Dosimetric comparison of AcurosBV with AAPM TG43 dose calculation formalism in cervical intraductal high-dose-rate brachytherapy using three different applicators

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Abstract

Purpose: To compare the dosimetric effects of American Association of Physicists in Medicine (AAPM) TG43 dose formalism and AcurosBV (grid-based Boltzmann solver, GBBS) formalism on high-dose-rate (HDR) brachytherapy planning for cervical cancer patients irradiated using three different applicators.

Methods: A TG43 plan and a AcurosBV plan were generated for each of the 30 patients. Twenty patients who had undergone whole pelvic radiotherapy followed by cervical HDR brachytherapy and the remaining 10 patients who underwent total hysterectomy only gave HDR brachytherapy also were enrolled in this study. The patients were divided into three groups according to the types of applicators used: tandem and ovoid (T&O), tandem and ring (T&R), and cylinder. To compare the dosimetric parameters, the cumulative dose-volume histograms (DVHs) were measured. We also compared the doses at 90% of the volume (D90%), the volume receiving 100% and 150% of the prescribed dose (V100% and V150%) for the clinical target volume (CTV-HR), and the doses of point A, the dose receiving 0.1 and 2 cc of the volume (D0.1cc and D2cc) for the organs-at-risk (OARs).

Results: Compared with the AcurosBV plans, TG43 plans predicted higher D90%, V100%, and V150% of CTV-HR, dose of point A, and D0.1cc and D2cc of OARs in three types of applicators. Except D2cc of sigmoid in T&R and cylinder applicators, the D90%, V100%, and V150% of CTV-HR; the dose of point A and the D0.1cc and D2cc of bladder, rectum, and small bowel exhibited significant discrepancies (all p < 0.05). The effects of the three types of applicators on the dose distribution were quite different due to the differences in the materials. The dose difference of CTV-HR and OARs was greatest (around 10%) for T&O applicators but only 1–5% for T&R and cylinder applicators.

Conclusions: AcurosBV was more accurate in calculating the doses in the air cavity and high-density substance than TG43. In the clinical setting, AcurosBV exhibited different dosimetric distributions in the cervix plans for HDR brachytherapy, especially in treatment planning when using T&O applicators. The AcurosBV algorithm should be...


1 | INTRODUCTION

Cervical cancer is one of the most common malignant tumors diagnosed in China. According to cancer statistics for China, cervical cancer accounts for 6.6–26.5% of cancer-related morbidity and is the fourth leading cause of cancer-related death in women.\(^1\) In addition to radical surgery, radiotherapy is a common treatment used for cervical cancer. In addition, postoperative chemoradiotherapy can effectively reduce local recurrence rates and improve the survival rates of patients with cervical cancer.\(^2,3\)

Intracavitary brachytherapy (BT) is an essential component of cervical carcinoma treatment\(^4\) and has been shown to significantly improve the radiotherapeutic outcome by improving the target dose distribution while reducing rectal and bladder toxicities.\(^4\) The method currently in use globally for accurately determining the dose delivered in brachytherapy treatments is based on the American Association of Physicists in Medicine Task Group (TG) 43.\(^5\) TG43 dose calculation formalism assumes the radiation is transported through an infinite homogeneous water phantom and therefore does not account for any heterogeneities within or outside the patient. This has implications for the accuracy of the dose calculation in regions close to air or bone. Since 2012, the TG186 report has described model-based dose calculation methods in brachytherapy that account for these heterogeneities.\(^6\)

According to previous studies, the TG43 formalism is known to overestimate the radiation dose in the air cavity and underestimate the dose at the high-density substance.\(^4,6\) Several studies have suggested that in brachytherapy cases such as prostate and cervix, if the tissue is relatively homogeneous, the treatment technique uses unshielded plastic applicators, and there are no air pockets nearby, then the model-based dose calculation algorithms (MBDCAs) have an average dosimetric influence of smaller than 5% compared with TG43.\(^7,8\)

The Acuros BV algorithm solves the linear Boltzmann transport equation or the grid-based Boltzmann solver (GBBS) algorithm and is similar to the Monte Carlo method (MC).\(^9,10\) The accuracy of Acuros BV dose calculation is defined by comparing it to the Monte Carlo simulation (MCNPX, converged statistics to 1%). Calculated dose distribution is generally required to be within 2% (2 mm). The accuracy limit is slightly less strict in regions close to the source (distance less than 5 mm) or in boundary areas of rapid material density change, where a 15% difference is allowed.\(^8,11,12\) Studies have shown that Acuros BV has been reported to estimate dose deposition more accurately than TG43 in heterogeneous media.\(^13,14\)

The present study aimed to analyze the dosimetric effect and compare the dose difference of AcurosBV and TG43 plans using three types of applicators for cervical cancer to guide clinicians regarding the algorithm selection for different applicators.

2 | METHODS

2.1 | Patient selection and contouring

A retrospective study including 30 patients with cervical cancer who had undergone postoperative brachytherapy was performed. The patients enrolled in the study were classified as stages II and III, as established by the International Federation of Gynecology and Obstetrics. External beam radiotherapy (EBRT) was performed with a volume rotational intensity modulated radiotherapy technique using a Varian 21EX™ linear accelerator. A total dose of 45 Gy with chemotherapy was prescribed in 1.8 Gy per fraction using a conventional fractionation schedule. All patients received image-guided HDR brachytherapy (IGBT) HDR brachytherapy, which was performed in four fractions, 7 Gy per fraction for the HR CTV within 2 weeks, usually starting in the last week of EBRT. These 30 patients were divided into three groups according to the different applicators used: 10 patients used tandem and ring (T&O) applicators, another 10 used tandem and ovoid (T&R) applicators, and 10 who underwent total hysterectomy used cylinder applicators. Pre-brachytherapy magnetic resonance imaging (MRI) was used to assess the position of the T&R and T&O applicators, and ultrasound-guided was performed during placing the applicators. Bowel preparation was performed to achieve an empty sigma and rectum. The bladder was emptied by opening the urinary catheter and was then filled with 50 ml of saline for computed tomography (CT) scan with 5 mm. The urinary catheter remained open during the entire planning process and the subsequent irradiation, which resulted in reproducible bladder filling of 50–100 ml. The delineation of clinical CTV HR, bladder, rectum, sigmoid, and small bowel was performed on post-implant CT and the vaginal wall was contoured on all available magnetic resonance images\(^15,16\) according to the International Commission on Radiation Units & Measurement Reports 50 and 83, in which prescribing, recording, and reporting doses have been standardized.\(^17,18\)
2.2 | Treatment planning

Plans based on TG43 and AcurosBV algorithms for 30 cervical patients were designed on the BrachyVision™ planning system (Varian Medical Systems) and then carried out by the machine of GammaMedPlus IX™ (Varian Medical Systems) using 192Ir with an initial contained activity of 10 Ci (reference air kerma rate of 40.7 mGy * m²/h). Two dose-reporting modes are available in Acuros BV: dose-to-water (Dw) and dose-to-medium (Dm); the latter mode was selected. For Acuros BV, version 13.5.0 of the physics material table was used. For all plans, the optimization was an automatic dose calculation. The dose calculation grid size was set at 2.5 mm for all 30 cases. The source step size was 5 mm. The total dose was equal to or greater than 28 Gy/4f, the fraction dose was no less than 7 Gy, and the prescription dose was required to surround the 90% volume of the CTV-HR was required to cover the prescription dose. We also considered the dose of point A, which was defined as a point 2 cm lateral to the central canal of the uterus and 2 cm up from the mucous membrane of the lateral fornix, in the axis of the uterus according to the ICRU Report 38. All 30 treatment plans generated using the TG43 algorithm and were also used in the patients’ clinical treatment in this study. Retrospectively, the plans were recalculated using the Acuros BV algorithms. The plans were not reoptimized and therefore the structure set, dwell positions, and dwell times were identical between the two plans.

For each patient, the cumulative dose was computed, consisting of EBRT and BT contributions normalized to 2 Gy per fraction (EQD2) using the linear-quadratic model with α/β ratios of 10 and 3 Gy for for of CTV-HR and OARs, respectively.19,20 The total dose limitations of the CTV-HR and OARs are shown in Table 1.21

2.3 | Evaluation and statistical analysis

Although D90% of CTV-HR and D2cc of OARs were used to evaluate the clinical plans, more parameters were selected to describe the dose differences in more detail. The following dose-volume parameters were used for quantitative evaluation of the plans: (1) V100% and V150%, the volumes of the CTV-HR receiving 100% and 150% of the prescribed dose (%);22 (2) D90%, the dose delivered to 90% volume of CTV-HR (Gy);23 (3) D0.1cc, D2cc, the minimal doses to the most exposed 0.1 cc of the critical organs (Gy);24 and (4) Dpoint A, the absolute dose to the irradiated point A.

Statistical analysis was performed using IBM SPSS Statistics for Windows (version 17.0; IBM Corporation). Quantitative data were expressed as the mean ± SD, and the Wilcoxon rank test was used to evaluate the statistical significance of differences between TG43 and Acuros BV. Differences were considered to be statistically significant at p < 0.05.25

3 | RESULTS

3.1 | Dosimetric comparison of target

The dose distributions of the plans using the three types of applicator are shown in Table 2 and Figure 1. In the three groups of plans, the largest volumes of CTV-HR were 35.6, 39.7, and 42.5 cc, and the smallest volumes were 35.6, 39.7, and 42.5 cc. The mean volumes were 35.6, 39.7, and 42.5 cc in T&O, T&R and Cylinder respectively. Regardless of the size of the targets, the D90%, V100% and V150% of the T&O and T&R plans and V100% and V150% of the cylinder plans using two algorithms were statistically significant (p < 0.05). The TG43 plans created more dose distribution to the target volume than Acuros BV: in the T&R plans, D90% was 7.07 ± 1.64 and 6.9 ± 1.62, V100% was 19.46 ± 6.34 and 19.16 ± 6.01 respectively; in T&O plans, D90% was 7.10 ± 1.21 and 6.9 ± 1.62, V100% was 19.89 ± 6.34 and 19.46 ± 6.01 respectively; in Cylinder plans, D90% was 6.03 ± 1.64 and 6.01 ± 2.50, V100% was 26.37 ± 5.14 and 26.41 ± 5.13 respectively. In T&O plans, D90% was 7.48 ± 1.31 and 7.10 ± 1.21 respectively; in T&R plans, D90% was 7.07 ± 1.64 and 6.9 ± 1.62 respectively. Comparing the three types of applicators from Table 2, the dose difference of T&O plans was the most obvious followed by the one from T&R planning, and then the cylinder planning. In fact, only the dose difference of T&O plans was around 10%, the difference of T&R and cylinder plans were not significant (1–5%). This

### TABLE 1 | The dose constraints of CTV-HR and OARs

| Structures | Total dose limit (EQD2) (BT + EBT) |
|------------|-----------------------------------|
| CTV-HR     | D90% > 84 Gy                      |
| Bladder    | D2cc < 90 Gy                      |
| Rectum     | D2cc < 75 Gy                      |
| Sigmoid    | D2cc < 75 Gy                      |
| Small bowel| D2cc < 75 Gy                      |

EQD2, Equivalent Dose in 2Gy/f; BT, Brachytherapy treatment; EBT, External brachytherapy treatment.

### TABLE 2 | Dosimetry of the targets in the TG43 and AcurosBV plans according to the type of applicator in patients with cervical cancer

| Target   | TG43         | AcurosBV    | p value |
|----------|--------------|-------------|---------|
| T&O      | D90%(Gy)     | 7.48 ± 1.31 | 7.10 ± 1.21 | 0.028 |
|          | V100%(cc)    | 23.11 ± 7.55| 21.26 ± 7.65| 0.008 |
|          | V150%(cc)    | 14.86 ± 5.43| 12.69 ± 5.16| 0.023 |
| T&R      | D90%(Gy)     | 7.07 ± 1.64 | 6.90 ± 1.62 | 0.005 |
|          | V100%(cc)    | 19.89 ± 6.26| 19.46 ± 6.34| 0.010 |
|          | V150%(cc)    | 11.78 ± 4.49| 11.39 ± 4.55| 0.006 |
| Cylinder | D90%(Gy)     | 6.03 ± 2.56 | 6.01 ± 2.50 | 0.364 |
|          | V100%(cc)    | 26.41 ± 5.13| 26.37 ± 5.14| 0.062 |
|          | V150%(cc)    | 21.32 ± 5.35| 21.01 ± 5.31| <0.001 |
can be evidenced in Figures 1 and 2. Figure 1 shows the dose mapping for the three applicators. CT images of a(3), b(3), and c(3) showed the residual dose mapping in the color wash, which were the results of dose distribution in TG43 plans shown in the CT images of a(1), b(1), and c(1) minus that in AcurosBV plans shown in the CT images of a(2), b(2), and c(2). The residual dose color wash in Figure 1B(3) was most evident in the three residual dose figures, and the high dose distribution was surrounded by the applicators. Figure 3 shows the DVH of CTV-HR in the TG43 and AcurosBV plans using three types of applicators. Among the three applicators, the T&O applicator still had the greatest impact on the dose distribution for the TG43 and AcurosBV plans. From Table 2 and Figures 1 and 2, we can draw the following conclusion: regardless of the type of applicator used, the dose distribution of the target in the TG43 plans was higher than that of the Acuros BV plans.

3.2 | Dosimetric comparison of OARs and point A

Quantification statistics were used in the present study. The dose distributions of the OARs and point A are presented in Table 3 and Figure 3. The dose difference between the two algorithms was similar to that of the targets mentioned above. In all patients, the dose to both OARs and point A was higher in TG43 plans than those in AcurosBV plans.

In the T&O group, the dose difference was the biggest in three groups: compared to Acuros BV plans, the point A of TG43 plan had a 9.6% higher dose (6.03 vs. 5.50 Gy, \( p = 0.002 \)), the \( D_{0.1cc} \) and \( D_{2cc} \) of bladder, sigmoid, rectum, and small bowel in TG43 plans had a 6–10% higher dose, and differences of the parameters were statistically significant (all \( p < 0.05 \)).
FIGURE 2  The DVH of CTV_HR in the TG43 (3D, black full line) and AcurosBV (AXB, red dashed line). Planning of three different applicators for cervical cancer, respectively: (A) the DVH of CTV_HR using cylinder applicator, (B) the DVH of CTV_HR using T&O applicator, and (C) the DVH of CTV_HR using T&R applicator.

TABLE 3 Dosimetry of point A and OARs in the TG43 and AcurosBV plans, according to the three types of applicator in patients with cervical cancer

| OARs       | T&O          | AcurosBV     | p value | T&O          | AcurosBV     | p value | T&O          | AcurosBV     | p value |
|------------|---------------|--------------|---------|---------------|--------------|---------|---------------|--------------|---------|
| Point A    | 6.03 ± 1.33   | 5.58 ± 1.24  | 0.002   | 5.16 ± 1.05   | 5.09 ± 1.03  | <0.001  |
| Bladder    | D0.1cc (Gy)   | 7.54 ± 1.11  | 0.001   | 6.85 ± 0.66   | 6.73 ± 0.68  | <0.001  | 6.01 ± 1.69   | 5.79 ± 1.63  | <0.001  |
|            | D2cc (Gy)     | 5.49 ± 1.04  | <0.001  | 4.9 ± 0.61    | 4.81 ± 0.6   | <0.001  | 4.37 ± 1.29   | 4.12 ± 1.33  | 0.029   |
| Sigmoid    | D0.1cc (Gy)   | 5.96 ± 1.24  | <0.001  | 5 ± 1.21      | 4.91 ± 1.21  | 0.001   | 4.05 ± 2.28   | 3.89 ± 2.21  | <0.001  |
|            | D2cc (Gy)     | 4.29 ± 0.88  | <0.001  | 3.46 ± 0.73   | 3.59 ± 0.95  | 0.519   | 2.29 ± 1.14   | 2.3 ± 1.25   | 0.941   |
| Rectum     | D0.1cc (Gy)   | 6.34 ± 1.74  | 0.001   | 4.42 ± 1.2    | 4.33 ± 1.18  | <0.001  | 7.65 ± 0.93   | 7.43 ± 0.9   | <0.001  |
|            | D2cc (Gy)     | 4.36 ± 1.08  | 0.001   | 3.06 ± 0.77   | 3.01 ± 0.75  | 0.002   | 5.22 ± 0.81   | 5.08 ± 0.79  | <0.001  |
| Small bowel| D0.1cc (Gy)   | 6.36 ± 2.63  | 0.011   | 4.17 ± 2.13   | 4.08 ± 2.1   | <0.001  | 2.56 ± 1.85   | 2.46 ± 1.78  | 0.002   |
|            | D2cc (Gy)     | 4.5 ± 1.35   | <0.001  | 3.06 ± 1.53   | 3.00 ± 1.51  | <0.001  | 1.41 ± 1.05   | 1.35 ± 1.01  | 0.001   |

In the T&R group, the point A dose in TG43 and AcurosBV plans were 5.16 ± 1.05 and 5.09 ± 1.03 (p < 0.001). Compared to the AcurosBV plan, D2cc of bladder, D0.1cc of sigmoid, D0.1cc, D2cc of rectum and small bowel had a 1–5% higher dose in TG43 plans (all p < 0.05).

In the cylinder group, the Acuros BV plan yielded a smaller D0.1cc and D2cc for the bladder, rectum, and small bowel (all p < 0.05) compared to the TG43 plans. The dose differences ranged from 1% to 3% for the TG43 and AcurosBV plans.

The dose difference was largest for T&O brachytherapy planning and smallest for cylinder planning in the three types of applicators. This conclusion can be confirmed from Figure 3. Among the three applicators, the T&O applicator still had the greatest impact on the dose distribution for the TG43 and AcurosBV plans. We also found that, regardless of the type of app used, the dose distribution of the OARs in the TG43 plans was higher than that of the Acuros BV plans.

4 | DISCUSSION

An example of a comparison of the AcurosBV dose and TG43 for a shielded cylinder applicator (GM11004380 06) in a water phantom shows that during plan optimization, more calculation time is needed but a better accuracy dose distribution can be gotten by using AcurosBV algorithm than TG-43. Many studies have confirmed this conclusion. Carrier et al. evaluated the impact of prostate treatment plans with 125I permanent seed implants. They compared the dose distributions of full MC with water prostate, and full MC with realistic prostate tissue using MC methods and TG43 calculation. For clinical treatment plans, differences of 4–5% for D90 (the minimum dose deposited in 90% of the prostate volume) between MC simulations in water (Drw) and prostate tissue (Dm,m) were found. Lymeropoulou et al. showed that Drw-TG43 calculated doses agreed with
FIGURE 3  The DVHs of OARs in the TG43 (black full line) and AcurosBV (red dashed line). Planning using cylinder, T&O, and T&R applicators for cervical cancer, respectively: (A) the DVH of the bladder, (B) the DVH of the rectum, (C) the DVH of the sigmoid, and (D) the DVH of the small bowel.

MC calculated values of $D_{m,m}$ in the planning tumor volume (PTV) of an $^{192}$Ir breast implant. However, doses calculated by $D_{max}$-TG43 were up to 5% larger than MC calculated values of $D_{m,m}$ for skin and up to 10% larger for lungs. Our results are consistent with the conclusion of the studies referenced above. Use of AcurosBV for brachytherapy dose calculation could reduce the uncertainty of dose distribution and around 3% of the total error in soft tissue (T&R and cylinder applicators). However, as the density difference between tissues increases, the dose can vary by up to 10% (T&O applicators). The materials of applicator and tissue homogeneity are considered when AcurosBV algorithm is used. According to the Varian BrachyVision Algorithms Reference Guide (www.MyVarian.com) Table 4 shows the material composition of these applicators in detail.

From Table 4, we can see that the T&O applicators consist of stainless steel and titanium materials, and have a higher density than the other two applicators. We also found that in T&O applicators, titanium and stainless steel make up 70–80% of the total mass. These two metals have a much higher density than water, therefore the dose difference was the highest among the three types of applicators in TG43 and Acuros BV plans. On the contrary, checking the Varian product instructions, the cylinder applicator is made solely of polyphenylsulfone, which has a density of 1.3 g/cm$^3$, and the composition elements are carbon, hydrogen, oxygen, and sulfur. The density is close to water, which can explain the small dose difference between the two algorithms. From the study, we can conclude that the difference in the influence of two different algorithms on dose depends on the material composition and material density of each applicator.

The American Association of Physicists in Medicine TG186 report recommended continued use of the TG43 methodology for clinical dose calculations in brachytherapy while performing MBDCA calculations in parallel. Clinical application of material heterogeneity corrections in EBRT is now standard practice for many modalities. This transition has been made possible by the emergence of MBDCAs such as collapsed-cone (CC) convolution, super position convolution, MC methods, and more recently GBBS, all of which can now be found in commercial planning software packages, as well as new treatment techniques and dose-time fractionation schedules, which require a more realistic appraisal of delivered absorbed dose. This study was conducted to contribute to the brachytherapy community’s understanding of the Varian’s MBDCAs (Acuros BV) belonging to
TABLE 4  Details of composition for the three types of applicator

| Applicator       | Materials   | Expected density (g/cm³) | Element | Weight fraction | Actual density (g/cm³) |
|------------------|-------------|--------------------------|---------|----------------|------------------------|
| T&O              | Polyphenylsulfone | 1.30                | H       | 0.04027        | 1.23                   |
| T&R Cylinder     |             |                         | C       | 0.71984        | 1.18                   |
|                  |             |                         | O       | 0.15982        | 1.23                   |
|                  |             |                         | S       | 0.08007        |                        |
| T&O              | Stainless steel | 8.00               | C       | 0.00080        | 8.00                   |
|                  |             |                         | Si      | 0.01000        |                        |
|                  |             |                         | P       | 0.00045        |                        |
|                  |             |                         | Cr      | 0.19000        |                        |
|                  |             |                         | Mn      | 0.02000        |                        |
|                  |             |                         | Fe      | 0.68375        |                        |
|                  |             |                         | Ni      | 0.09500        |                        |
| T&O              | Titanium    | 4.42               | Al      | 0.06000        | 4.42                   |
|                  |             |                         | Ti      | 0.90000        |                        |
|                  |             |                         | V       | 0.04000        |                        |

GBBS, providing data on the use of the new hounsfield unit (HU)-based method of dose calculation, and has demonstrated that the differences between TG43 and TG186 as implemented in three different applicators plans, especially T&O applicator plans, are clinically significant in the vicinity of the treatment area and nearby OARs.

The ways to ensure the precision of brachytherapy treatment should include the following aspects: the precision of contouring of target and organs at risk, implantation location of the applicators, dose calculation, and positioning before treatment. Regardless of the precision, the goal is to reach an accurate dose distribution. The data set presented in this study may be used in conjunction with other studies to contribute towards correlation of MBDCA calculated doses with clinical outcomes and has great clinical significance for future research on brachytherapy.

5  CONCLUSION

The TG43 algorithm would overestimate the dose of the target and OARs compared with using the AcurosBV algorithm in the plans with the same dwell position and dwell time, although the plan of applying the two algorithms can meet the clinical requirements. In clinical practice, the material composition of the T&O applicator is very different from the surrounding tissue (around 10%), so AcurosBV is clinically recommended when using T&O applicators. However, in the plans based on the T&R and cylinder applicators, although the TG43 algorithm overestimated the tissue dose, the difference in dose distribution caused by the two algorithms was almost negligible because the difference in dose distribution was not much (1–5%) and both were located around the applicator. Considering the AcurosBV algorithm requires more calculation time, TG43 can still be selected clinically when using T&O or cylinder applicators.

AUTHOR CONTRIBUTIONS
Su-yan Bi: Participation in the whole work, generating treatment plans, drafting of the article, data analysis, and final approval of the version to be published. Zhi-jian Chen: Drafting and final approval of the version to be published. Xing-ru Sun: Data analysis and drafting of the article. Zhitao Dai: Participation in the whole work, perception and design, drafting of the article, data analysis, and final approval of the version to be published.

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CONFLICT OF INTEREST
The authors state that they have no competing interests.

ETHICS STATEMENT
The study was approved by the institutional review board of National Cancer Center/National Clinical Research Center for Cancer/Cancer Hospital & Shenzhen Hospital. We confirm that all methods were carried out in accordance with relevant guidelines and regulations.

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