Improvement of Calculation Accuracy in the Electron Monte Carlo Algorithm with Optional Air Profile Measurements

Jiwon Sung[1], Hyeongmin Jin[1], Jeongho Kim[1], Jong Min Park[1,2,3,4], Jung-in Kim[1,2,3], Chang Heon Choi[1,2,3], Minsoo Chun[1,2,3]

[1]Department of Radiation Oncology, Seoul National University Hospital, [2]Biomedical Research Institute, Seoul National University Hospital, [3]Institute of Radiation Medicine, Seoul National University Medical Research Center, [4]Department of Radiation Oncology, Seoul National University College of Medicine, Seoul, Korea

Purpose: In this study, the accuracies of electron Monte Carlo (eMC) calculation algorithms were evaluated to determine whether electron beams were modeled by optional air profiles (APs) designed for each applicator size.
Methods: Electron beams with the energies of 6, 9, 12, and 16 MeV for VitalBeam (Varian Medical System, Palo Alto, CA, USA) and 6, 9, 12, 16, and 20 MeV for Clinac iX (Varian Medical System) were used. Optional APs were measured at the source-to-detector distance of 95 cm with jaw openings appropriate for each machine, electron beam energy, and applicator size. The measured optional APs were postprocessed and converted into the w2CAD format. Then, the electron beams were modeled and calculated with and without optional APs. Measured profiles, percentage depth doses, penumbras with respect to each machine, and energy were compared to calculated dose distributions.
Results: For VitalBeam, the profile differences between the measurement and calculation were reduced by 0.35%, 0.15%, 0.14%, and 0.38% at 6, 9, 12, and 16 MeV, respectively, when the beams were modeled with APs. For Clinac iX, the differences were decreased by 0.16%, −0.31%, 0.94%, 0.42%, and 0.74%, at 6, 9, 12, 16, and 20 MeV, respectively, with the insertion of APs. Of note, no significant improvements in penumbra and percentage depth dose were observed, although the beam models were configured with APs.
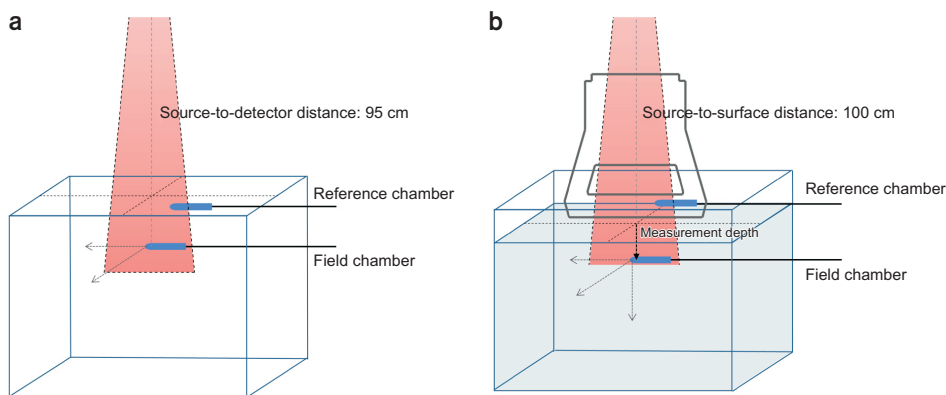**Conclusions:** The accuracy of the eMC calculation can be improved in profiles when electron beams are modeled with optional APs.

Keywords: Electron Monte Carlo, Air profile measurement, Electron applicator, Beam configuration, Eclipse treatment planning system

Introduction

Monte Carlo (MC) simulation is one of the most accurate methods for calculating dose distributions, particularly in heterogeneous tissues, where the effects of electron transport cannot be accurately modeled with conventional deterministic dose calculation algorithms [1,2]. Despite the accuracy of the MC simulation, large calculation times have limited its application in clinical routines [3]. Recently, with an increase in the computer processing speed, the

a

Source-to-detector distance: 95 cm

Reference chamber

Field chamber

b

Source-to-surface distance: 100 cm

Reference chamber

Measurement depth

Field chamber

Fig. 1. Schematic diagrams of the measurement setup for (a) optional air profiles and (b) verifications.

performance of the MC algorithm has been improved, and the MC dose calculation became acceptable for clinical treatment planning with electron beams [4–6]. The electron Monte Carlo (eMC) algorithm is based on the macro MC method for the electron beam in the Eclipse treatment planning system (Varian Medical System, Palo Alto, CA, USA) [7–9]. The eMC algorithm increases the calculation speed while preserving the calculation accuracy in heterogeneous internal parts of patients, such as the lung and oral cavity [10,11].

However, some limitations hinder the use of the eMC algorithm. Several studies have demonstrated discrepancies between measurements and calculations, particularly for lower electron energies, smaller applicator sizes, and larger source-to-surface distances (SSDs) [10,12–14]. In the buildup region at 4 MeV, the eMC algorithm produces up to 5.4% lower absorbed dose than that of the full MC model. In the penumbra and out-of-field regions in water, the eMC calculation underestimates the absorbed doses by up to 3.3%, compared to the full MC model [15]. The eMC calculation overestimates the absorbed dose toward the shoulder region with a 25×25 cm^2 applicator at increased SSDs [15].

Varian Medical System has announced that the beam configuration with air profiles (APs) can improve the calculation accuracy with AP measurements at the source-to-detector distance (SDD) of 95 cm where the collimator jaws open appropriately for each machine, energy, and applicator [16]. The purpose of this study is to evaluate the performances of the eMC algorithm with the insertion of APs in terms of profile, percentage depth dose (PDD), and penumbra.

Materials and Methods

1. AP measurements and beam configuration

This study was conducted within electron energy ranges used at the author's hospital. The electron energies of 6, 9, 12, and 16 MeV for VitalBeam (Varian Medical System) and 6, 9, 12, 16, and 20 MeV for the Clinac iX linear accelerator were used in this study. A Blue Phantom^2 scanning system (IBA Dosimetry GmbH, Schwarzenbruck, Germany) and two CC13 cylindrical ionization chambers (IBA Dosimetry GmbH) were used to acquire APs. The field chamber was placed at the SDD of 95 cm in air to measure APs. To remove pulsed beam fluctuations, the reference chamber was placed so that the active volume could be fully covered by the corresponding field sizes [17]. The measurement setup for APs is illustrated in Fig. 1a. The in-line and cross-line APs were measured, in which jaw positions were opened according to the applicator without an attached applicator [16]. The jaw sizes for each machine, energy, and applicator size are shown in Table 1. The measured APs were postprocessed by smoothing and rescaling; then, they were converted into the w2CAD format to register the measured beam data to Eclipse. The final APs with the w2CAD format were imported and configured according to the Eclipse reference guide document [16].

2. Measurement of the reference dose distribution

To evaluate the accuracy of the eMC algorithm with APs, the dose profiles and PDD curves were measured using the Blue Phantom^2 scanning system. The measurement setup

Table 1. Jaw openings according to the applicator sizes and energies for VitalBeam and Clinac iX

Applicator size (cm^2)	Jaw openings (cm^2)								
	VitalBeam				Clinac iX				
	6 MeV	9 MeV	12 MeV	16 MeV	6 MeV	9 MeV	12 MeV	16 MeV	20 MeV
6×6	20×20	20×20	11×11	11×11	20×20	20×20	11×11	11×11	11×11
10×10	22×22	20×20	15×15	15×15	20×20	20×20	14×14	14×14	14×14
15×15	22×22	20×20	19×19	18×18	20×20	20×20	17×17	17×17	17×17
20×20	27×27	25×25	25×25	23×23	25×25	25×25	25×25	23×23	22×22
25×25	32×32	30×30	30×30	28×28	30×30	30×30	30×30	28×28	27×27

for reference dose distributions is shown in Fig. 1b. Blue Phantom^2 was positioned with the SSD of 100 cm. Similar to the measurement of APs, to remove pulsed beam fluctuations, the reference chamber was placed where the active volume could be fully covered by the corresponding field sizes [17]. For VitalBeam, the profiles were measured at the depth of 1.18, 1.58, 2.20 and 2.90 cm at 6, 9, 12, and 16 MeV, respectively. For Clinac iX, the measurement depths were 1.00, 1.40, 2.00, 2.70, and 3.30 cm at 6, 9, 12, 16, and 20 MeV, respectively. The depths were shifted upward by 0.15 cm, considering the effective measurement point, with an A25 applicator (25×25 cm^2) and normalized to 100% at the center of the profiles. The PDD curves were measured with an A10 applicator (10×10 cm^2) and normalized to 100% at the depth of the maximum dose.

3. eMC calculation

The dose distributions were calculated in a 40×40×40 cm^3 virtual water phantom using beam models with and without APs. The eMC calculation options used in this study are listed in Table 2. For the number of particle histories option, the zero value means that the eMC calculation uses as many particles as required to reach the statistical uncertainty set in statistical uncertainty option. The random generator seed number is defined as the random number sequence used in the particle generator. If the seed value is set to 0, the EMC algorithm uses a randomly selected seed. The dose threshold for uncertainty was defined as the dose threshold to calculate statistical uncertainty [16]. The dose distributions with A25 applicators were exported in the coronal plane and normalized to 100% at the center of the profile using the RIT software (Radiological Imaging Technology,

Table 2. Electron Monte Carlo (eMC) calculation parameters used in this study

Calculation parameter	Value
Statistical uncertainty	1
Statistical uncertainty limit	3
Calculation grid size in cm	0.25
Random generator seed number	0
Number of particle histories	0
Dose threshold for uncertainty	50
Smoothing method	Three-dimensional Gaussian
Smoothing level	Medium

Inc., Colorado Springs, CO, USA). The absolute differences between calculated and measured dose distributions were averaged in the range of –10 to 10 cm to represent the discrepancies between the models with and without APs. The PDDs with A10 applicators were obtained and normalized to 100% at the depth of the dose maximum. Considering the effective measurement point, the comparison between the calculated and measured PDDs was started from the depth of 0.15 cm. Both calculated and measured penumbras were obtained by averaging the distances of the right and left sides between 20% and 90% of the central axis dose in the dose profiles [18].
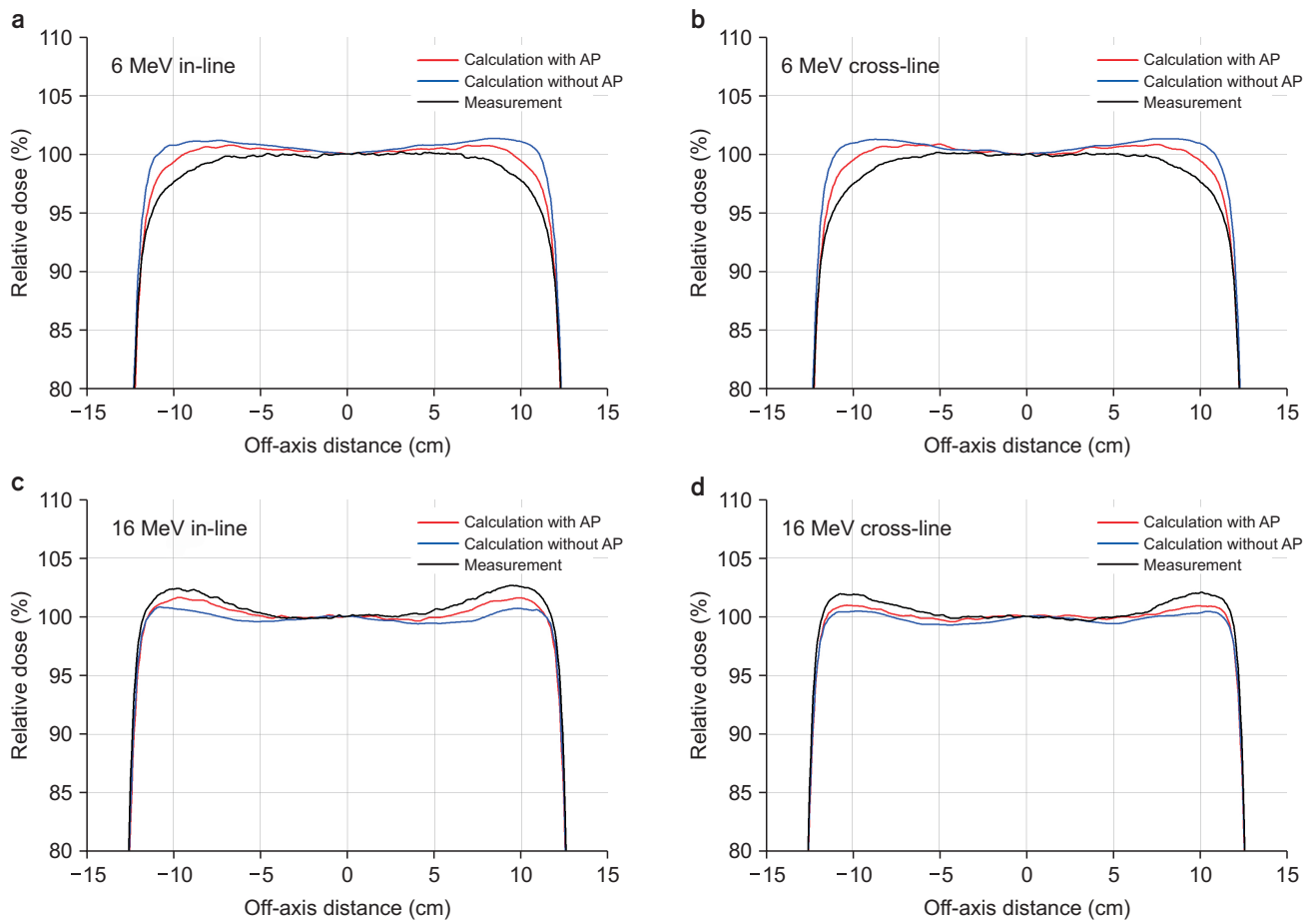
Results

The discrepancies in the profiles between the measurements and calculations for VitalBeam are summarized in Table 3, while the sample distributions at 6 and 16 MeV are shown in Fig. 2. The accuracy of calculated profile was improved by 0.35%, 0.15%, 0.14%, and 0.38% on average at 6, 9, 12, and 16 MeV, respectively, when the beams were modeled with APs. For all energies, the calculations with

Table 3. Improvements between measurements and calculations for VitalBeam and Clinac iX

Energy (MeV)	Direction	VitalBeam				Clinac iX			
		Measurement depth (cm)	Calculation–measurement* (%)		Improvement (%)	Measurement depth (cm)	Calculation–measurement* (%)		Improvement (%)
			Without AP	With AP			Without AP	With AP	
6	In-line	1.18	1.08	0.69	0.38	1.00	0.65	0.45	0.20
	Cross-line		1.07	0.75	0.32		0.48	0.37	0.11
9	In-line	1.58	0.91	0.67	0.24	1.40	0.23	0.40	−0.17
	Cross-line		0.76	0.71	0.05		0.15	0.60	−0.45
12	In-line	2.20	0.32	0.12	0.20	2.00	1.16	0.21	0.95
	Cross-line		0.19	0.11	0.08		1.20	0.28	0.92
16	In-line	2.90	0.96	0.46	0.50	2.70	0.69	0.22	0.47
	Cross-line		0.66	0.40	0.26		0.95	0.59	0.36
20	In-line	-	-	-	-	3.30	1.31	0.45	0.86
	Cross-line		-	-	-		1.07	0.46	0.61

AP, air profile; -, no data.

*Calculation–measurement: average value of differences between the calculated and measured profiles in the range of −10 to 10 cm.

Fig. 2. Measured and calculated profiles with and without air profiles (APs) for VitalBeam: (a, c) in-line and (b, d) cross-line profiles at 6 and 16 MeV, respectively.
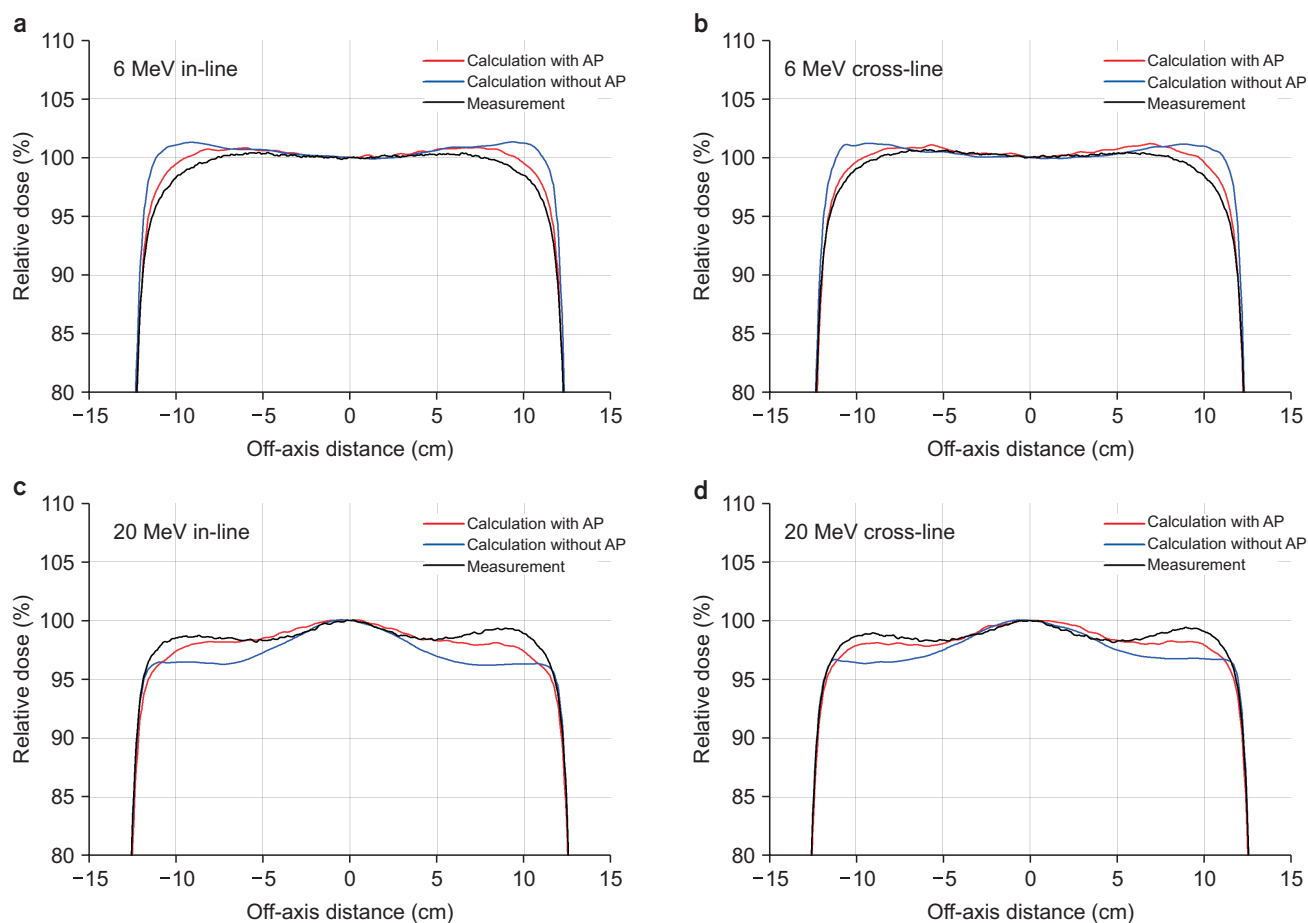
Fig. 3. Measured and calculated profiles with and without air profiles (APs) for Clinac iX: (a, c) in-line and (b, d) cross-line profiles at 6 and 20 MeV, respectively.

APs improved the accuracy up to 0.5%. Although the calculations with APs still exhibited over- and under-estimation tendencies, the discrepancies were reduced at both low and high energies. The discrepancies in the profiles between the measurements and calculations for Clinac iX are summarized in Table 3, while the sample distributions at 6 and 20 MeV are shown in Fig. 3. The discrepancies were reduced by 0.16%, −0.31%, 0.94%, 0.42%, and 0.74% on average at 6, 9, 12, 16, and 20 MeV, respectively, with the insertion of APs. Except at 9 MeV, the calculations with APs improved the accuracy up to 0.95%. The calculations with APs at 9 MeV had lower accuracy than those without APs of 0.17% and 0.45% for the in-line and cross-line profiles, respectively.

The penumbras are shown in Table 4. For Clinac iX, the penumbra difference between the measurement and calculation without AP was up to 0.10 cm, while that with AP was up to 0.15 cm. For VitalBeam, the maximum difference

between the measurement and calculation was 0.25 cm for both cases. Of note, no significant change in the difference between the measured and calculated penumbras was observed between the cases with and without AP. Table 5 shows the maximum and average difference between the PDD measurement and calculation with or without APs, while the sample distributions at low (6 MeV) and high (16 and 20 MeV) energies are shown in Fig. 4. For VitalBeam, although the measured PDDs exhibited differences up to 6.09%, 2.99%, 1.71%, and 1.45% without APs, those with APs were 5.68%, 3.02%, 1.95%, and 1.13% at 6, 9, 12, and 16 MeV, respectively. For Clinac iX, the measured PDDs exhibited differences up to 5.07%, 2.82%, 1.72%, 1.74%, and 0.82% without APs, while those with APs were 5.24%, 3.03%, 1.50%, 1.29%, and 1.00% at 6, 9, 12, 16, and 20 MeV, respectively. Large discrepancies were usually observed in the buildup region, particularly at low energies. This could not be im-

Table 4. Comparison between the measurements and calculations for the penumbras for VitalBeam and Clinac iX

Energy (MeV)	Direction	VitalBeam				Clinac iX			
		Measurement depth (cm)	Calculation (cm)		Measurement (cm)	Measurement depth (cm)	Calculation (cm)		Measurement (cm)
			Without AP	With AP			Without AP	With AP	
6	In-line	1.18	1.30	1.38	1.33	1.00	1.20	1.30	1.30
	Cross-line		1.30	1.35	1.30		1.20	1.30	1.28
9	In-line	1.58	1.10	1.10	0.98	1.40	1.15	1.18	1.15
	Cross-line		1.05	1.10	0.95		1.10	1.15	1.05
12	In-line	2.20	1.15	1.15	0.95	2.00	1.13	1.18	1.05
	Cross-line		1.15	1.15	0.95		1.15	1.10	1.08
16	In-line	2.90	1.25	1.28	1.03	2.70	1.18	1.23	1.13
	Cross-line		1.25	1.25	1.00		1.20	1.20	1.15
20	In-line	-	-	-	-	3.30	1.33	1.43	1.28
	Cross-line		-	-	-		1.30	1.40	1.30

AP, air profile; -, no data.

Table 5. Comparison of the mean and maximum differences in PDDs between the measurements and calculations for VitalBeam and Clinac iX

Energy (MeV)	VitalBeam				Clinac iX			
	With AP		Without AP		With AP		Without AP	
	Mean (%)	Maximum (%)	Mean (%)	Maximum (%)	Mean (%)	Maximum (%)	Mean (%)	Maximum (%)
6	1.45	5.68	1.52	6.09	0.64	5.24	0.62	5.07
9	1.28	3.02	1.35	2.99	0.50	3.03	0.47	2.82
12	0.94	1.95	0.84	1.71	0.29	1.50	0.36	1.72
16	0.48	1.13	0.42	1.45	0.33	1.29	0.55	1.74
20	-	-	-	-	0.16	1.00	0.22	0.82

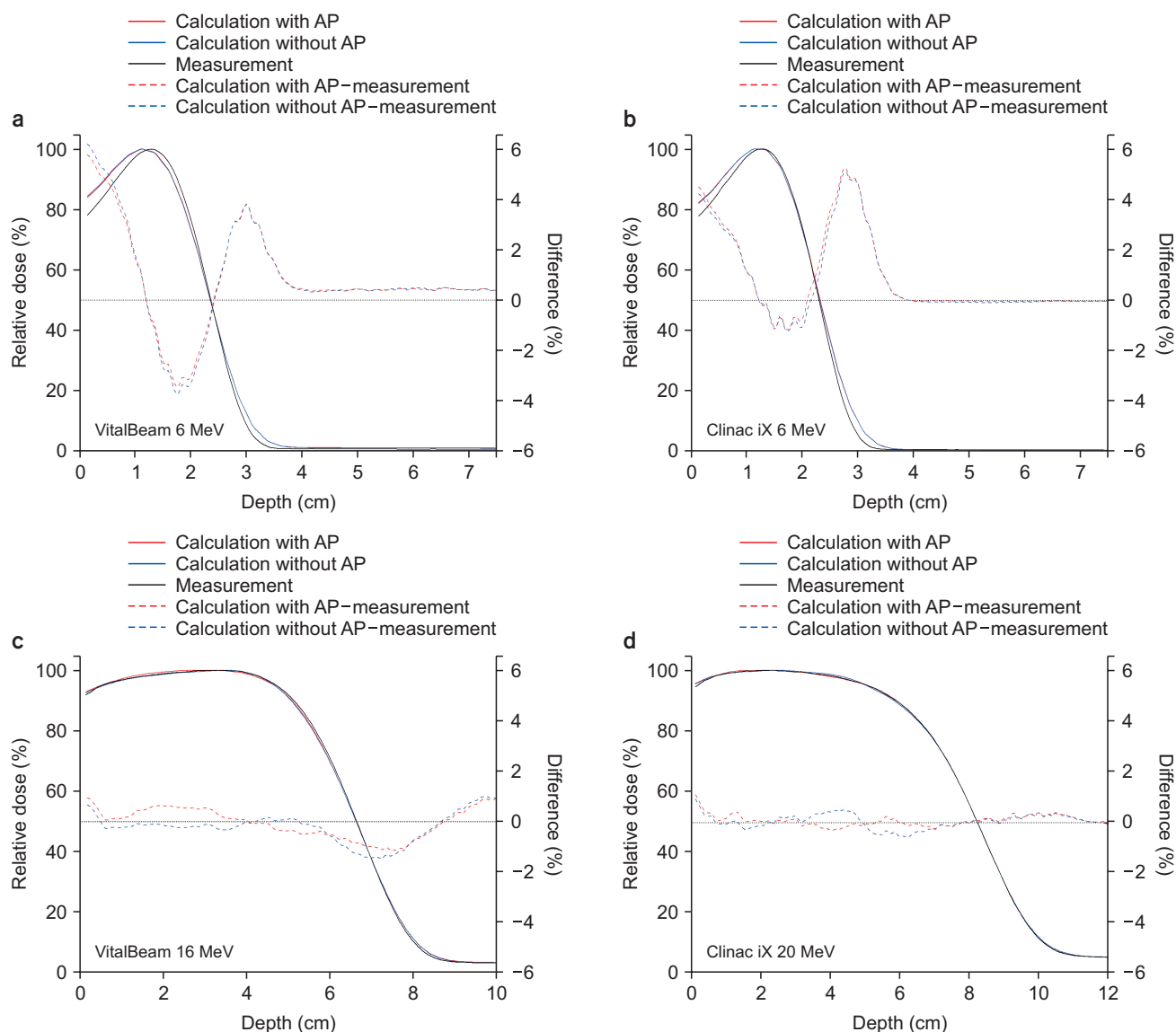PDD, percentage depth dose; AP, air profile; -, no data.

proved even using eMC models with APs.

Discussion

In this study, the accuracy of the eMC calculation was evaluated when the electron beams were modeled with optional APs in the treatment planning system. The accuracies of profiles were improved by modeling the electron beam with optional APs. The differences could be minimized when the electron beams were modeled by adding optional APs. Specifically, this reduction was considerable in the shoulder regions where the profiles were near the dose fall-off. According to the manufacturer's document, optional APs could construct two-dimensional fluences in beam modeling. If optional AP was not measured, the radially symmetric fluences from the open field APs (40×40 cm^2) are used for dose calculation. Because the actual fluences for

each applicator size differ from those of open fields, the jaw size-specific measurements can improve the accuracies. The dose calculation accuracy for a given applicator can be improved by constructing a two-dimensional fluence that is appropriate for each applicator. Otherwise, the symmetric fluence in air with a 40×40 cm^2 open field can be applied for all applicators during the dose calculation [14,16]. To consider these properties, Varian Medical System recommends to include optional APs for the electron beam configuration [16].

Although no significant improvements in PDDs and penumbras were observed when eMCs were modeled with optional APs, the accuracies of profiles were improved overall. The PDD differences between measurement and eMC calculation have been reported in many studies [4,19,20], although electron beams have been modeled without optional APs. For 4 MeV, the eMC algorithm produced up to 5.4%

Fig. 4. Comparison of the measured and calculated percentage depth dose (PDD) curves with and without air profiles (Aps) and corresponding dose differences at (a) 6 and (c) 16 MeV for VitalBeam and at (b) 6 and (d) 20 MeV for Clinac iX. Calculation with AP–measurement, difference between the calculation with AP and measurement value; Calculation without AP–measurement, difference between the calculation without AP and measurement value.

lower doses than those of the full MC model in the buildup region and over-estimated the dose by up to 5.2% beyond the depth of the dose maximum, particularly at the end of the electron range [15]. This result could not be improved even with APs. The eMC algorithm largely underestimated the doses near the surface and overestimated them near the end point of the fall-off region compared to the measurement. Because this behavior was emphasized at low energies, the treatment plan should be carefully designed at low electron energy and prescription depth in the superficial region. It is necessary to improve the eMC algorithm to improve the calculation accuracy at low energy.

Conclusions

The accuracy of eMC calculation can be improved in dose profiles when the electron beams are modeled with optional APs.

Acknowledgements

Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

Author Contributions

Conceptualization: Minsoo Chun, Jung-in Kim. Data curation and formal analysis: Jeongho Kim, Jiwon Sung. Funding acquisition: Minsoo Chun, Chang Heon Choi. Investigation: Jiwon Sung, Minsoo Chun. Methodology: Jiwon Sung, Hyeongmin Jin, Minsoo Chun. Supervision: Minsoo Chun, Jong Min Park, Jung-in Kim. Validation: Jiwon Sung, Jeongho Kim. Writing–original draft: Jiwon Sung. Writing–review & editing: Minsoo Chun.

References

1. Ma CMC, Chetty IJ, Deng J, Faddegon B, Jiang SB, Li J, et al. Beam modeling and beam model commissioning for Monte Carlo dose calculation-based radiation therapy treatment planning: Report of AAPM Task Group 157. Med Phys. 2020;47:e1-e18.

2. Wanklyn MD, Kidane G, Crees L. Verification measurements of an eMC algorithm using a 2D ion chamber array. J Appl Clin Med Phys. 2016;17:320-328.

3. Chetty IJ, Curran B, Cygler JE, DeMarco JJ, Ezzell G, Faddegon BA, et al. Report of the AAPM Task Group No. 105: issues associated with clinical implementation of Monte Carlo-based photon and electron external beam treatment planning. Med Phys. 2007;34:4818-4853.

4. Pemler P, Besserer J, Schneider U, Neuenschwander H. Evaluation of a commercial electron treatment planning system based on Monte Carlo techniques (eMC). Z Med Phys. 2006;16:313-329.

5. Fix MK, Frei D, Volken W, Neuenschwander H, Born EJ, Manser P. Monte Carlo dose calculation improvements for low energy electron beams using eMC. Phys Med Biol. 2010;55:4577-4588.

6. Cygler JE, Daskalov GM, Chan GH, Ding GX. Evaluation of the first commercial Monte Carlo dose calculation engine for electron beam treatment planning. Med Phys. 2004;31: 142-153.

7. Xu Z, Walsh SE, Telivala TP, Meek AG, Yang G. Evaluation of the eclipse electron Monte Carlo dose calculation for small fields. J Appl Clin Med Phys. 2009;10:75-85.

8. Ding GX, Duggan DM, Coffey CW, Shokrani P, Cygler JE. First macro Monte Carlo based commercial dose calculation module for electron beam treatment planning--new issues for clinical consideration. Phys Med Biol. 2006;51: 2781-2799.

9. Neuenschwander H, Born EJ. A macro Monte Carlo method for electron beam dose calculations. Phys Med Biol. 1992; 37:107-125.

10. Zhang A, Wen N, Nurushev T, Burmeister J, Chetty IJ. Comprehensive evaluation and clinical implementation of commercially available Monte Carlo dose calculation algorithm. J Appl Clin Med Phys. 2013;14:127-145.

11. Chamberland E, Beaulieu L, Lachance B. Evaluation of an electron Monte Carlo dose calculation algorithm for treatment planning. J Appl Clin Med Phys. 2015;16:60-79.

12. Łukomska S, Kukołowicz P, Zawadzka A, Gruda M, Giżyńska M, Jankowska A, et al. Evaluation of the usefulness of the electron Monte Carlo algorithm for planning radiotherapy with the use of electron beams. Pol J Med Phys Eng. 2016;22:49-54.

13. Jong WL, Ung NM, Tiong AHL, Rosenfeld AB, Wong JHD. Characterisation of a MOSFET-based detector for dose measurement under megavoltage electron beam radiotherapy. Radiat Phys Chem. 2018;144:76-84.

14. Fix MK, Cygler J, Frei D, Volken W, Neuenschwander H, Born EJ, et al. Generalized eMC implementation for Monte Carlo dose calculation of electron beams from different

machine types. Phys Med Biol. 2013;58:2841-2859.

15. Ojala J, Kapanen M, Hyödynmaa S. Full Monte Carlo and measurement-based overall performance assessment of improved clinical implementation of eMC algorithm with emphasis on lower energy range. Phys Med. 2016;32:801-811.

16. Varian Medical Systems. Eclipse photon and electron algorithms reference guide. Palo Alto: Varian Medical Systems; 2015.

17. Shimozato T, Kojima T, Sakamoto M, Hata Y, Sasaki K, Araki N. Evaluating the output stability of LINAC with a reference detector using 3D water phantom. Igaku Butsuri. 2012;32:176-181.

18. Khan FM, Gibbons JP. Khan's the physics of radiation therapy. Philadelphia: Lippincott Williams & Wilkins; 2014.

19. Brualla L, Palanco-Zamora R, Wittig A, Sempau J, Sauerwein W. Comparison between PENELOPE and electron Monte Carlo simulations of electron fields used in the treatment of conjunctival lymphoma. Phys Med Biol. 2009; 54:5469-5481.

20. Edimo P, Kwato Njock MG, Vynckier S. Validation of XiO Electron Monte Carlo-based calculations by measurements in a homogeneous phantom and by EGSnrc calculations in a heterogeneous phantom. Phys Med. 2013;29:631-638.