Treatment planning of a skin-sparing conical breast brachytherapy applicator using conventional brachytherapy software

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Purpose: AccuBoost is a noninvasive image-guided technique for the delivery of partial breast irradiation to the tumor bed and currently serves as an alternate to conventional electron beam boost. To irradiate the target volume while providing dose sparing to the skin, the round applicator design was augmented through the addition of an internally truncated conical shield and the reduction of the source to skin distance.

Methods: Brachytherapy dose distributions for two types of conical applicators were simulated and estimated using Monte Carlo (MC) methods for radiation transport and a conventional treatment planning system (TPS). MC-derived and TPS-generated dose volume histograms (DVHs) and dose distribution data were compared for both the conical and round applicators for benchmarking purposes.

Results: Agreement using the gamma-index test was $\geq 99.95\%$ for distance to agreement and dose accuracy criteria of 2 mm and 2%, respectively. After observing good agreement, TPS DVHs and dose distributions for the conical and round applicators were obtained and compared. Brachytherapy dose distributions generated using Pinnacle³ for ten CT data sets showed that the parallel-opposed beams of the conical applicators provided similar PTV coverage to the round applicators and reduced the maximum dose to skin, chest wall, and lung by up to 27%, 42%, and 43%, respectively.

Conclusions: Brachytherapy dose distributions for the conical applicators have been generated using MC methods and entered into the Pinnacle³ TPS via the Tufts technique. Treatment planning metrics for the conical AccuBoost applicators were significantly improved in comparison to those for conventional electron beam breast boost. © 2011 American Association of Physicists in Medicine. [DOI: [10.1118/1.3552921](https://doi.org/10.1118/1.3552921)]

Key words: brachytherapy, conical applicator, treatment planning, breast boost, AccuBoost

I. INTRODUCTION

The AccuBoost (Advanced Radiation Therapy LLC, Tyngsboro, MA) D-shaped and round applicators have been dosimetrically characterized by Yang and Rivard¹ and by Rivard *et al.*² in 2009. Both applicator types are used as an alternative to conventional electron beam breast boost irradiation. Compared to electron boost, the round applicators reduce the maximum dose D_{MAX} to organs at risk (OARs) such as the skin, chest wall, and lung by 20%, 86%, and 90%, respectively.³ The conical applicators were developed to further reduce skin dose and were dosimetrically characterized by Yang and Rivard in 2010.⁴ The conical applicators with internal diameters of 5–8 cm (in 1 cm increments) and 31 mm applicator height have been shown to reduce D_{MAX} by 15%–32% while maintaining planning target volume (PTV) dose within 3% for a constant exposure time compared to the equivalent diameter round applicators.⁴ However, these clinical benefits are difficult to quantify without the ability to perform treatment planning dosimetry to guide optimal applicator selection.

Current clinical brachytherapy treatment planning systems (TPSs) based on the AAPM TG-43 formalism⁵ cannot accurately account for intersource attenuation,⁶ dose calcula-

tions to media other than water,⁷ clinical radiation scattering conditions,^{8,9} or high-Z shields.¹⁰ The Tufts technique¹¹ has been developed based on a hybrid approach to the AAPM TG-43 formalism^{12–14} and could be applied in some clinical situations where the accuracy of conventional TPS is not acceptable. The Tufts technique has been implemented in Pinnacle³ (version 8.0m, Philips Medical Systems, Cleveland, OH) for several brachytherapy applicators including the AccuBoost round applicators.¹¹ The purpose of this study is to benchmark TPS calculations based on the Tufts technique against reference Monte Carlo (MC) simulations and to compare dose distributions from conical and round applicators toward obtaining guidance for clinical decision making.

II. METHODS AND MATERIALS

Compared to conical applicators having a solid frustum as examined by Yang and Rivard,⁴ a new conical breast brachytherapy applicator has been designed. This modification includes hollowing the frustum interior to reduce applicator weight without significantly affecting the dose distribution and a decrease in applicator outside height from 31 to either 19 or 25 mm for reducing treatment time. The 19 mm high

FIG. 1. Cross-sectional views of the 19 mm (a) and 25 mm (b) reduced-height AccuBoost conical applicators with hollowed-out cones. Both the applicator wall and the cone shielding are made from tungsten alloy. The cone shield is attached to the round applicator with a steel screw. The HDR ^{192}Ir source enters the applicator through a catheter, held in place by a retaining polycarbonate guide. The applicator is separated from the breast by a 3.67 mm compression paddle. The photograph (c) shows the final assembly.

applicators [marketed as dose-rate optimized (DRO) applicators] were designed to provide substantial reductions in treatment time with similar maximum skin dose compared to the round applicators, while the 25 mm high applicators [marketed as skin-dose optimized (SDO) applicators] were designed to provide a modest decrease in treatment time with substantial skin-dose reductions. The internal diameter of these conical applicators range from 5 to 8 cm and are referred to as 5C19, 6C19, 7C19, and 8C19 for the DRO applicators and 5C25, 6C25, 7C25, and 8C25 for the SDO applicators, respectively. MC simulations were performed using the MCNP5 radiation transport code (v 1.40) for eight conical applicators to complement previous simulations performed for the round applicators using identical methods.² The reader is referred to work by Yang and Rivard and Rivard *et al.* for specifics on the MC methods.^{1,2,4} As modeled in the MC environment, cross-sectional views of the 6C19 and 6C25 conical applicators are shown in Fig. 1. Compari-

sons were then performed between the MC and TPS results for dose distributions and dose volume histograms (DVHs) for the conical and round applicators.

II.A. Benchmarking TPS results

AAPM TG-43 brachytherapy dosimetry parameters for the conical applicators were deduced from MC simulations using the Tufts technique and entered into the TPS as previously done for the round applicators.¹¹ The coordinate system origin was set 1 cm from the breast surface with the z -axis aligned with the applicator axis of symmetry. The radial dose function $g(r)$ data were in the range $1.0 \text{ cm} \leq r \leq 15.4 \text{ cm}$ and two-dimensional (2D) anisotropy function $F(x, z)$ data were in the ranges $0.0 \text{ cm} \leq x \leq 12.5 \text{ cm}$ and $2.767 \text{ cm} \leq z \leq 10.767 \text{ cm}$. With 0.05 cm increments, 161 and 40 411 data points were used for $g(r)$ and $F(x, z)$ characterizations, respectively. For applicator treatment planning, a calculation grid size of 0.05 cm was used covering a spatial extent of 8 cm in all directions.

Planar samplings (also using 0.05 cm grid resolutions) for both the MC-simulated and TPS-calculated dose distributions for a single applicator and 8 cm thick breast were imported into the IBA Dosimetry OmniPro I'mRT software (v 1.6; IBA Dosimetry America, Bartlett, TN). The OmniPro software performs dose comparison based on gamma-index calculation as shown in Eq. (1).¹⁵

$$\gamma(r_{\text{MC}}) = \min \left\{ \sqrt{\frac{r^2(r_{\text{MC}}, r_{\text{TPS}})}{\Delta d^2} + \frac{\delta^2(r_{\text{MC}}, r_{\text{TPS}})}{\Delta D^2}} \right\} \forall \{r_{\text{TPS}}\} \quad (1)$$

$r(r_{\text{MC}}, r_{\text{TPS}})$ is the distance between the reference point r_{MC} and calculated dose point r_{TPS} , Δd is the distance to agreement criterion, $\delta(r_{\text{MC}}, r_{\text{TPS}})$ is the difference between dose at reference and calculated points, and ΔD is the dose difference criterion. To meet the gamma-index tolerance $\gamma \leq 1$, $r(r_{\text{MC}}, r_{\text{TPS}}) > \Delta d$ and $\delta(r_{\text{MC}}, r_{\text{TPS}}) > \Delta D$ cannot be satisfied

TABLE I. Dimensional and volumetric information for the ten CT data sets using parallel-opposed beams. GTV, the maximum GTV lengths in the midplane of the compressed breast ($_{\text{GTV}}L_{\text{MAX}}$), planning target volume for APBI (PTV_{APBI}), planning target volume for boost ($\text{PTV}_{\text{Boost}}$), and the breast thickness (T) were obtained from TPS for all ten CT data sets. The three CT data sets not amenable that failed for APBI are indicated with boldface.

Patient	GTV (cm ³)	$_{\text{GTV}}L_{\text{MAX}}$ (cm)	PTV_{APBI} (cm ³)	$\text{PTV}_{\text{Boost}}$ (cm ³)	T (cm)
1ML	9.77	3.9	69.88	33.80	5.9
1CC	6.72	4.1	68.26	31.59	5.2
2ML	9.55	3.1	60.85	31.06	6.9
2CC	10.83	3.5	66.22	34.12	5.5
3ML	1.79	1.4	29.74	11.39	7.3
3CC	3.40	2.3	35.78	15.82	6.7
4ML	24.45	5.5	142.88	81.70	7.1
4CC	25.83	5.1	129.40	77.01	5.6
5ML	13.40	6.2	89.79	43.51	8.1
5CC	51.35	7.6	202.49	123.16	8.8

FIG. 2. Comparisons of Monte Carlo depth dose profiles 6C19 applicator (left) with the 6R applicator (right) for both (a) single beam and (b) two parallel-opposed beams. The rectangular line at the top indicates the applicator internal diameter. The isodose intervals are in 0.10 Gy increments with the dose at a depth of 3.0 cm normalized to 1.00 Gy.

simultaneously. Since there are no accepted standards for using the gamma-index comparison method such as in the AAPM Task Group 56 report,¹⁶ sensitivity to Δd and ΔD values were investigated for application to brachytherapy dose calculations. Δd criteria of 1–5 mm in 1 mm increments and ΔD criteria of 1%–5% in 1% increments were considered.

Another purpose of this study was to determine the optimal applicator type and size for patient treatment after applicator commissioning in the TPS. This goal was achieved by comparing DVHs for the PTVs and OARs using the TPS. However, before comparing DVHs for patient plans, a sub-study was performed to check the reproducibility of DVH generation within the TPS. The breast skin was modeled as a right cylinder 0.3 cm thick and 10 cm in diameter in the MC and TPS environments. Differences between MC-derived and TPS-generated skin DVHs were examined.

II.B. TPS comparison of conical and round applicators

Ten CT image data sets were obtained for five patients with breast compressed in the medial-lateral (ML) and cranial-caudal (CC) directions. These ten data sets were used for treatment planning of the aforementioned four round applicators and 8 conical applicators. Dose for all 12 applicators was delivered using parallel-opposed beams and normalized to 1.00 Gy midway through the compressed breast along the applicator central axis. For each patient, the D_{MAX} to the PTVs and OARs were determined. The breast skin subtended the first 0.3 cm from the outer surface.¹⁷

While the AccuBoost applicators are mainly used as a boost technique at present, the conical applicators offer the potential for enhanced skin-dose sparing in accelerated partial breast irradiation (APBI). The PTV for APBI (PTV_{APBI})

was defined to be gross target volume (GTV) plus a 1.0 cm expansion and the PTV for boost technique (PTV_{Boost}) was defined to be GTV plus a 0.5 cm expansion. Both PTV_{APBI} and PTV_{Boost} were never within 0.5 cm of the skin surface and consequently did not need trimming subsequent to GTV expansion. Each CT data set was planned using all 12 applicators and DVHs were obtained for PTV_{APBI}, PTV_{Boost}, and the three OARs for each treatment plan. The optimal applicator type and size for each data set was determined to achieve at least 90% of the prescription dose to 90% of the PTV volume ($_{PTV}V_{90} \geq 90\%$) while minimizing OAR dose.¹⁸ Table I shows volumetric and dimensional information used for guiding the applicator selection.

II.C. PTV coverage of conical and round applicators

2D dose distributions for a single beam application or two parallel-opposed beams can be derived from the MC simulation. The 2D dose distributions indicate the 2D PTV dose coverage directly. To determine the dose coverage for each applicator, the maximum PTV dimension length covered by the 90% isodose line ($_{PTV}L_{90}$) on the midplane of the compressed breast was obtained for breast thicknesses of 3–8 cm with 1 cm increments. $_{PTV}L_{90}$ was normal to the applicator central axis and was determined from both MC simulation and TPS calculation.

III. RESULTS

III.A. MC comparison of conical and round applicators

The result of MC simulation for the 6C19 applicator is compared to the 6R applicator in Fig. 2(a) for a single beam application. D_{MAX} was on the skin surface for the round applicators and $z \leq 0.5$ cm on the central axis for the conical applicators. Thus, the conical applicators should only be used to treat patients with cavities at least 0.5 cm beyond the breast skin surface. The conical applicators provided almost the same $_{PTV}D_{MAX}$ and about 10% lower dose outside the applicator aperture compared to the round applicators.

For a parallel-opposed beam configuration, the DRO applicators reduced the treatment time by 19%–34% in comparison with a round applicator having the same diameter. Treatment time was reduced by 8%–17% for the SDO applicators for the same comparison. Further, the $_{skin}D_{MAX}$ reduced up to 12% and 21% for the DRO and SDO applicators, respectively. Dose distributions for parallel-opposed beam configurations of the 6C19 and 6R applicators are shown in Fig. 2(b).

III.B. TPS benchmarking results

Comparisons of the MC-simulated to the TPS-calculated dose distributions for the conical and round applicators are presented in Table II for four Δd and two ΔD possibilities. For the most restrictive criteria of $\Delta d=1$ mm and $\Delta D=1\%$, all applicators had a pass rate of at least 98.08% with an average of 99.24%. The regions of gamma-index failure were near the surface at the applicator aperture and near the

TABLE II. Gamma-index comparison between MC-simulated and TPS-calculated dose distributions for both round and conical applicators, showing the percentage of pixels passing the gamma-index test. At least 98.08% of pixels passed the gamma-index comparison for all 12 applicators and for $\Delta d \geq 1$ mm and $\Delta D \geq 1\%$.

Applicator	Passing rate (%)			
	$\Delta D=1\%$		$\Delta D=2\%$	
	$\Delta d=1$ mm	$\Delta d=2$ mm	$\Delta d=1$ mm	$\Delta d=2$ mm
5C19	99.77	99.95	99.96	100.00
5C25	99.77	99.96	99.97	100.00
5R	99.81	99.98	99.97	100.00
6C19	99.51	99.84	99.80	99.96
6C25	99.61	99.95	99.87	99.98
6R	99.75	99.98	99.98	100.00
7C19	98.78	99.82	99.36	99.96
7C25	99.09	99.89	99.62	99.97
7R	99.28	99.95	99.82	99.99
8C19	98.08	99.77	98.96	99.95
8C25	98.47	99.85	99.33	99.97
8R	98.98	99.94	99.74	99.97

internal truncated cone with high-dose gradients (Fig. 3). Using the $\Delta d=2$ mm and $\Delta D=2\%$ criteria, $\gamma \leq 1$ for over 99.95% of the pixels for all applicators with an average of 99.98%. For $\Delta d \geq 3$ mm and $\Delta D \geq 3\%$ criteria, $\gamma \leq 1$ for all pixels.

MC-derived and TPS-generated $_{skin}DVH$ results generally agreed within 5% (Fig. 4). While large differences were observed in the low and high-dose regions, the absolute skin volume differences were small. There was an average of 1% variation over $V_{20} \leq V \leq V_{170}$ and a maximum of 10% for $V < V_{20}$. Furthermore, the total skin volume from the TPS was 27.5 cm³ and the ratio of TPS-generated skin volume to MC-derived volume was 1.000 035. This substudy indicated that the Tufts technique can accurately reproduce MC-based dose distributions and DVH data.

Fig. 3. Gamma-index comparison of dose distributions from MC simulation and TPS calculation for the 6C19 applicator with $\Delta d=1$ mm and $\Delta D=1\%$.

FIG. 4. Comparisons of MC-derived and TPS-generated DVHs (a) for breast skin of 0.3 cm thickness and 5.0 cm radius. For the patient IML plan with a prescription dose of 1.00 Gy to the breast center from the TPS, (b) DVHs for the skin, (c) PTV_{APBI} , and (d) PTV_{Boost} from two parallel-opposed beams were obtained for all 12 applicators with $PTV_{APBI} V_{90} \geq 90\%$ and $PTV_{Boost} V_{90} \geq 90\%$ to determine applicator selection.

III.C. TPS comparison of conical and round applicators

As there was at least one applicator which satisfied the $PTV_{Boost} V_{90} \geq 90\%$ criterion for all ten CT image data sets, use of the AccuBoost applicators for breast boost brachytherapy was possible for all patients. Meanwhile for three of the ten CT image data sets, no applicator could meet the $PTV_{APBI} V_{90} \geq 90\%$ criterion. From Table I, it is clear that three data sets (4ML, 4CC, and 5CC) had large tumor volumes and subsequently large PTV_{L90} . The round applicators provide better PTV_{APBI} and PTV_{Boost} coverage than the conical applicators midway through the compressed breast, which is examined in Sec. III D.

Comparisons of DVHs for the skin, PTV_{APBI} , and PTV_{Boost} for patient IML from all 12 applicators are shown in Fig. 4. The $PTV_{APBI} V_{90} \geq 90\%$ criterion was met for round applicators ≥ 6 cm and conical applicators ≥ 7 cm. The $PTV_{Boost} V_{90} \geq 90\%$ criterion was met for round applicators ≥ 5 cm and conical applicators ≥ 6 cm. As the 7C25 applicator provided low $skin D_{MAX}$ and $skin D_{MEAN}$ values, it was determined to be the optimal ABPI choice for patient IML. Similarly, 6C25 was determined to be the optimal boost choice for patient IML. Larger applicator apertures provided lower $skin D_{MAX}$ and better PTV coverage. However, the improved coverage was at the expense of higher $skin D_{MEAN}$ and larger volumes of irradiated skin and breast tissue. This method was performed for the remaining nine data sets where comparable results were observed.

For all ten CT data sets, $skin D_{MAX}$, $chest\ wall D_{MAX}$, and $lung D_{MAX}$ changed by +14.1% to -26.6%, +18.2% to

-42.1%, and +4.0% to -42.6%, respectively, for the conical applicators compared to the equivalent round applicators. All positive values were from the DRO applicators. Increasing applicator diameter or breast thickness caused increasing $skin D_{MAX}$. For APBI, the maximum acceptable skin dose was 145% of the prescription dose according to NSABP B-39/ RTOG 0413.¹⁸ However, $skin D_{MAX}$ is larger than twice that of the prescription dose. This is solved by using a four-field arrangement, in which $skin D_{MAX}$ is divided by 2 when assuming no skin overlap between the two orthogonal axes. Compared to $skin D_{MAX}$, $chest\ wall D_{MAX}$ and $lung D_{MAX}$ would not be divided by 2 because dose these two OARs are included for four-field beam arrangements.

III.D. PTV coverage of conical and round applicators

There is an upper limit on the tumor size for which the applicator can provide 90% dose coverage. The PTV_{L90} for each applicator with two parallel-opposed beams and 3–8 cm breast thickness is tabulated in Table III for both MC simulation and TPS calculation. From Fig. 2(b) for both the conical and round applicators, PTV coverage improves as cavity position is located further from the breast center. Differences between PTV_{L90} from MC simulations and TPS calculations were 0.13 cm on average (max. 0.7 cm, min. 0.0 cm). The conical applicators provided low dose near the applicator wall within the applicator aperture. This effect is compensated by the parallel-opposed arrangements of four beams (two orthogonal axes). Generally, larger applicators provided better PTV coverage at the expense of larger volumes of irradiated breast tissue. The DRO applicators provided PTV

TABLE III. The maximum PTV lengths in the midplane of the compressed breast, which was covered by 90% isodose line. $_{PTV}L_{90}$ values were obtained for conical and round applicators with two parallel-opposed beams from both MC simulation and TPS calculation. Breast thickness ranged from 3 to 8 cm with 1 cm increments.

	3 cm	4 cm	5 cm	6 cm	7 cm	8 cm
MC						
5C19	2.9	3.7	3.8	3.8	3.8	4.0
5C25	2.2	3.0	3.7	3.9	3.8	4.3
5R	3.9	3.7	4.0	4.0	4.4	4.4
6C19	3.9	4.5	4.5	4.6	4.5	5.2
6C25	2.7	3.6	4.2	4.4	4.2	4.4
6R	4.9	4.4	4.3	4.6	4.8	4.7
7C19	5.2	5.5	5.5	5.2	5.5	5.2
7C25	3.5	4.4	5.3	4.9	5.2	5.0
7R	5.7	4.8	5.2	5.2	5.2	5.5
8C19	7.4	7.1	7.0	6.4	5.9	5.5
8C25	5.1	5.7	5.9	5.9	5.4	5.7
8R	6.8	6.3	5.9	6.3	5.6	5.8
TPS						
5C19	3.0	3.7	3.8	3.8	3.9	4.0
5C25	2.2	3.0	3.5	3.7	4.0	4.0
5R	4.0	3.8	3.9	4.1	4.4	4.1
6C19	3.8	4.6	4.5	4.5	4.4	4.7
6C25	2.7	3.7	4.2	4.3	4.5	4.4
6R	4.7	4.4	4.5	4.7	4.7	4.7
7C19	5.3	5.5	5.5	5.1	5.2	5.2
7C25	3.5	4.4	5.0	5.1	5.1	5.2
7R	5.6	5.5	5.0	5.3	5.2	5.3
8C19	7.5	6.7	6.9	6.5	6.0	5.6
8C25	4.7	5.2	6.0	5.9	5.4	5.6
8R	6.9	6.3	6.0	6.1	5.3	5.9

coverage more similar to the round applicator than the SDO applicators. However, the relationship between PTV coverage and AccuBoost applicator size was not monotonic and depended on the applicator type, height, and breast thickness. While the radiation oncologist should exercise caution when choosing the appropriate applicator, Table III may be used as a guide for applicator selection.

IV. DISCUSSION

Comparisons of MC-simulated and TPS-calculated dose distributions for the round applicators were previously performed by sampling 64 uniformly positioned points for each applicator size using the Tufts technique.¹¹ The current study is more advanced by using the gamma-index comparison method for comprehensive planar evaluations over the calculation space using 0.5 mm resolution and 40 411 pixels. This approach demonstrated good agreement between MC-simulated and TPS-calculated dose distributions, even in the high-dose gradient region.

For external-beam radiotherapy QA such as for IMRT, there are no standard criteria (Δd and ΔD) for gamma-index comparisons and the use of this method for brachytherapy is novel to our knowledge. For external-beam dosimetry, it has been suggested to specify different agreement criteria in regions having small and large dose gradients.^{19–23} While re-

gions of high-dose gradients have been defined as $>3\%/mm$ for external beam,²³ dose gradients $>60\%/mm$ were observed in the current study using a shielded ^{192}Ir brachytherapy applicator. Consequently, the results are deemed favorable upon considering the region where the gamma-index test failed and the use of $(0.5\text{ mm})^3$ voxels in the MC and TPS environments. It seems that $\Delta d=2\text{ mm}$ and $\Delta D=2\%$ can be a useful standard for the current benchmarking study, with gamma-index pass rates exceeding 99.95% for all applicators studied. We suggest the medical physics community investigate and consider standardized tolerances for QA comparisons of brachytherapy dose distributions.

When using a four-field arrangement with superposition of two orthogonal parallel-opposed beams without tissue deformity, the conical applicators are dosimetrically more favorable than conventional electron beam boost through reduction of D_{MAX} to the skin, chest wall, and lung.³ Consequently, the reduced-height conical applicators may be promising tools for APBI considering higher doses prescribed per fraction and higher resultant skin doses. When chest wall D_{MAX} and lung D_{MAX} are deemed too high if the PTV is in close proximity to the chest wall, these limitations may be averted by using the D-shaped applicators with smaller proximal penumbra. D-shaped applicators with internal shields for similar OAR dose reduction are under development.

V. CONCLUSION

Brachytherapy dose distributions for the new conical applicators have been generated using MC methods and entered into the Pinnacle³ TPS via the Tufts technique. Typical agreement between the MC and TPS dose distributions was within 99.95% for all 12 different applicators using a 2 mm distance to agreement criterion and 2% dose tolerance. TPS-calculated dose distributions showed that the conical applicators can provide similar PTV coverage to the round applicators, yet with lower dose to the breast skin, chest wall, and lung. Treatment planning metrics for the conical AccuBoost applicators were significantly improved in comparison with that for conventional electron beam breast boost.

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