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IMAGING

Accuracy of Intracavitary Applicator Reconstruction for Cervix Cancer Brachytherapy

Hussein ALMasri [1] · Yasumasa Kakinohana [2] · Takafumi Toita [3] · Takuro Ariga [3] · Goro Kasuya [4] · Sadayuki Murayama [3]

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Abstract

The accuracy of intracavitary applicator reconstruction for cervical cancer was assessed. A homemade phantom that mimics clinical applicator placement and reference points was used. Three stainless steel (15°, 30°, and 45°) tandems, x-ray markers, and three reference points were used to compare radiography- and CT-based systems. For CT reconstructions, two Fletcher CT compatible (15° and 30°) tandems, two ovoids, and two reference points, with and without inserted x-ray markers, were used. A 2.5-mm CT slice thickness was used. To check for inter- and intra-operator variations in CT, only a 30° tandem without x-ray markers and 1.25-mm CT slice thickness were used. Applicators were reconstructed three times for each image set to verify the operator reproducibility. A 6 Gy dose was prescribed and normalized at AL-point. Source dwell times were compared to check for dose variation at A-point. Maximum standard deviations SD (σ) for radiography and CT reconstructions were 0.35 and 0.83 mm, respectively. Analysis of variance for the means of 15° and 30° tandems showed no significant difference. Levene's test proved insignificant difference for 15° tandem (p value = 0.131), whereas it showed a significant difference for 30° tandem (p value = 0.011). This phantom study showed that the variance of dwell times between the two methods for 30° tandem was statistically significant due to increased applicator curvature. CT proves superiority to radiography. X-ray marker method was more accurate but has less image quality. Inter- and intra-oncologist variations showed good agreement.

Keywords Brachytherapy · Intracavitary · Radiography · Computed tomography · Catheter reconstruction

Introduction

With the introduction of image-guided brachytherapy, cervical cancer brachytherapy has evolved rapidly in the last decade. Traditionally, coordinates of brachytherapy applicators where x-ray markers pass were evaluated based on two x-ray images taken from different angles. However, the use of computed tomography (CT) and magnetic resonance imaging (MRI) has increased considerably in the last few years [1] as they provide 3-dimensional (3D) imaging for delineating organ boundaries [2, 3]. Due to the high-dose gradient in brachytherapy, any error in reconstruction might lead to a substantial deviation in the planned dose to the target and also to organs at risk. Therefore, applicator reconstruction must be correctly implemented to minimize any subsequent errors.

Recently, our facility made a transition from utilizing radiography and catheter describing points (x-ray markers) for reconstructing metal applicators to the use of CT and applicator model-based reconstruction for CT/MR compatible applicators. Also, in addition to CT, MRI is partially employed for image acquisition. The purposes of this study are to check for reconstruction accuracy and to verify source positions inside the lumen of intracavitary applicators using radiography- and CT-based systems. The reproducibility of CT-based reconstruction using x-ray markers and model-based methods was checked. Inter- and intra-operator variability for the CT/MR applicator reconstruction was also investigated.

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✉ Hussein ALMasri
halmasri81@staff.alquds.edu

[1] Medical Imaging Department, Al-Quds University, P.O. Box 51000, Abu Dies, Jerusalem, Palestine

[2] Medipolis Proton Therapy and Research Center, 4423 Higashikata, Ibusuki, Kagoshima 891-0304, Japan

[3] Department of Radiology, Graduate School of Medical Science, University of the Ryukyus, 207 Uehara, Nishihara-cho, Okinawa 903-0215, Japan

[4] Hospital of the National Institute of Radiological Sciences, National Institutes for Quantum and Radiological Science and Technology, Chiba, Japan

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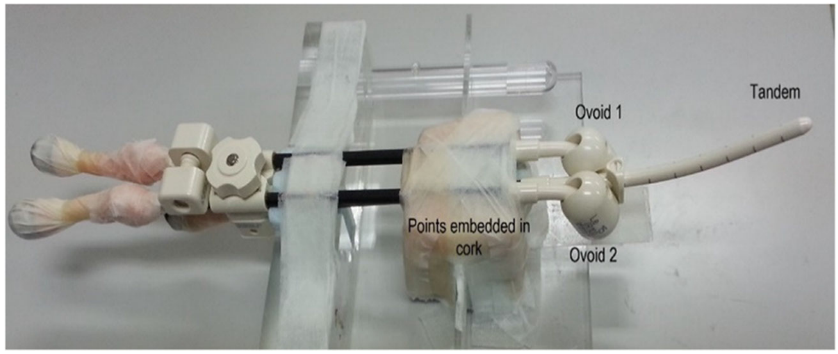

Fig. 1 Experimental phantom for cervix brachytherapy applicator including tandem and two ovoids. The points used for distance measurements are embedded in the cork under the applicators

Methods

Applicators

A phantom that mimics clinical applicator placement and reference points was developed. The homemade phantom containing Fletcher Williamson stainless steel (15°, 30°, and 45°) tandem applicators supplied by Nucletron, an Elekta company (Elekta AB, Stockholm, Sweden), x-ray markers, and three plastic points (P1, P2, and P3) around the applicator was used to make geometrical measurements and compare radiography- and CT-based systems. Additional point (P4) was used for dose normalization at 100% (Figs. 1 and 2). For comparing reconstruction methods in CT, the phantom was remade with two Fletcher CT/MR compatible (15° and 30°) tandem applicators, two ovoids, and two fixed reference points (point A and point R), with and without inserted x-ray markers (Fig. 3). A 2.5-mm slice thickness was used in all CT scans of the phantom. To check for inter- and intra-operator variations in CT, only a 30° tandem without x-ray markers and thinner (1.25 mm) CT slice thickness was used. Point A was fixed on the left side of tandems as it simulates the point A which is described in the Manchester system for the treatment of cervical carcinoma. Point AL (left) is located 2 cm on the left lateral to the central canal of the uterus and 2 cm above the mucus membrane of the lateral fornix [4]. Point R simulates the rectum reference point which is found on an anteroposterior line that passes perpendicularly through the center of the flange or the lower end of the intrauterine applicator. Point R is located 0.5 cm posterior to the vaginal wall [5].

Due to the difference between radiography and CT coordinate systems, the X, Y, and Z coordinates of reference points were used to compare the distances of these points from tandem applicator's tip. X-, Y-, and Z-axes represent patient left-right, head-feet, and anterior-posterior, respectively. Applicator reconstruction was repeated three times for each image set (one scan) to verify the operator reproducibility using one image set. Resulting images were reconstructed using Oncentra Brachy (software BPA v4.0, Elekta AB, Stockholm, Sweden) to measure the applicator dimensions and localize x-ray markers positions. The dose was always normalized at AL-point. A 6 Gy dose was prescribed for all reconstructions.

Table 1 Geometrical measurements and doses at reference points around 15°, 30°, and 45°applicators. Inter-operator dwell times for 15° and 30° CT/MR applicators are included

Metal applicator	15°	30°	45°
Average distance ± σ (mm)			
Radiography			
Tip ~ P1	67.42 ± 0.24	67.7 ± 0.27	70.69 ± 0.53
Tip ~ P2	75.52 ± 0.16	75.19 ± 0.20	76.82 ± 0.33
Tip ~ P3	62.31 ± 0.13	57.23 ± 0.16	57.35 ± 0.26
CT			
Tip ~ P1	67.41 ± 0.36	67.97 ± 0.29	70.36 ± 0.58
Tip ~ P2	75.39 ± 0.33	75.39 ± 0.28	76.38 ± 0.70
Tip ~ P3	62.50 ± 0.34	57.58 ± 0.37	56.98 ± 0.29
Average dose ± σ (Gy)			
Radiography			
P1	10.062 ± 0.0019	9.444 ± 0.0024	8.803 ± 0.0065
P2	7.533 ± 0.0023	7.056 ± 0.0014	6.641 ± 0.0067
P3	8.453 ± 0.002	8.444 ± 0.0015	8.382 ± 0.0074
CT			
P1	10.063 ± 0.0019	9.443 ± 0.0021	8.805 ± 0.0076
P2	7.533 ± 0.0017	7.056 ± 0.0022	6.640 ± 0.0083
P3	8.454 ± 0.002	8.444 ± 0.0033	8.383 ± 0.0066
CT/MR applicator (CT scan only)			
Average distance ± σ (mm)			
X-ray marker			
Tip ~ A	85.47 ± 0.2	99.81 ± 0.33	–
Tip ~ R	84.19 ± 0.2	96.82 ± 0.57	–
Model-based			
Tip ~ A	85.32 ± 0.37	99.80 ± 0.56	–
Tip ~ R	84.12 ± 0.26	96.82 ± 0.66	–
Average dwell time ± σ (sec)			
X-ray marker	129.09 ± 2.03	191.17 ± 1.65	–
Model-based	130.67 ± 3.56	191.70 ± 4.46	–
Inter-operator average dwell time ± σ (sec) (CT/MR 30° tandem, model-based only)			
Oncologist 1	–	24.98 ± 1.21	–
Oncologist 2	–	25.45 ± 1.18	–
Oncologist 3	–	25.41 ± 1.10	–
Maximum coordinate shift (mm) σ (CT/MR 30° tandem, model-based only)			
		X Y Z	
Oncologist 1	–	0.26 0.21 0.46	–
Oncologist 2	–	1.7 1.8 1.73	–
Oncologist 3	–	2.73 2.86 2.78	–

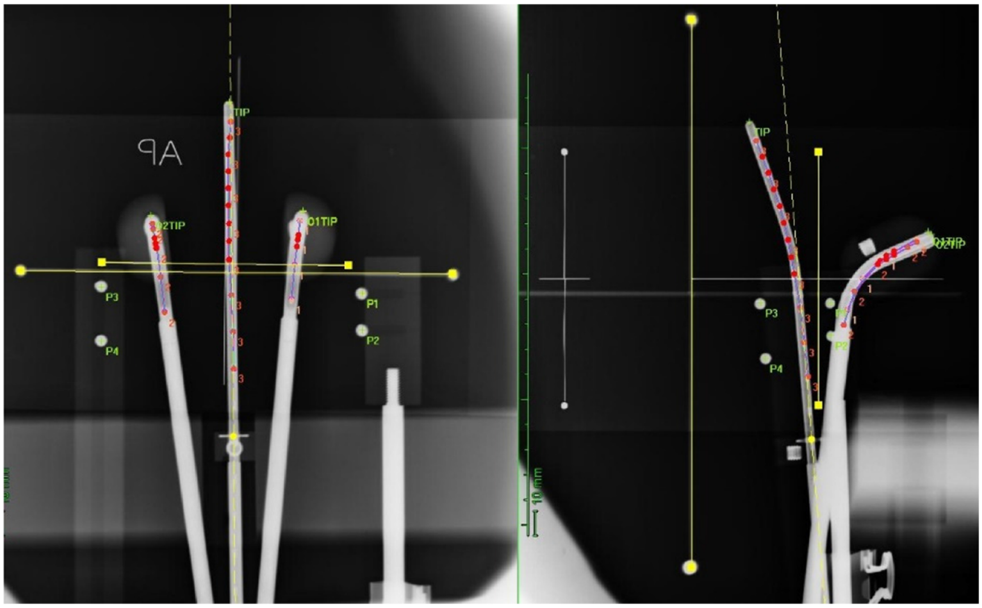

Fig. 2 2D x-ray radiograph of the phantom using the CR imaging system showing the applicators and four points. Three points (P1, P2, and P3) were used for distance measurements from applicators tips. P4 was used for dose normalization (100%)

Fig. 3 CT imaging for 15°and 30° CT/MR applicators along with active dwell positions

Image Acquisition and Reconstruction Methods

Each applicator set was acquired three times to estimate intra-scan error. Radiography-based acquisition has been in use for many years. It provides two views of applicators and surrounding structures (Fig. 2). Two radiographs are taken at orthogonal angles showing the catheter, which enables the system to reconstruct a 3D view of the catheters. Alternatively, using CT images that provide 3D views of applicators and surrounding organs, catheter reconstruction can be done easily by scrolling through consecutive images.

CT image-based reconstruction can be done through catheter describing points or model-based methods. The catheter describing points' method is based on the use of x-ray markers which are inserted in the applicator. It is done by placing strategic points along the length of catheter. Each x-ray marker corresponds to a position which could be occupied by the radioactive source as a dwell position. This helps in checking the correct reconstruction of a catheter depending on x-ray markers' positions. Alternatively, a 3D applicator model is predefined in the software library. When utilized, it forms a light field that cast a 3D shadow of the applicator model on the CT image. Model-based reconstruction can be used with/without x-ray markers. However, many oncologists prefer to use model-based method without x-ray markers to avoid metal artifact.

Inter- and Intra-operator Comparisons

Applicator reconstruction was repeated three times for each image set by three radiation oncologists. Source

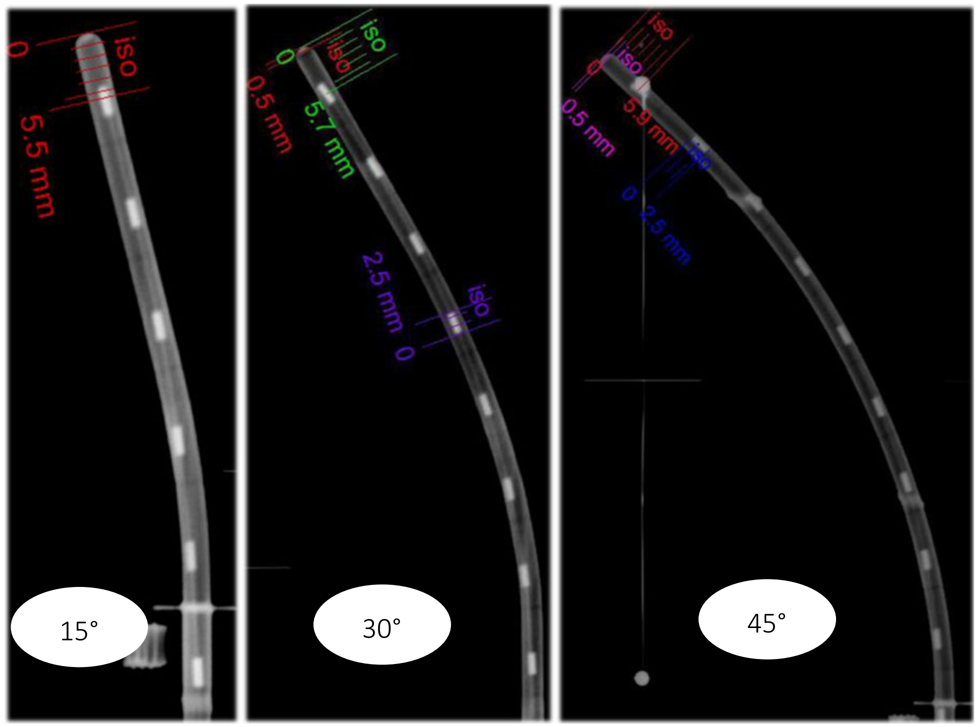

Fig. 4 X-ray radiograph using the CR imaging system along with distance measurements for three different applicator angles. The measured applicator wall thickness was about 0.5 mm. The distance from the outer tip end to the midpoint of first dwell position was about 5.5, 5.7, and 5.9 mm, for the 15°, 30°, and 45° applicator angulations, respectively

dwell times were compared. Inter- and intra-oncologist variations were derived to check for reconstruction precision. The three oncologists are skilled with one to 2 years of experience on Oncentra brachytherapy [Elekta AB] software. Inter- and intra-oncologist deviations were estimated from the dwell time of three scans (nine reconstructions). Dwell times were averaged, and their standard deviations SD (σ) were determined. For each oncologist, intra-scan SD is the variation within one scan, which is composed of three repeated reconstructions. Another source of SD is the inter-scan variation, which represents the variation between three independent scans. The intra-scan SD and total SD were determined as follows:

$$\sigma_{\text{intra-scan}} = \sqrt{\frac{\sigma_{S_1}^2 + \sigma_{S_2}^2 + \sigma_{S_3}^2}{3}} \quad (1)$$

$$\sigma_{total} = \sqrt{\sigma_{\text{intra}-scans}^2 + \sigma_{\text{inter}-scans}^2} \quad (2)$$

where σ_{S_1}, σ_{S_2}, and σ_{S_3} are standard deviations associated with three repeated reconstructions for a single scan, while$\sigma_{\text{inter}-scans}$ represents the standard deviations associated with three independent scans.

Data Analysis

Three metal and two CT/MR tandem applicators were compared to check the applicators' angle dependency of the dose to fixed points. The coordinates of the source dwell positions were also used to check for any shift of active points between repeated reconstructions. Tandems were reconstructed either using x-ray markers or predefined 3D models. Source dwell times in both reconstruction methods were compared to conclude an idea about the dose variation at A-point. The time duration spent for a complete applicator reconstruction was also checked.

Results

Image Acquisition Methods

Results indicate accurately reconstructed applicators and fixed points in both radiography and CT with precise locations of the x-ray markers and the reference points around the applicator. The measured distances between reference points and applicator's tip showed good agreement with a difference of less than 1 mm in both radiography and CT. The maximum standard deviations (σ) for repeated reconstructions (i.e., operator reproducibility) were less than 0.35 and 0.83 mm for radiography and CT, respectively. Table 1 shows calculated doses at reference points around 15°, 30°, and 45° steel tandem applicators reconstructed using radiography and CT. The measured applicator wall thickness was about 0.5 mm. The distance from the outer tip to the midpoint of the first x-ray marker point was about 5.5, 5.7, and 5.9 mm, for the 15°, 30°, and 45° metal tandem applicators, respectively (Fig. 4).

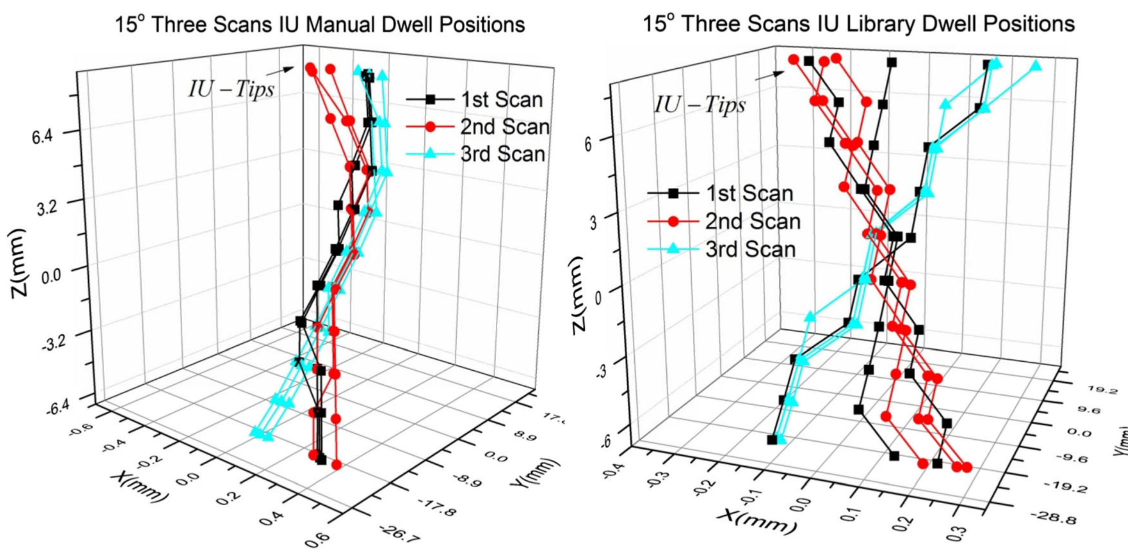

Fig. 5 Distance shift for active dwell positions for 15° tandem CT/MR applicator. It is noted that manual definition of dwell position is more accurate and reproducible between scans

CT Image-Based Reconstruction Method (X-Ray Markers–3D Model-Based)

Maximum reconstruction difference for distances measured between Fletcher CT/MR applicator tip and reference points for x-ray markers and model-based methods were less than 1 mm. For checking the radiation dosage to reference points, we compared the source dwell time between repeated reconstructions. Dwell times had wider variation (σ) for both 15° and 30° applicators using 3D model-based method. Table 1 shows the means and standard deviations (σ) of measured distances and dwell times in both methods for CT/MR applicators.

Analysis of variance for the means of 15° and 30° tandems showed insignificant difference. A test for SD using Levene's test for homogeneity of variance between x-ray makers and model-based methods showed insignificant difference with (p value = 0.131) for 15° tandem (Fig. 5), whereas it showed a significant difference for 30° tandem (p value = 0.011) (Fig. 6). Statistically, the variance of dwell time had significant difference between both methods for 30° tandem. However, such a difference should be checked in clinical settings to be applied in clinical practice. The mean dwell time for three oncologists was similar. Care should be taken while using model-based method since variation gets wider for greater curvature tandems. The SD (σ) expressed in Table 1 has two sources. First is the intra-scan SD (σ), which represents the variation between three repeated reconstructions within one scan. Another source of (σ) is the inter-scan

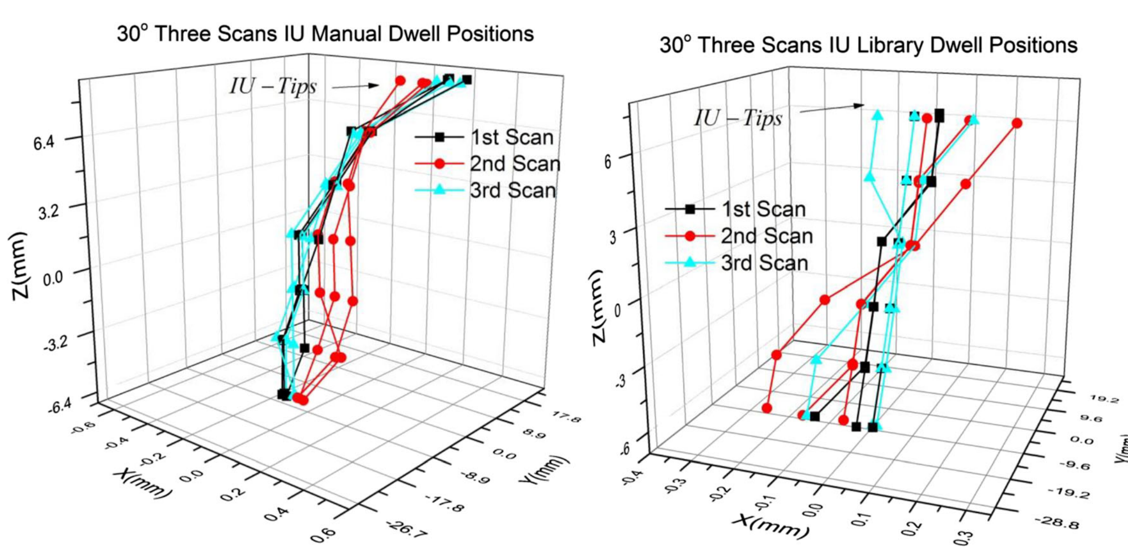

Fig. 6 Distance shift for active dwell positions for 30° tandem CT/MR applicator. It is noted that manual definition of dwell position is more accurate and reproducible between scans

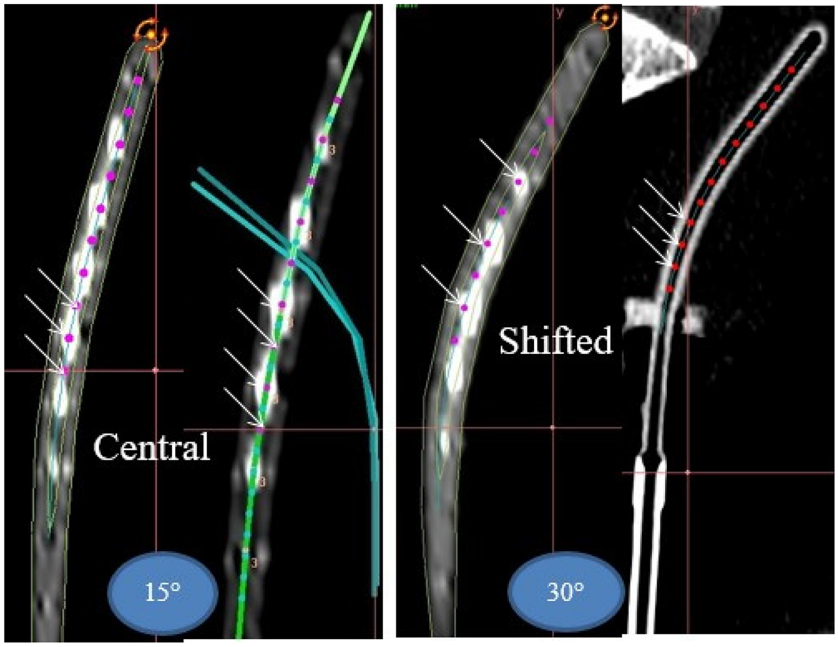

Fig. 7 Dwell position shift for active dwell positions within 30° tandem CT/MR applicator. It is noted that less curved applicator gives accurate point localization which results in accurate and reproducible reconstruction

variation. It represents variation between three independent scans. The average reconstruction time duration spent by operators in both methods was 10 ~ 13 min.

Inter- and Intra-operator Comparison (Model-Based)

The maximum intra-oncologist dwell time variation was ~ 1.21 s, whereas the inter-oncologist dwell time variation among three oncologists was ~ 0.26 s. The average intra-oncologist dwell time and maximum dwell position shift in the X, Y, and Z coordinates are given in Table 1. X-, Y-, and Z-axes represent patient left-right, head-feet, and anterior-posterior, respectively. Detailed check for the 3D X, Y, and Z coordinates of the catheter describing points showed that the maximum shift was on the Y and Z directions. Analysis of variance for the means of dwell time showed no significant difference (p value = 0.65). Levene's test for homogeneity of variance (SD) showed no significant difference (p value = 0.89). Therefore, it can be concluded that the inter-oncologist variation is insignificant. In other words, three oncologists utilized and followed similar reconstruction protocols, which produced similar treatment planning and dosage.

Discussion

Both modalities show similar measurements, but CT shows wider variation for doses to reference points especially for greater curvature tandems. Radiography has higher advantage when dealing with metal applicators. However, CT is superior to radiography due to its ability to demonstrate 3D viewing and also dose distribution to organs at risk.

Both methods are reliable for geometrical measurements of 15° and 30°, and 45° applicators. In catheter describing points reconstruction (x-ray markers) with CT, every point along the catheter can be defined in three CT views, i.e., axial, sagittal, and coronal. The center of each marker point can be selected carefully resulting in precise repeated reconstructions. However, model-based reconstruction has predefined catheter points which cannot be manipulated or selected individually. A measurement of the distance between source dwell positions and points A and R revealed that when a model is moved or rotated to fit inside the applicator's lumen, all of its catheter points move together. In general, even operators with high experience cannot perform identical 3D model rotation or tilting in repeated reconstructions, which results in a lower reproducibility of the model-based method.

The mean and standard deviation of dwell times differ slightly among three oncologists due to the dwell positioning shift in repeated reconstructions. This shift was more detected in the Y direction because of the applicator tip misplacement and in the Z direction due to the applicator greater (30°) curvature (Fig. 7). For a specific oncologist, the exact applicator placement in repeated reconstructions cannot be performed with a 100% precision, which results in a detectable inter- and intra-oncologist variation. The duration of the reconstruction time might be similar, but the dwell time in model-based method showed a wider variation. The choice to reconstruct using x-ray markers or built-in models is operator dependent. If the primary concern is to achieve maximum reproducibility, x-ray markers reconstruction would be recommended. If CT image quality is desired without metal artifact, operator can apply model-based method.

Inter- and intra-oncologist comparison was carried out to address any differences in reconstruction procedures. Average dwell times were found to be in close proximity. Variance of dwell times showed insignificant differences indicating accurate and similar protocol utilization within the facility. All oncologists followed similar applicator reconstruction protocol. Therefore, inter- and intra-oncologist variations were small and showed good agreement. Within our facility, the preferred intracavitary applicator reconstruction choice is to acquire CT images for CT/MR applicators without x-ray markers, thus avoiding metal artifact and applying predefined models, which provide easy reconstruction and accurate treatment planning and dosage.

Conclusions

Inter- and intra-oncologist comparisons were made to address any differences in reconstruction procedures within our facility. CT is preferred over radiography. Average dwell times were found to be in close proximity. Variance of dwell times showed an insignificant difference for 15° applicator. However, it showed a significant difference for 30° applicator due to Y and Z directions misplacement. In order to apply our phantom study results in clinical settings, an investigation for clinical measurements could be carried out in a further study. All oncologists followed similar applicator reconstruction procedure, and therefore, inter- and intra-oncologist variations were small and showed good agreement.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Ethical Approval This article does not contain any studies with human participants performed by any of the authors.

Informed Consent This article does not contain any studies with human participants performed by any of the authors and therefore no informed consents were obtained.

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