Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2018

Development of an Applicator for Endometrial Cancer Treatment using a Miniature X-ray Tube

Juhyuk Lee[a], Hyun Nam Kim[a], and Sung Oh Cho[*]
[a,*]*Department of Nuclear and Quantum Engineering, KAIST, Daejeon 34141, Republic of Korea*
[*]*socho@kaist.ac.kr*

1. Introduction

Recently, the endometrial cancer is the most common gynecologic cancer with high incidence worldwide. In the treatment of endometrial cancer, the brachytherapy inserting a postoperative radiation source into the vagina is widely used. In the case of endometrial cancer patients whose ages are mostly older and who have a different birth rate, the size of the patient varies depending on the individual. Therefore, it is necessary to develop a patient-specific applicator that matches the size of the vagina for each patient. Meanwhile, compared to conventional radioisotopes used as a brachytherapy source, the miniature X-ray tubes are less expensive and have less stringent protection standards, potentially replacing radioactive isotopes[1][2]. Therefore, in this study, we developed a patient-specific applicator for the treatment of endometrial cancer using a miniature X-ray tube and optimized the dose distribution to satisfy the treatment conditions of endometrial cancer.

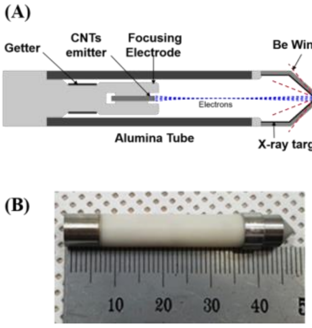

Fig 1. (A) Schematic and (B) Fabricated product of miniature X-ray tube

2. Experiments

The patient-specific applicators were fabricated using 3D printer. One unique feature of 3D printing is the capability of varying the density of the printed object, by varying the infill percentage (IFP) cylindrical applicators with various IFPs for 30 mm and 40 mm diameter using the AEP 3D printer. The 30 mm and 40 mm diameters are the most widely used diameters of vaginal applicator; therefore, they were adopted as representative values. The phantoms which simulates vagina canals with diameter of 30 mm and 40 mm were fabricated using polymethyl methacrylate (PMMA) plates to measure the tendency of the dose to decrease as the X-rays generated inside the applicator with various IFPs entered into the human tissue

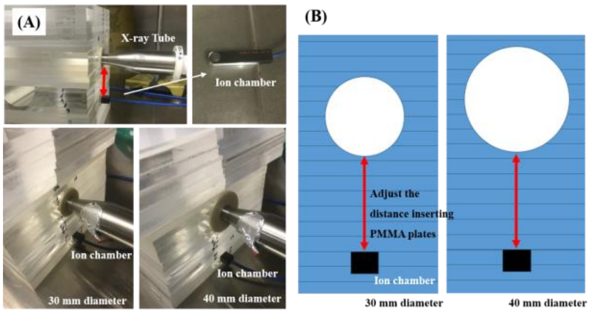

Fig 2. (A) Experimental setup and (B) Schematic of the measurement of dose fall-off

It is necessary to achieve the cylindrical dose distribution required for treatment requirement since the dose distribution of the miniature X-ray tube appears spherical[3]. The dwell positions and dwell times were optimized by Monte Carlo n-particle (MCNP6.1) code developed by Los Alamos National Laboratory. The miniature X-ray tube and appliccator with 30 mm diameter were modeled for MC calculation.

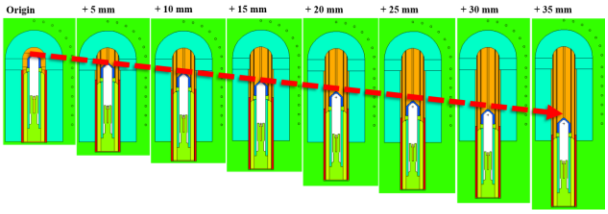

Fig 3. MCNP6 modeling when the distance between dwell positions is 5 mm

Gafchromic EBT3 film was calibrated for dosimetry of low energy photon-emitting electronic brachytherapy source. The total uncertainty of 3% or less can be obtained if the uncertainties associated with relative orientation of the film and homogeneity on the bed of the scanner are removed. Regarding the orientation of the film that contributes the most to the uncertainty, all the pieces of the film were marked with the letter “4” so that the four directions of the film to match the irradiation and scanning direction. Films were irradiated at the dose levels in the range of 10 – 7000 mGy for calibration. A calibrated PTW T34013 ion chamber was used to check the X-ray output constancy for the miniature X-ray tube. All films were scanned with an Epson Expression 11000XL flatbed scanner once at a time in the center of the scanner to minimize the uncertainty induced by scanner. The scanned image only extracts the R-value that most sensitive to X-rays in RGB, and converted to net optical density (OD). Finally, after dose conversion in net OD, fitting function was obtained with Mathlab built-in function and calibration was completed. Prior to measurement, the inserting part of the existing X-ray tube was increased to satisfy the treatment requirements

Fig. 4. Design modification of the miniature X-ray tube and the applicator to apply dwell positions

The calibrated EBT3 film was sandwiched between the PMMA plates and the miniature X-ray tube was placed inside the applicator while it was positioned at the predefined dwell position. The films were irradiated for the same time, one film per one dwell position. The dose distribution around the applicators with diameters of 30 mm and 40 mm were measure and analyzed.

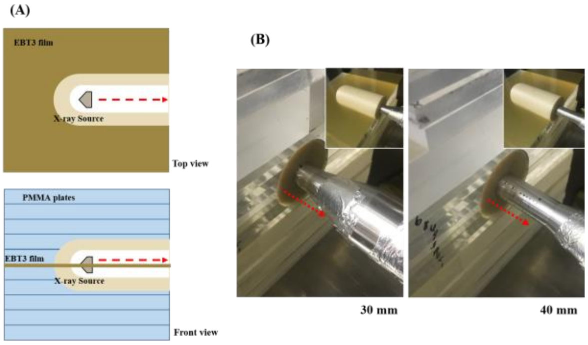

Fig. 5. (A) Schematic and (B) experimental setup to measure dose distribution

3. Results and Discussion

The dose fall-off was measured for 30 mm and 40 mm diameter of applicators with various IFPs First, we plotted the depth dose curves when the IFP of applicator with 30 mm diameter is 10, 50, and 100%, respectively. Likewise, the depth dose curves were drawn when the IFP of applicator with 40 mm is 10, 20, 30, 50, and 100%, respectively. Then, the IFP of an applicator with 40 mm diameter that matches when the IFP of an applicator with 30 mm diameter is 100% was found. The IFP of the applicator with 40 mm diameter with a dose fall-off characteristic equal to the applicator with 30 mm diameter and 100% IFP was 25%. In other words, we found that even if the diameter of the applicator changes, the dose fall-off characteristic with distance can be equalized by changing the IFP of 3D printed output. Based on these results, the applicators with 30 mm diameter and 100% IFP and the applicator with 40 mm diameter and 25% IFP were manufactured in long version to satisfy the actual treatment requirements.

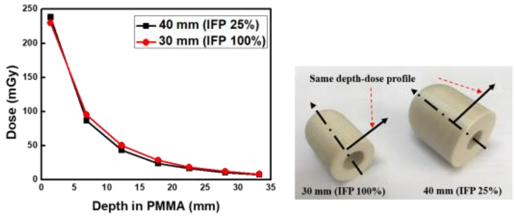

Fig. 6. Different diameters of applicators with IFPs having the same dep-dose profile

MCNP calculations were performed to optimize the dwell positions and to obtain a methodology to optimize dwell time given dwell position. First, the dose distribution at each position was obtained when the dwell position interval was 5 mm. While the source part of the miniature X-ray tube moves, it can be confirmed that the portion where the dose is generated also moves. The results of applying the optimized dwell time ratios show that the dose distribution at prescription depth after optimization process is generally seen as constant but vary between -7% and 8%. Although not significantly deviate from the treatment requirements of endometrial cancer, it is considered that the uniformity can be further improved by subdividing the dwell positions in the previous curved area; therefore, the same procedure was repeated by dividing the interval between dwell positions, which had been 5 mm, to 2 mm in the former curved portion. The results after applying optimized dwell times are represented improved uniformity within ±5% and the dose distribution around the applicator being uniformly visible in the 2-dimensional dose-mapping image. Thus, the dwell positions were selected at intervals of 2 mm from the origin to 1 cm from the origin, and then at intervals of 5mm thereafter, the actual experiments were carried out.

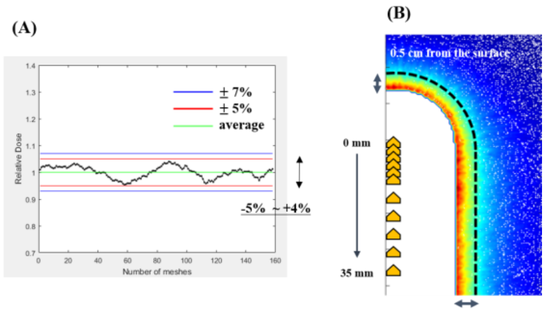

Fig. 7. (A) Dose distribution at the prescription depth and (B) 2-diminsional dose mapping after applying optimized dwell time ratio when subdivided intervals (MCNP).

The X-ray generated from the miniature X-ray tube was irradiated at the same time for each position when the source part was positioned at the dwell position optimized by MCNP calculation. First, when the applicator with the diameter of 30 mm and the IFP of 100% was used, the EBT3 films irradiated were scanned, thereafter the R-values were converted to dose. However, it is difficult to analyze the dose distribution properly due to color distortion occurring on the cut edge of the EBT3 film unless there is any process about removing the discolored edge. Therefore, the water-jet cutting process was employed to remove 1mm of the edge of the EBT3 film, and then the dose distribution can be clearly seen that the part with high dose was moved according to the movement of the source. The dose distribution at the prescription depth was obtained when the source is located at each dwell position. Lastly, the dose distribution at prescription depth was able to obtain sufficient uniformity within ±5% after applying the optimized dwell time ratio. The same procedure was repeated for an applicator having a diameter of 40 mm and an IFP of 25%. When tubes were placed in their respective dwell positions within a 40 mm diameter applicator, the EBT3 film irradiated with X-rays was scanned and converted to a dose likewise. The dose distribution at the prescription depth is presented By applying the optimized dwell time ratio, uniformity within ±7% was achieved. These results satisfy the treatment requirement; therefore, we have applied the optimized dwell position and dwell time so that the actual prescription dose of 5 Gy was applied to the prescription depth of 5 mm from the applicator. For this purpose, one sheet of film and the applicator were fixed and tube only was moved inside the applicator applying optimized dwell position and dwell time.

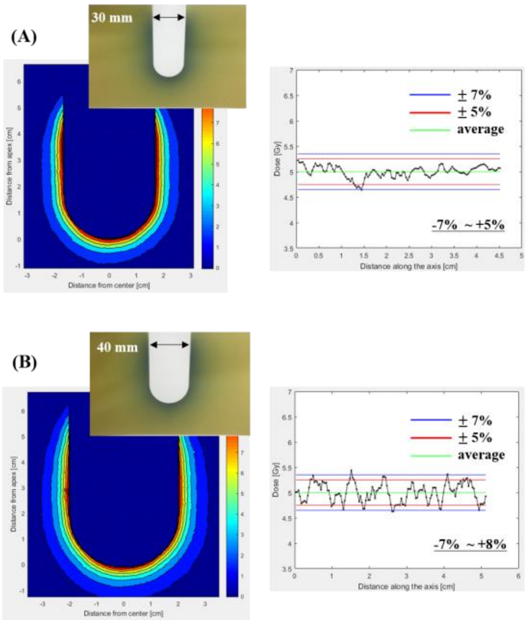

Fig. 8. 2-diminsional dose mapping and dose distribution at the prescription depth when the applicator with (A) 3 mm dia. and 100% IFP and (B) 4 mm dia. and 25% IFP.

4. Conclusion

In this study, patient-specific applicator was developed for endometrial cancer patients with different vagina sizes using a 3D printer. We used miniature X-ray tube based on field emission to generate low-energy X-rays of less than 50 kV. We optimized the dwell positon using MCNP simulations and fabricated a longer applicator to allow the tube to move internally according to actual treatment requirements for both diameters of 30 mm and 40 mm before the experiment. Using the optimized dwell positon and dwell time, the prescription dose of 5 Gy was applied to the prescription depth of 5 mm. As a result, both applicators were able to obtain a dose distribution that satisfy treatment requirements.

REFERENCES

[1] Heo, Sung Hwan, et al. "A vacuum-sealed miniature X-ray tube based on carbon nanotube field emitters." Nanoscale research letters 7.1 (2012): 258.

[2] Kim, Hyun Nam, et al. "Surface Applicator of a Miniature X-ray Tube for Superficial Electronic Brachytherapy of Skin Cancer." Medical Physics (2017).

[3] Schneider, Frank, et al. "A novel device for intravaginal electronic brachytherapy." International Journal of Radiation Oncology* Biology* Physics 74.4 (2009): 1298-1305.