

Feasibility of 3D Printer to Design an Intracavitary Applicator for the Treatment of Cervical Cancer Patients with a High Dose Rate Brachytherapy System

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Research Article

Keywords: Brachytherapy Applicator, Gynecologic Brachytherapy, Brachytherapy Device, Medical Devices, Powder Bed Fusion Additive, 3-D Printing, Cervical Cancer Brachytherapy

Posted Date: July 19th, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-2052596/v1>

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Version of Record: A version of this preprint was published at Physical and Engineering Sciences in Medicine on March 3rd, 2025. See the published version at <https://doi.org/10.1007/s13246-025-01529-x>.

Abstract

Purpose

To design Tandem-Ovoid based intracavitary brachytherapy applicator with 3D printer and evaluate its feasibility for the treatment of Cervical Cancer patients with High Dose Rate (HDR) brachytherapy system.

Methods

SolidWorks, Computer Aided design software was used for the design of the intracavitary brachytherapy applicator. Raise3D Printer and Hewlett-Packard (HP) Jet Fusion 4200 was used for printing different parts of applicators with PLA and PA-12 material. Radiograph and CT images of printed material parts were taken in the air and water medium to see the visualization. Before use in the patient, necessary quality assurance tests were carried out by coupling it with a microSelectron HDR machine. X-ray markers were used to visualize the source path inside the uterine and vaginal tandems. Physical and clinical evaluations were performed with prototype 3D-printed applicator to check its suitability for clinical use.

Results

Final Applicator design was created from multiple hit and trial methods in SolidWorks. Printed PA-12 of ovoid parts having a mean Hounsfield unit (HU) value of -75 HU. Whereas the mean HU value of the PLA outer layer and inner regions were - 203 HU and - 417 HU respectively. Quality tests on the PA-12 intracavitary applicator performed with the microSelectron HDR brachytherapy machine were passed. Chances of uterine perforation were less due to the semi-rigidity of the PA-12 applicator. The newly designed T-O-based applicator and dummy marker do not produce any artifacts on the CT images.

Conclusions

Powder-based 3D printing of brachytherapy applicator has more usability as compared to fused deposition-based printer. A low-cost flexible plastic applicator was developed that allowed the user to guide the tandem into the uterus of a patient. The developed PA-12 intracavitary brachytherapy applicator did not produce artifacts on CT images.

Introduction

Chemotherapy, External Beam Radiation Therapy (EBRT), and Brachytherapy (BT) are used due to their proven efficacy for the treatment of cervical cancer patients [1, 2]. Intracavitary brachytherapy (ICBT)

applicators are medical devices used to guide a radioactive source in and around the cervical region tumor for delivering a high radiation dose.

The selection of a brachytherapy applicator to deliver an adequate dose to the tumor depends on the stage of cervical cancer and patient anatomy. Furthermore, the selection of the applicators is also based on the imaging modalities to be used for applicator reconstruction and treatment planning.

In the past five decades, commonly used intracavitary applicator shapes include ovoids, rings, and cylinders with a central intrauterine tube. These shapes have been designed to obtain a historic standard pear-shaped dose distribution. For advanced-stage cervical cancer, a hybrid applicator having combination of intracavitary (IC) and the interstitial applicator is used to treat the entire disease in the region of the cervical, vagina, and lateral parametrium. Presently various types of commercial applicators like Tandem-Ovoid, Tandem-Ring [3], Mold applicator [4], hybrid applicator [5, 6], Static/Dynamic Intensity modulated brachytherapy (S/D-IMBT) applicator [7, 8] and Three-dimensional (3D) printed applicator [9] are used for the treatment of cervical cancer patients.

3D printing or additive manufacturing (AM) is a technology used to fabricate three-dimensional solid objects layer-by-layer by adding materials from a computer-created design [10, 11]. Processing of 3D printing primer materials could be divided into the categories of solid, liquid, and powder [12]. The powder-based 3D-printing techniques is popular for medical devices due to faster production speed, strong functional parts, and a large range of biocompatible materials [13–16].

Polyamide 12 (PA-12) is a nylon polymer that is synthesized from either ω -aminolauric acid or laurolactam monomers. It can be obtained in powder form, making it suitable for use in 3D printing applications. One of its interesting characteristics is that its X-ray attenuation coefficient decreases as the tube voltage increases from 40 to 120 kVp. Additionally, PA-12 has a density and effective atomic number similar to that of water and biocompatible due to its chemical properties [17–19].

In Tandem-Ovoid based ICBT Applicators, Ovoids are available in different diameters to fit them snugly in the fornices. An intrauterine tube has variable lengths and angles according to the size of the uterus. Initially, the applicators were made up of rubber which were subsequently replaced with metal and plastic. The metallic applicators produce streak artifacts in CT images and they are not MRI-compatible. Therefore, the selection of applicator material becomes important depending upon the imaging modalities (CT, MRI, and Ultrasound) used to visualize the applicator position relative to patient anatomy.

Now a day 3D printed applicators are used for patient-specific tailor-made treatment and replacing the old conventional applicators. Newer advancements in technology have greatly influenced the neoteric designs of ICBT applicators. Currently, 3D printers are used to design intensity-modulated vaginal brachytherapy applicators [20], Polycarbonate gynecological HDR brachytherapy applicators [21], MRI-compatible vaginal applicator with curved needle channels [22], and patient-specific superficial brachytherapy applicator [23, 24].

Commercially available Tandem-ovoid applicators are rigid and used for the tumor in the region of the cervical region with deep fornices. On the other hand, Tandem-ring design is suitable for cervical region tumor with shallow fornices. In contrast, individualized designed mold applicators can be used to tailor the treatment depending upon the anatomy and size of the tumor but they are time-consuming. Applicators with the facility of interstitial needles may be used for the treatment of bulky tumors to achieve adequate dose coverage in the predefined target volume. Each of these applicators have their own set of advantages or disadvantages.

The need of the hour is to have CT, MRI compatible applicators which can be easily accommodated inside the uterus and fornices. The 3D printing technology has enabled users to design BT applicators that are patient-tailored with fixed geometry applicators (Tandem-Ovoid, Tandem-Ring, and Tandem-Cylinder) as an alternative to commercial applicators.

Therefore, the present study aims to design a PLA and Polyamide-12 material based Tandem-Ovoid intracavitary applicator with the help of a 3D printer. The objective of the study was to develop a low-cost, semi-rigid, CT and MRI-compatible intracavitary brachytherapy applicator to be used with commercially available brachytherapy machine.

Materials and Methods

ICBT Applicator design

The digital model of the ICBT applicator is generated with CAD (Computer aided design) software (SolidWorks 2013, Dassault Systèmes SolidWorks Corporation, Waltham, Massachusetts, USA), and design files were saved in stl (stereolithography) format for 3D printing.

3D Printer

The initial prototype design of the applicator was printed using Raise3D Printer based on FDM (Fused Deposition Modeling) technology. This was a low-resolution printer having a nozzle diameter of 0.4 mm with a build volume of 205 mm x 205 mm x 205 mm (8.62 L). Due to design and resolution issues, the applicator design had to be modified. As a result, a new model of the applicator was printed using a high-resolution HP printer (Hewlett-Packard Jet Fusion 4200, Palo Alto, California, United States) having Multi Jet Fusion (MJF) process to improve the quality and design of applicator. This is a 600-dpi printer having a maximum buildup volume of 380 mm x 284 mm x 380 mm (41.00 L) with build rate of up to 4115 cm³/hr and a minimum layer height of 0.08 mm.

3D printing Material

For Raise3D Printer, PLA (Polylactic Acid) material in the form of solid filament wire having an external diameter of 1.75 mm was used. Whereas, PA-12 (HP Polyamide-12) material in powder form was used with HP 4200 3D printer for applicator printing. The PA-12 has the advantage of sterilization by

autoclave, ethylene oxide (EtO), or irradiation methods. It is a USP Class I-VI approved biocompatible material having high flexural and tensile strength required for medical applications [25].

Image Compatibility & CT Fiducial

3D printed ICBT applicator was fixed inside the plastic container to obtain Computed Tomography (CT) and X-ray planar images. Radiograph and CT images of this container were taken both with and without distilled water (to simulate air medium) to assess the visualization properties of the applicator both inside and outside the patient. Radiographs were obtained with X-ray simulator (IMAGIN, Panacea Medical Technologies, Bengaluru, India) at 80 cm Source to Surface distance (SSD). To obtain optimal imaging of the ICBT applicator and its surrounding medium, a radiograph with a tube voltage ranging from 70 to 100 kV and mV was typically utilized. In order to visualize specific parts of the applicator in air or water medium using CT images, a manual and predefined imaging window adjustments of Hounsfield units (HU) option strategy was employed utilizing the Oncentra Treatment Planning System (TPS) (Oncentra Brachy, v.4.6.0 Elekta AB, Stockholm, Sweden). To visualize the parts of the applicator, manual adjustments to the imaging window done for air/water mediums CT images and denoted as Manual_{air} & Manual_{water}. Additionally, predefine selection of imaging window using contouring tool available in oncentra TPS performed i.e Lung (center – 600 HU, width 1600 HU), Larynx (center 40 HU and width 250 HU), soft tissue (center 40 HU, width 350 HU), Liver (center 50 HU, width 350 HU), Pelvis (center 250 HU, width 1000 HU), dental (center 400 HU, width 2000 HU), and Bone (center 450 HU, width 1600 HU). To obtain Hounsfield units (HU) for analysis, data was extracted from the DICOM-RT files.

The feasibility of copper wire as a fiducial marker for source path visualization inside the tube of the tandem-ovoid printed applicator was checked. A copper wire (Atomic number [Z] = 29) of 1 mm diameter was used as a fiducial marker and placed into the internal void space of the applicator.

Quality Assurance for Applicator

Multiple quality assurance (QA) tests such as Coupling with HDR machine (microSelectron V3.0, Elekta AB, Stockholm, Sweden), Ir-192 radioactive source compatibility, and image artifact were carried out before clinical use of this applicator. The coupling between the machine transfer tube and 3D printed applicator was tested 30 times by positioning the dummy and radioactive source at the first dwell position. Physical examination of the 3D printed ICBT applicator was carried out for any crack, damage, irregular surface, and blockage of source path.

CT Scan & Treatment Planning

The whole procedure of image-based brachytherapy was explained to the patient and informed consent was obtained. The applicator insertion was performed under local anesthesia. CT scan images of the pelvic region were acquired with a 1 mm slice thickness using GE LightSpeed VCT 64 (General Electric Medical Systems, Waukesha, Wisconsin) on a 64 Slice diagnostic machine. Acquired images were imported to the treatment planning system (TPS). After image acquisition, delineation of the target volume High Risk-Clinical Target Volume (HR-CTV), and OARs (Bladder, rectum, Sigmoid) was done as

per ABS and GEC-ESTRO guidelines [26, 27]. The 3D-printed applicator was used in one patient treated with 7 Gy X 3 fractions. The first two fractions were delivered with a 3D printed applicator and the last fraction was delivered with a commercial metallic intracavitary applicator (Fletcher-Williamson Asia-Pacific, Elekta AB, Stockholm, Sweden). Manual optimized treatment planning according to HR-CTV was performed using a brachytherapy TPS.

Ethical approval

The study was approved by the ethical committee of Institute of Medical Sciences, Banaras Hindu University (approval number: Dean/2019/EC/1732, dated November 18, 2019) having title Modelling and quantitative assessment of neoteric devices for dose delivery in brachytherapy. A written informed consent was taken from all the patients.

Results

CAD and Printed Applicator

The ICBT Applicator (ovoids, intrauterine and vaginal tandems) printed with PLA material provide confidence that a 3D printer could be used to get an intracavitary applicator. Nevertheless, initial prototypes constructed from PLA material were deemed inadequate for dosimetry or treatment purposes due to suboptimal quality. Thus, the design of the applicator was revised, and the applicator was printed using PA-12 material, which offers biocompatibility and semi-rigid characteristics. The new design consisted of an Intrauterine tandem measuring 30 cm in length,, a Cervical Stopper, right & left Ovoids with a diameter of 1.5 cm, an external cylindrical obturator having three internal holes, and a Perineal bar.

Hounsfield number

From CT images it was found that mean HU value of PA-12 ovoid parts was -75. Whereas, the mean HU value of the PLA outer layer was -203 and for inner layer, it was -417.

Image Compatibility

Radiographic images of the applicators printed with both PA-12 and PLA materials were captured ranging from 70 to 100 kV in an air medium, and the resulting images were clearly discernible (Fig. 3b-q). The CT images of applicator printed with PA-12 material was visualized in all predefined window levels. Whereas, the applicator printed with PLA material was found to be discernible only in specific imaging windows, including Manual_{air} (center -631 HU, width 1847 HU), Lung (center -600 HU, width 1600 HU), and dental (center 400 HU, width 2000 HU) settings. However, PLA applicators were not discernible in Larynx (center 40 HU and width 250 HU), Soft tissue (center 40 HU, width 350 HU), Liver (center 50 HU,

width 350 HU), Pelvis (center 250 HU, width 1000 HU), and Bone (center 450 HU, width 1600 HU) setting windows, as observed in (Fig. 3r-y).

In the distilled water medium, both PLA and PA-12 printed applicator components were discernible in the radiographic images acquired using 70 to 100 kV of X-ray. As the kV value increased with a constant mA, the differentiation in visibility between the water and printed applicator material on the radiographic images also increased (as shown in Fig. 4b-q). On the other hand, in CT scan images, PLA material was visible in all predefined imaging window, while PA-12 printed material was only partially discernible on Manual_{water} (center -7 HU, width 251 HU), Larynx, soft tissue and Liver imaging windows (as shown in Fig. 4r-y). Notably, no artifacts were observed in the CT images produced by PA-12 and PLA materials.

QA of 3D Printed Applicator

Prior to clinical use of PLA and PA-12 materials in a patient, quality assurance tests were carried out (Table 1). PLA material was flexible and its internal diameter was blocked after 3D printing. Therefore, its coupling with the transfer tube did not happen and it was not found compatible with the microSelectron HDR machine. Conversely, the PA-12 applicator, coupling of the transfer tube with the applicator was satisfactorily done and tested 30 times. Both the radioactive source (^{192}Ir) and dummy source traveled to the topmost first dwell position of the intracavitary applicator without obstruction. Since the Internal diameter of the tube was 2.0 mm, the applicator was found to be compatible with Ir-192 and Co-60 brachytherapy sources. All the above-mentioned QA tests were performed on the PA-12 intracavitary applicator with a microSelectron HDR brachytherapy machine and found this applicator compatible with the HDR machine (Fig. 5).

Clinical Application

All the quality assurance tests were passed by PA-12 based 3D printed applicator as compared to PLA material. Therefore, the PA-12 intracavitary applicator was selected for clinical application for the initial two fractions. The uterine tandem of the PA-12 applicator was inserted smoothly inside the uterus of the patient and negotiating well inside the uterine canal. Copper wires were used as X-ray marker inside the applicator for applicator reconstruction on CT images (Fig. 6 a,b). The last fraction (3rd) was treated with a Fletcher-Williamson (F-W) metallic applicator. This applicator produced artifacts on the CT images due to metallic parts (Fig. 6 c).

D₉₀ (Dose received to 90 % of HR-CTV) was 100% in both PA-12 and F-W applicators. Bladder doses were low with the PA-12 applicator as compared to the F-W applicator. However, the rectum and sigmoid doses were high (Table 2).

Discussion

Printed applicator

The designed & developed intracavitary applicator consisted of intrauterine tandem, right and left ovoids, cervical stopper, external cylindrical obturator, and perineal bar. The intrauterine tandem (IUT) was inserted smoothly into the uterus to deliver a high radiation dose without the risk of perforation. The cervical stopper fixed on the intrauterine tandem does not allow it to move beyond the external cervical os. The intrauterine tandem, right and left ovoids were fixed to each other at the cervical os (inferior to cervical stopper) with external cylindrical obturator, which helps in reproducing the applicator geometry inside the patient. The whole applicator assembly inside the patient can rotate due to the flexible nature of the applicator. To restrict its movement, in the present study, the external cylindrical obturator (having three holes to accommodate tandems) was fixed to the external perineal bar. This mechanism prevented the rotation of the whole applicator assembly inside the patient as well as immobilized the applicator. The T-shape perineal bar consists of one large hole to accommodate the cylindrical obturator and three small holes to fix it externally with the help of a cotton string tied around the patient in the pelvic region. It fixed the 3-D printed ICBT applicator to the patient and prevented its movement.

In the present study, initially, we used a low-resolution PLA filament-based 3-D printer to print the ICR brachytherapy applicator. Therefore, 2mm internal diameter lumens of the applicator tandems itself blocked with PLA material. The surface of the printed PLA applicator exhibited a rough and irregular texture, rendering it unsuitable for use in clinical applications. The only advantage of PLA filament-based 3D printing was to get the prototype design of the intracavitary brachytherapy applicator.

To overcome the problems of low resolution and blockage of tandem lumens, the powder-based high-resolution 3D printer was used to design the ICBT applicator. The applicator printed with this printer was smooth but the lumen of the tandems was blocked with powder. The powder from the lumens was removed manually and it was a tedious process. However, after removing the powder, the lumen was smooth and the internal diameter was as per design.

Hounsfield Number

Printed PA-12 ovoid showed mean HU value of -75 HU, which was near to fat or water. This means that it has low radiodensity, and on a CT scan, it would appear similar to these tissues, making it difficult to distinguish.

Applicator printed with FDM printer had a thick external surface due to high percentage of fill density whereas its inner portion was less dense due to a low percentage of fill density. Therefore, mean HU value on the external superficial layer of the material printed with PLA was -203 HU whereas the inner region was -417 HU due to 50 % infill density. Because of the difference in HU values between the surface and core of ovoids, they were visible on the CT images taken in water and air medium. Ma et.al. in their study showed that powder-printed PA-12 has -88 HU and PLA samples with printed fused deposition modeling have 144 HU value [19]. However, the PA-12 material HU value of the present study

was found close to Ma et.al. study but not that of PLA material. The difference in the HU value of PLA material arose because Ma et.al. did not mention the infill density of 3D printed material in their study. Whereas the present study, HU values of PLA printed inner portion regions were close to Park et.al. They showed that the 3-dimension printing of PLA material at 60% infill density has a mean value of -530 HU [28].

Image Visualization

In air, Radiograph and CT images of PA-12 printed material were visible because of the difference in attenuation value of PA-12 and air. Whereas, PLA-printed applicator parts were visible on the radiograph. However, CT images of the PLA applicator were visible only in wider imaging window such as Manual, Lung, and dental settings but not in the narrower imaging window i.e., Soft tissue, Liver, Pelvis, and Larynx windows.

In the water medium, the printed PLA and PA-12 applicators were visible on radiograph images. The visibility of the PLA applicator was more as compared to the PA-12 printed applicator inside the water medium because of the presence of air inside the PLA printed ovoids. Similarly, on CT images, PLA was visible on all predefined imaging window but PA-12 was not because the HU value of PA-12 was closer to water. Therefore, PA-12 material will not be clearly visible if inserted in the cervical region of the patient. To address this limitation, a copper wire of 1 mm diameter was inserted in the lumen of the tandems to track the source path and facilitate reconstruction of the applicator on CT images.

QA of 3D Printed Applicator

For the PA-12 applicator, a Nylon tube with an outer diameter of 2 mm was attached to the end of the applicator tube and subsequently connected to the microSelectron HDR brachytherapy machine with the aid of a transfer tube. During testing there was no obstruction in the movement of the dummy and Ir-192 source within the PA-12 applicator. It showed that the coupling of the transfer tube with the applicator was satisfactory and source movement was smooth. However, for the PLA applicator, the internal diameter was blocked after printing, and coupling could not be established, thereby preventing further quality assurance (QA) testing.

Artifacts

Both the printed PLA and PA-12 applicators did not produce artifacts on the CT images as their HU values were close to air and fat. Unlike metallic applicators, PLA and PA-12 applicators did not produce streak artifacts, leading to improved target and organ-at-risk (OAR) delineation on the CT images. The absence of artifacts in the images facilitated the contouring of the target volume, bladder, rectum, and sigmoid walls with greater ease compared to metallic applicators.

Clinical Application

Due to the low atomic number of the 3D-printed PA-12 applicator, the source channel path indiscernible on CT images and even become nearly transparent on radiographic images. Hence, to overcome this limitation, CT fiducial copper wire was used in the plastic applicator to distinguish the applicator and its source channel path. Because of the difference in the atomic number of the applicator and fiducial marker, its identification was done easily on CT images. In comparison, reconstructing the source path in a metallic applicator was simpler due to the atomic number disparity between the applicator, surrounding tissue, and the applicator cavity.

For rigid F-W applicator, the position of the uterus was observed to change as compared to PA-12 applicator. In CT-based optimized planning, results were nearly the same for both applicators in terms of D_{90} to HRCTV due to optimization. However, the dose to the bladder and rectum was lower with the rigid applicator because it straightens the uterus and gauze packing was inserted into the vagina cavity.

Whereas, the PA-12 material exhibits a HU value closer to fat or water, and possesses a relatively low atomic number, thereby minimizing the likelihood of producing image artifacts during computed tomography (CT) imaging. Whereas the F-W applicator was made up of stainless-steel applicator of high atomic number, therefore it produces artifacts on CT images. However, due to the flexibility of the PA-12 plastic applicator, it bends and takes the shape of the uterus which brings it closer to the bladder or rectum depending upon the position of the uterus (anteverted or retroverted). In such instances, the proximity of the radioactive sources in the uterus to the bladder and rectum results in elevated radiation doses to these organs. Acceptable doses to the bladder and rectum with adequate doses to HR-CTV for an optimized plan were achieved in present study, when D_{90} was equal to or near 100 % of the prescribed dose.

The advantage of the PA-12 flexible applicator over the metallic applicator includes its ability to takes the shape of the uterus, lack of artifacts, inexpensive, disposable, and chances of perforations are negligible due to the semi-rigidity. Whereas, the disadvantages include chances of breaking inside the patient, could not be used if the uterus is anteverted or retroverted, and lack of visibility of the source path without an X-ray marker.

Although the designed applicator was MRI-compatible, its performance in an MR environment could not be assessed. The study was limited by the unavailability of MRI facilities in the department, thus preventing the acquisition of MR images in the present study. PA-12-based material is easy for printing but powder gets stuck inside the printed applicator hollow tubes because of its smaller inner diameter of 2.0 mm and longer length of 30 cm. The powder was removed from the printed part manually with the assistance of a 1 mm diameter stainless steel wire. The cost of the Applicator is less than the commercial applicator available in the market. The complete intracavitary 3D printed applicator was created with a \$50 value for one-time use.

Conclusion

Powder-based 3D printing of intracavitary brachytherapy applicator has more usability as compared to fused deposition-based printer. A low-cost flexible plastic applicator was developed that allowed the user to guide the tandem into the uterus of a patient. The developed intracavitary PA-12 brachytherapy applicator did not produce artifacts on CT images indicating its compatibility with imaging modalities.

Declarations

Data Sharing

“Research data are stored in an institutional repository and will be shared upon request to the corresponding author.”

Acknowledgements: This work was supported by the department of science and technology (BDTD programme of YDT Division) vide Grant No. TDP/BDTD/65/2021/General.

Conflict of Interest: Ankur Mourya, Lalit M Aggarwal, Sunil Choudhary, Neeraj Sharma, Ritusha MishraChandra Prakash, and Uday Pratap Shahi declare that they have no competing interests.

Funding: This work was supported by the department of science and technology (BDTD programme of YDT Division) vide Grant No. TDP/BDTD/65/2021/General.

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Tables

Table 1 Quality assurance tests carried out with the 3D Printed applicator				
S.No	QA Test carried out	Freq.	Results	
1	Coupling of Transfer tube with applicator		PLA	PA-12
	a) Dummy source	30	No	Yes
	b) Radioactive source	30	No	Yes
2	Kink Free	30	No	Yes
3	Artifacts on CT image	1	No	No
4	microSelectron V.3.0 HDR brachytherapy	1	No	Yes

Table 2 Dose parameter based on the insertion of 3D printed PA-12 applicator application in the patient.								
Applicator	HR-CTV		Bladder		Rectum		Sigmoid	
	D ₁₀₀	D ₉₀	D _{0.1cc}	D _{2cc}	D _{0.1cc}	D _{2cc}	D _{0.1cc}	D _{2cc}
F1 (PA-12 Applicator)	60.00	100.83	114.55	65.28	94.43	71.8	104.9	69.69
F2 (PA-12 Applicator)	58.74	100.73	134.47	80.97	116.52	75.44	111.06	75.97
F3 (F-W Applicator)	58.63	100.20	120.26	87.28	76.56	57.38	47.40	35.91
Abbreviation: PA-12 = Polyamide-12; F-W Applicator: Fletcher Williamson applicator								

Figures



Figure 1

Computer Aided Design developed for Intracavitary brachytherapy applicator **a)** Frontal View **b)** Lateral View.

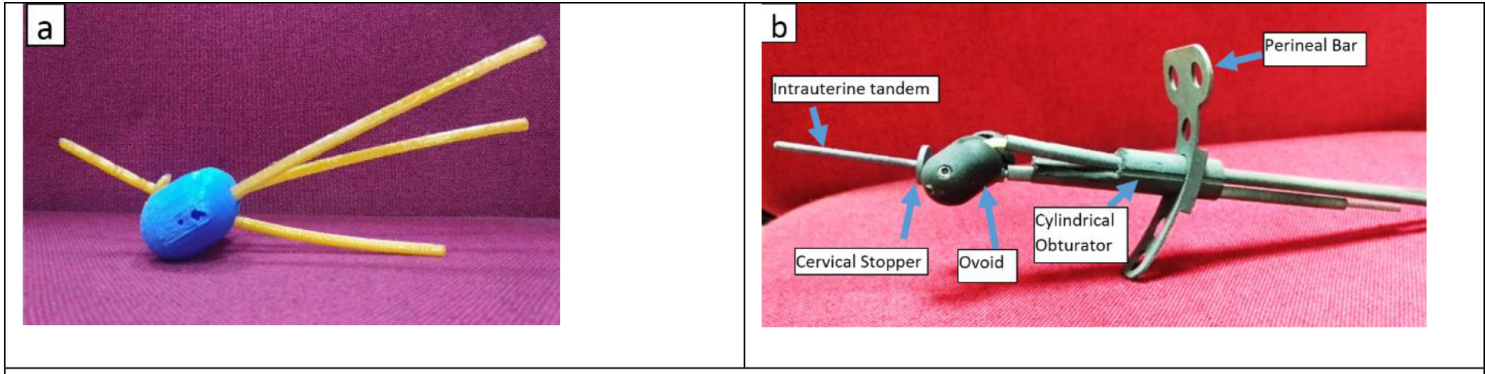


Figure 2

Two different 3D printed designs of Intracavitary brachytherapy applicator **a)** initial design with PLA material **b)**final design with PA-12 material.

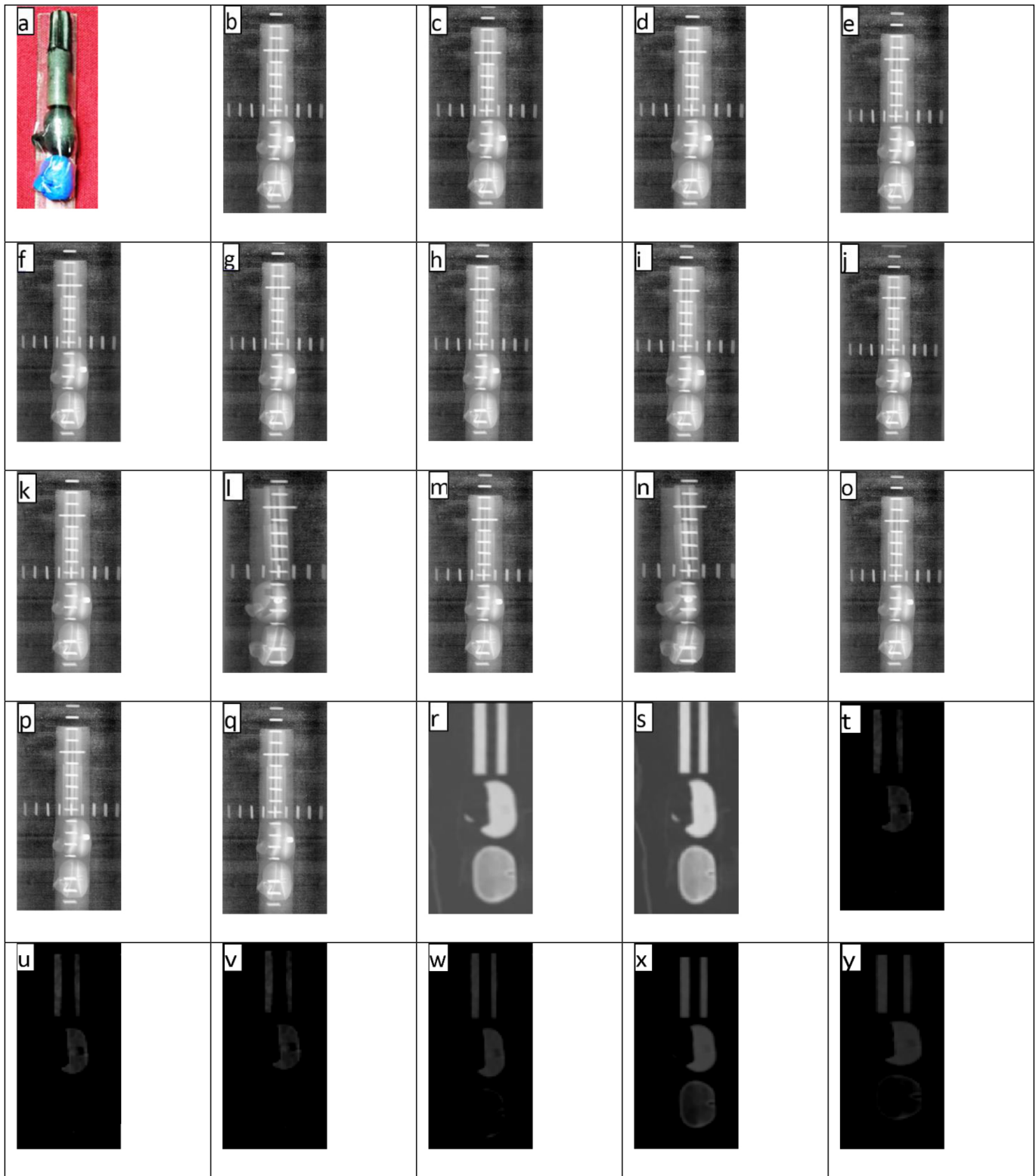


Figure 3

Radiograph and CT scan images of 3D printed applicator parts in air (a) displays the original parts of the printed applicator, which includes a cylindrical obturator printed from PA-12 and ovoids printed from PA-12 (black color) and PLA (blue color). Radiograph images for different mA and kV settings (b-e) mA=70, kV=70 to 100, (f-i) mA=80, kV=70 to 100, (j-m) mA=90, kV=70 to 100, (n-q) mA=100, kV=70 to 100. In addition, different predefined imaging window of CT images are demonstrated, including (r-x) Manual_{air},

Lung, Larynx, Soft tissue, Liver, Pelvis, Dental, Bone. *Abbreviation* PA-12= Polyamide-12; PLA= Polylactic Acid; kV = kilovoltage; mA = Milliampere;

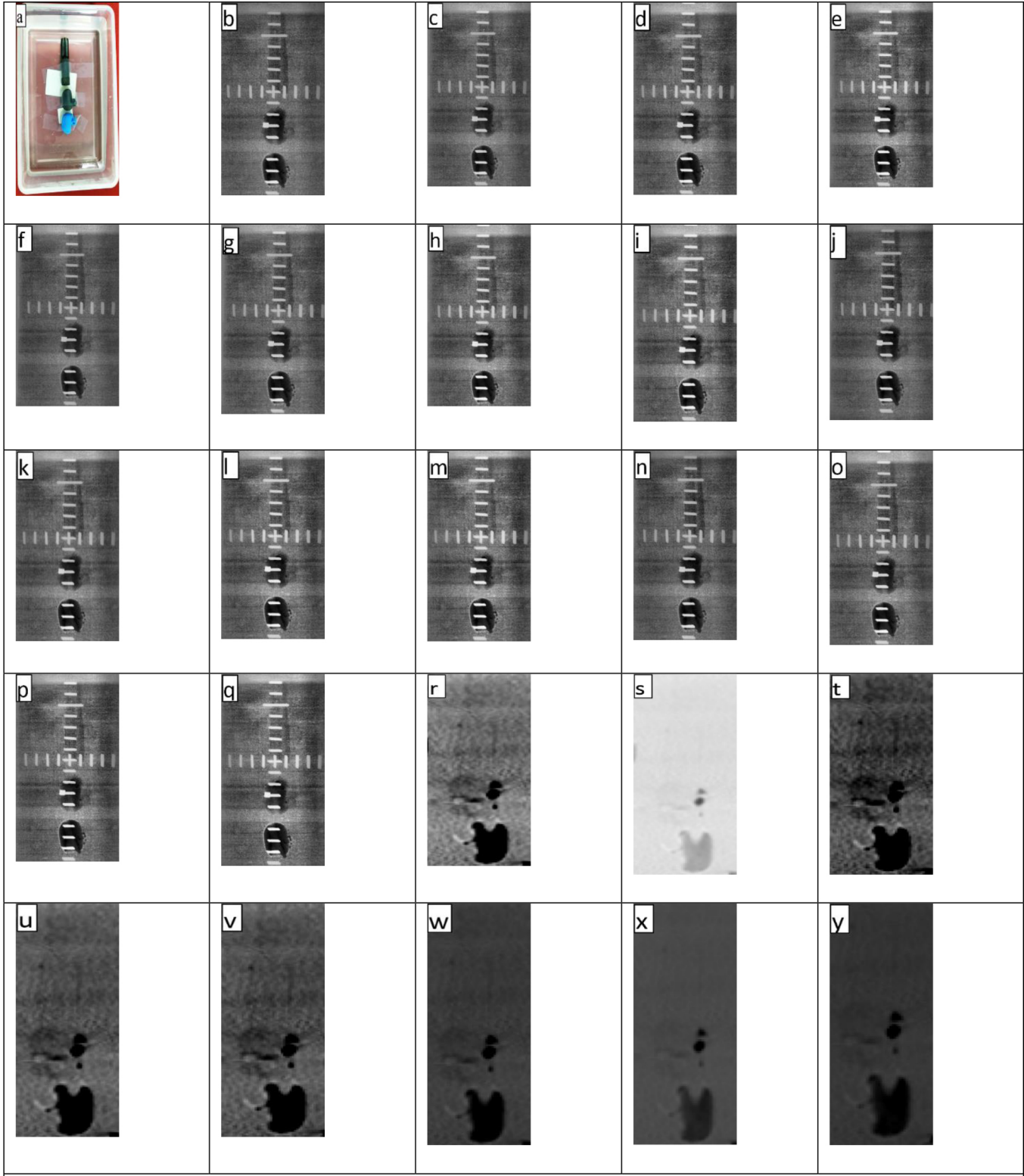


Figure 4

Radiograph and CT scan images of 3D printed applicator parts in water medium. (a) displays the original parts of the printed applicator, which include a external cylindrical obturator and ovoids printed from Polyamide-12 (PA-12) (black color) and Polylactic Acid (PLA) (blue color). Radiograph images for

different mA and kV settings (b-e) mA=70, kV=70 to 100, (f-i) mA=80, kV=70 to 100, (j-m) mA=90, kV=70 to 100, (n-q) mA=100, kV=70 to 100. In addition, predefined imaging window of CT images are demonstrated, including (r-x) Manual_{water}, Lung, Larynx, Soft tissue, Liver, Pelvis, Dental, Bone
Abbreviation PA-12= Polyamide-12; PLA= Polylactic Acid; kV = kilovoltage; mA = Milliampere;

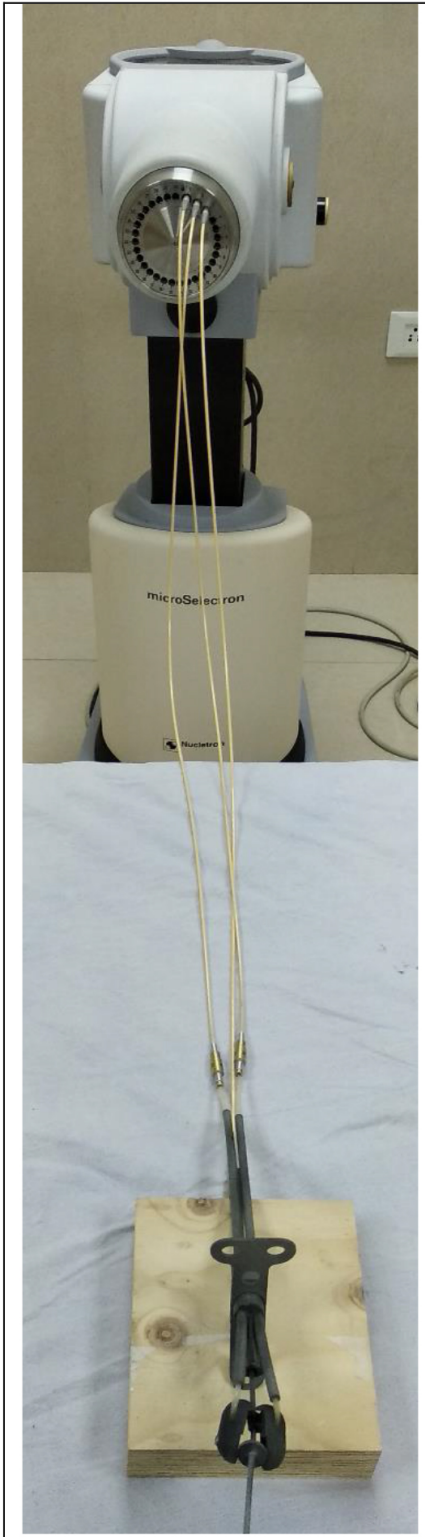


Figure 5

Coupling of the PA-12 intracavitary applicator attached with transfer tube to microSelectron HDR machine.

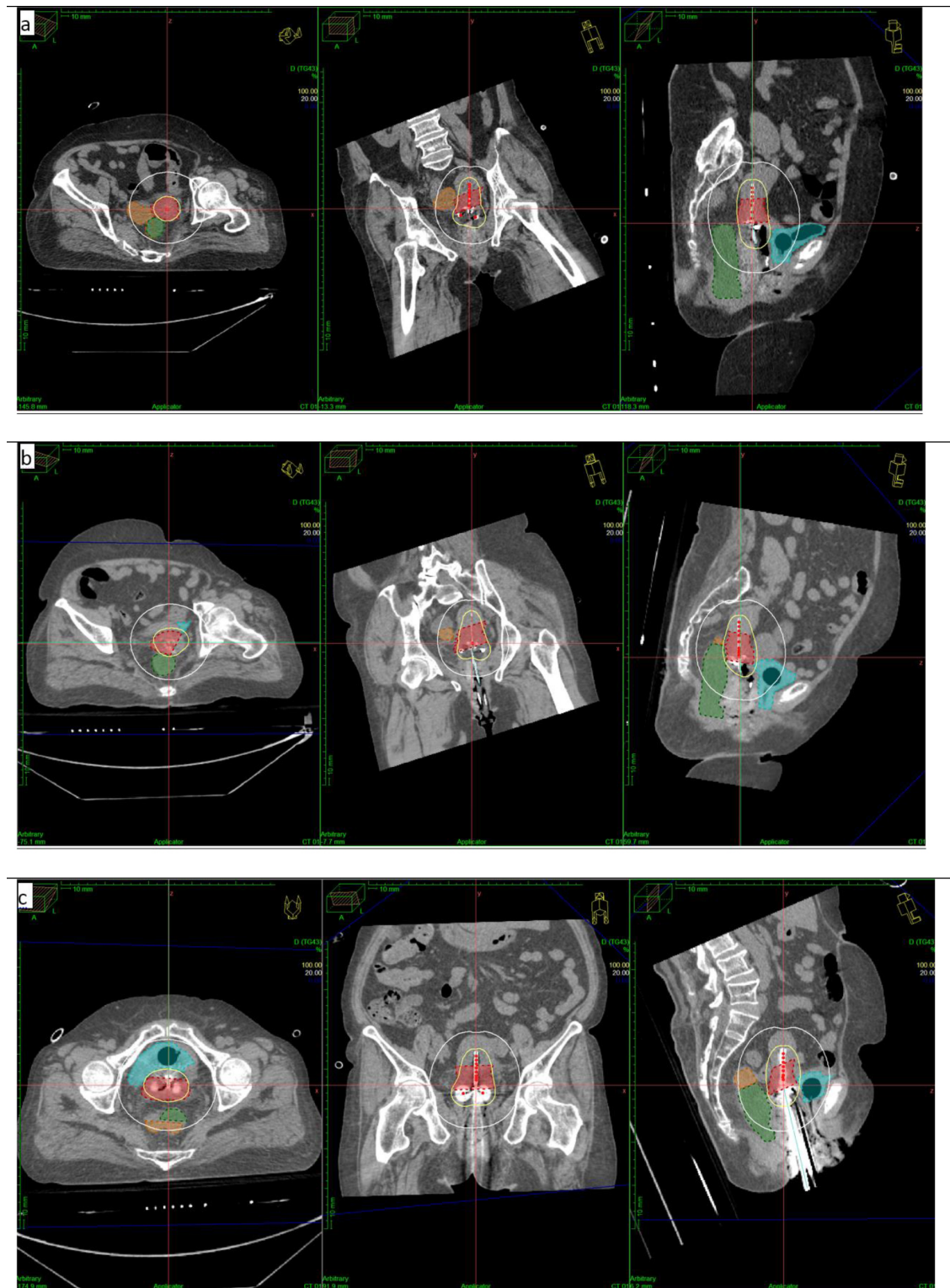


Figure 6

Clinical application and dose distribution of Intracavitary applicator in the patient (a,b) Coronal, Axial, and Sagittal CT scan images with PA-12 applicator in first and second Fraction. c) Fletcher-Williamson

applicator used in the third Fraction. The Yellow and white lines show the 100 % and 20 % isodose lines of the prescribed dose respectively.