograph of the fabricated plate showing legends of all four slots.

and 12.0 %, 9.4 %, and 4.3 %, without and with air pockets respectively at all locations (A, B and C) using formula 1. The deviation with the presence of air pocket was attributed to the size of gap at respective location. However, the mean percentage deviation of measured dose without and with presence of air pocket at locations

Table 1. Comparison of Measured EBT3 Film Doses without and with Air Pockets at Slots A, B and C.

Prescription Dose (cGy)	Air pocket location location	Measured dose (cGy) by EBT3 film				% Deviation (formula 2)
		Without air pocket		With air pocket		
		Dose (cGy)	% Deviation (formula 1)	Dose (cGy)	% Deviation (formula 1)	
200	A	192.6	-3.7	219.4	9.7	13.9
	B	194.9	-2.6	215.9	8	10.8
	C	193.7	-3.2	205.7	2.8	6.2
300	A	300.2	0.1	341	13.7	13.6
	B	298.5	-0.5	331.9	10.6	11.2
	C	295.6	-1.5	314.2	4.7	6.3
400	A	393.9	-1.5	450.2	12.6	14.3
	B	394.2	-1.5	438	9.5	11.1
	C	395.4	-1.2	421.5	5.4	6.6

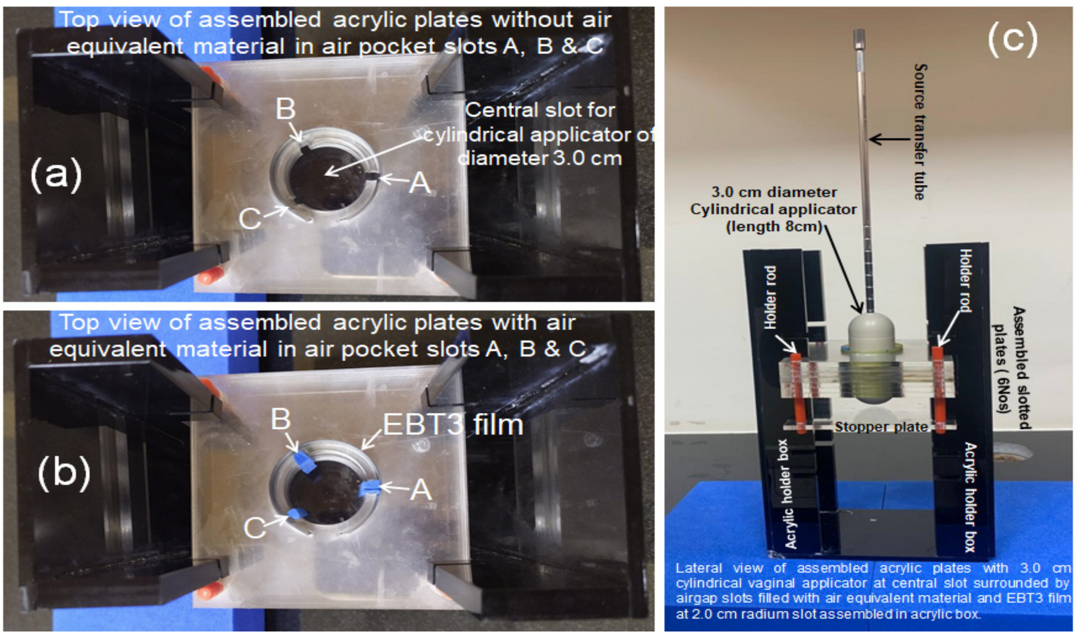

Figure 3 (a) and (b) represents the photograph of top end of assembled plated having air pocket slots without and with placement of thermocol piece in place. (c) shows the later view of assembled portion of plates, applicator, air equivalent material and film in place in an acrylic box.

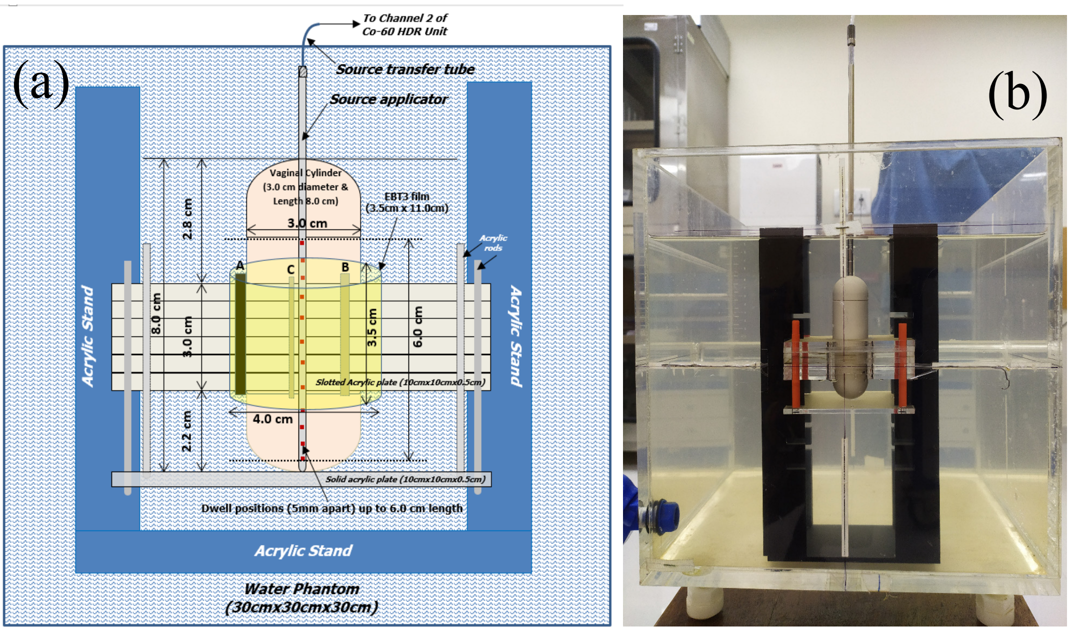

Figure 4. (a) shows the lateral view of schematic diagram of assembled device having dimensions and water phantom. (b) shows the irradiation setup of assembled device in water phantom.

A, B and C was 13.9%, 11.0% and 6.4% respectively for all dose prescriptions (as calculated from formula 2).

Discussion

In this dosimetric study, we estimated the deviations in delivered radiation dose due to occluded air spaces in VVBT applications using a locally developed and built phantom with 3.0 cm diameter cylindrical applicator at prescription dose distance of 0.5 cm from the applicator surface.

When radiation beams travel through a homogeneous medium, their dose decreases in inverse proportion to the square of the distance from the source as well with the attenuation of medium. The dose changes rapidly when radiation passes through media with varying atomic number, density, and electron density. When radiation passes via an interface between low and high atomic number materials, the high atomic number tissue backscatters a significant fraction of the secondary electrons toward the interface. This effect significantly increases the dosage at the interface (Binger et al., 2008). Such differences in dosage intensity are most visible at the interfaces of different densities of media. The transition from a low-density medium (air) to a dense medium (water) results in a sharp decrease in dose at the interface. The opposite circumstance causes increase in dose near the interface. Anatomically, such changes affect dose distribution by boosting PDD values inside the BT treatment area (Engelsman et al., 2001; Azam et al., 1994).

In a study by Celik et al., (2018) sudden dose increases and decreases were observed at the water–air–water interfaces. These effects were expected and the results were consistent with the literature and within the tolerance limits stated in the clinical dose guidelines. The most important point of their results is that the PDD curve of the radiation in the air medium through to the water medium is different from the only water medium.

Zabihzadeh et al., (2013) have found air heterogeneity dose increases as 9.11–10.2%, 9.11–10.0%, 8.62–10.08%

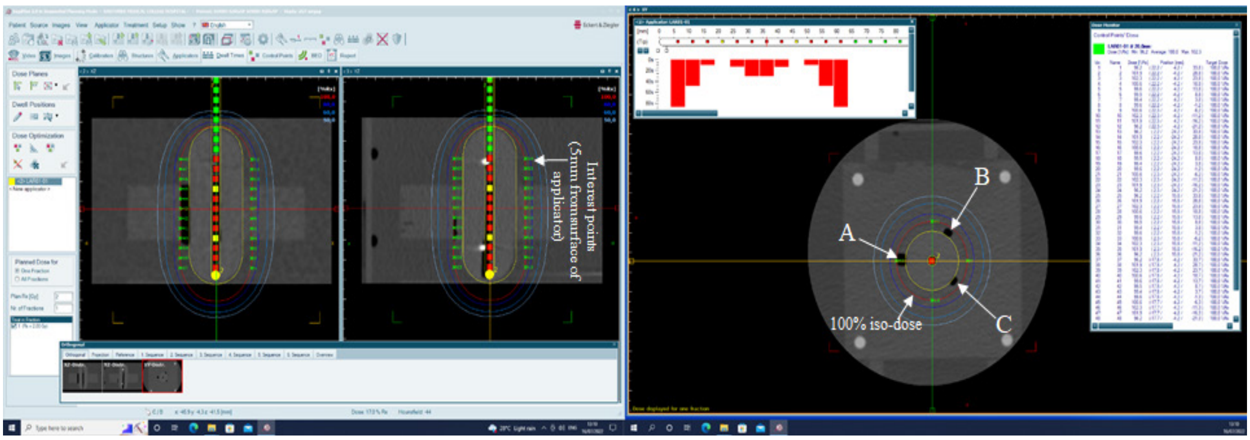

Figure 5. Shows the Iso-Dose Distribution (100% shown in red color) in TPS around the Applicator and Location of Three Air Pockets (A, B and C) around the Cylinder in the Transverse Image.

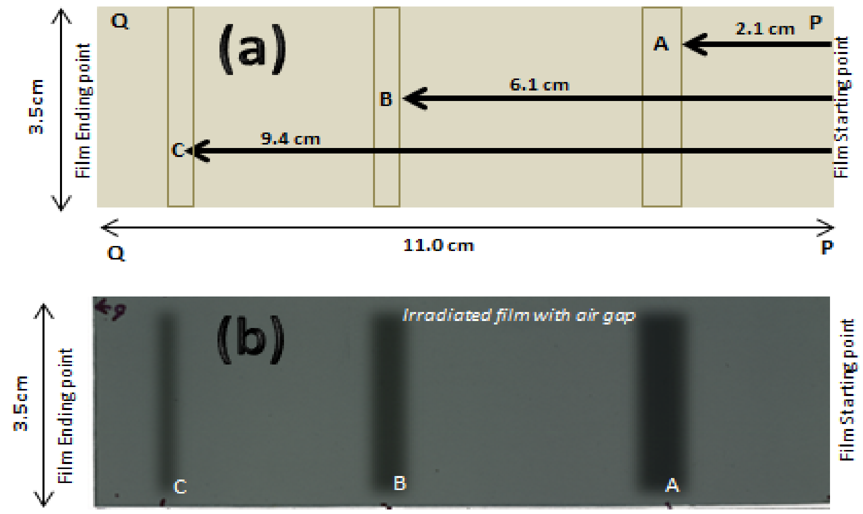

Figure 6. (a) & (b) represents the schematic diagram with dimensions of film and location of air gap slots (A,B & C) and scanned image of irradiated film in presence of air equivalent material in place of respective slots. The doses measured at respective slot locations are tabulated.

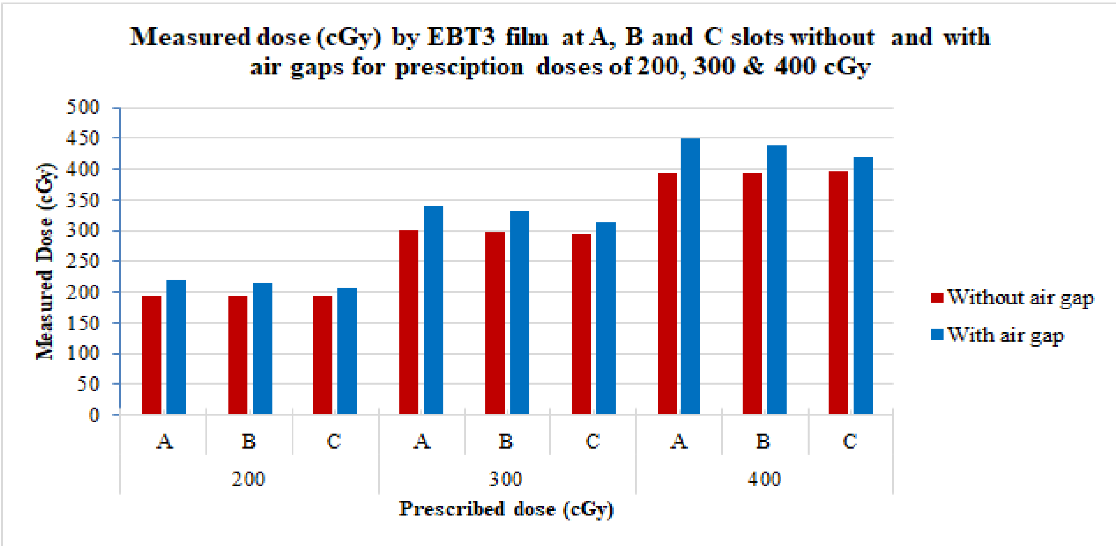

Figure 7. Shows the Comparison of Measure Doses by EBT3 Film without and with Air Pockets at slots A, B and C for 200, 300 and 400 cGy prescription.

and 8.5–10.07%, respectively, for 5, 10, 20 and 30mm distances from the source. In a study by Terribilini et al., air at a distance of 10 mm from the source produced heterogeneity that was 7% higher than the corresponding value of the control water medium (Terribilini et al., 2007). In a similar study, Chandola et al., (2010) have found that the corresponding doses behind heterogeneities were 5.5–6.5% higher and 4.5–5% lower than water phantom values in the presence of air and cortical bone, respectively.

According to published studies, air gaps between the surface of the applicator and the mucosa of the vagina affected 10% to 27% of the prescribed doses (Cameron et al., 2008; Onal et al., 2015; Richardson et al., 2010; Hassouna et al., 2014).

Cameron et al., (2008) found that the dose at the mucosa over the air gaps received at 0.5 cm was on average 86.7% (range, 54.7-97.3%) of that which it would have received if there was no air gap. However, the dose at 0.5 cm of the whole vaginal mucosa within the target volume was 99.6% (range, 96-100%) of that prescribed. According to Onal et al., (2015) they identified a clear correlation between the mucosal displacement of the air gap and the ratio of the measured dosage at the surface of the air gap in 11 patients, which was still 93.9% of the prescription dose (range, 79.0-99.2%). Richardson et al., (2010) reported a 27% (range, 9% - 58%) dosage decrease to the vaginal mucosa at the air pocket. However, the total vaginal mucosal dosage was not recorded.

In our study, since the film was held at dose prescription distance (0.5cm from the surface of the applicator) and there was no attenuation of photons radially through the air pocket, the increase in dose ranged from 6.4% to 13.9% as the air pocket size expanded radially from 0.2cm to 0.5cm mm (from slot location C to A). While in actual clinical applications of VVBT, the mucosal displacement occurs radially in relation to the size of the air pocket. Outcome of our results are in at agreements with the above published literature (Celik et al., 2018; Zabihzadeh et al., 2013; Terribilini et al., 2007; Chandola et al., 2010).

If the placement film had been positioned at the displacement site of the mucosa and the dose analyzed in presence of air pocket, the most feasible condition of VVBT when air pockets were found may have been recreated. This could be a limitation of this study and any further research in this direction can be pursued.

In conclusions, Ovoid's and custom moulds are two of the vaginal applicator options utilized in VVBT, although the single-line source cylinder is by far the most popular. Selecting the right size cylinder is essential for both proper dosage at depth and inter-fraction repeatability due to the varied architecture of the vagina from the apex to the introitus, particularly after surgery due to cuff retraction. Even if the American Association of Physicists in Medicine (AAPM) Task Group report 43 ignores heterogeneous dose changes, the results of our investigation indicate that heterogeneity changes in dose distributions should be considered in brachytherapy planning's (Saw et al.,1998). The present study can be carried out with a 3D printed phantom that simulates the VVBT application having air pockets of different dimensions at different locations with a suitable detector and also the dose deviations with Monte Carlo simulations. It is suggested that the dose effect of air gaps be taken into account in order to accurately estimate the dose and correlate clinical outcomes with actual doses delivered.

Author Contribution Statement

CS & DL conducted the experiments. CS & RR was the contributor in literature search, designing and fabrication of the experiment, writing manuscript. CS, AT, SB, JS, and AK, has corrected the manuscript subjectively, spelling and grammar checks. SA & AKS helped in calibration of EBT3 films under cobalt-60 unit. All authors read and approved the final manuscript.

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Ethics approval

This study was approved by the Institutional Ethics Committee (that handles all ethical issues of scientific study proposals), Kasturba Medical College, Mangalore, Karnataka State, India, under the approved protocol No. IEC KMC MLR 03/2022/76.

Consent for publication

Author declares that this study was carried out at Department of Radiation Oncology, Kasturba Medical College (A constituent Institution of Manipal Academy of Higher Education), Mangalore, Karnataka, India. All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version. Availability of data and material not applicable.

Availability of data

Not applicable.

Conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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