Comparison of the Sensitive Volume Response of the Three Different Cylindrical Ionization Chambers with GEANT4 Simulations Using the Concept of Output Factor

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OBJECTIVE
This study aims to contribute to the literature the broadened demonstration of energy-related and field size-related responses of three different cylindrical ionization chambers, commonly used for clinical applications of the therapeutic photon beams, using GEANT4 code.

METHODS
GEANT4 simulation of Varian TrueBeam STx was compared with the real-time measurements. The variations in the output factor (OF) measurements depending on field sizes ranging from 0.6×0.6 cm² to 30×30 cm² and photon energies of 6MV, 6MV-FFF, 10MV, 10MV-FFF, and 15MV were recorded for each chamber and compared with the GEANT4 simulations. Response of the chambers was analyzed depending on those OFs.

RESULTS
The GEANT4 simulation model was validated. All the chambers were in a good agreement within 1.5% for field sizes between 4×4 cm² and 30×30 cm². The farmer chamber presented a major deviation up to 22% for the field sizes smaller than 4×4 cm². Semiflex and pinpoint chambers have an agreement within 2% and 5.5% for 3×3cm² and 2×2 cm², respectively.

CONCLUSION
The chambers evaluated in this study can be used reliably for all photon energies and field sizes between 4×4 cm² and 30×30 cm². To obtain accurate measurements for field sizes smaller than 3×3 cm², it is recommended to use detectors with a smaller sensitive volume instead of the detectors used in this study.

Keywords: Detector sensitive volume; GEANT4; Monte Carlo; output factor.
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INTRODUCTION

The output factor (OF) measurements of a medical linear accelerator are one of the most critical parameters affecting the accuracy of radiation therapy. Incorrect acquisition of this factor causes an error in the determination of the Monitor Unit (MU) therefore incorrect radiation treatment.

The OF is defined as the ratio of the adjusted electrometer readings in the non-reference condition to the measurement in the reference condition.[1] Dose profiles, percentage depth doses (PDD), and OFs should be measured using suitable detectors and techniques in all energies for varied field sizes. The selection of the appropriate detector is important, especially for the small fields, because of the detector size limitation that causes lateral charge particle disequilibrium.[2,3]

For many years, researchers have focused on measurements and reducing the uncertainties of OFs. Thus, various methods have been proposed over time. Besides the experimental methods, Monte Carlo (MC) simulation is a useful and reliable method for investigating the variables effecting the calculation of the OFs. The characterizations of the different detectors were evaluated for small cone or square fields using the MC method in the literature.[3–5] Furthermore, the modeling of detector sizes and materials has been examined. In a previous study by Haryanto et al.[4] four different materials were used to simulate sensitive volumes of detectors to show the detector reaction during dose deposition due to their sensitive materials. In addition, 1 mm and 5 mm voxel sizes were chosen to model the size of the detectors. The authors of the study have reported that a good agreement was obtained between the measured and the calculated OFs for 6 MV photon beam energy by ignoring the effects of the voxel size and the material of the detector for the field sizes larger than 1×1 cm². [4] In another study that the OFs of MC and real-time measurement have been compared for FFF beams, Cheng et al.[3] simulated and calculated the OFs with the voxel sizes of 0.25 mm and 0.5 mm for the conical fields of 4 mm and 5 mm. The differences have been reported as smaller than 1%. It has been expressed that there is no volume-averaging effect between different voxel sizes for MC simulations. In some other studies, OFs have been investigated for square and rectangular fields with various widths and lengths. In these studies, the authors found that the OF differences between the MC simulations and the real-time measurements were within 1.5% for the field sizes varying from 4×4 cm² to 40×40 cm². It is also indicated that photon OFs can be predicted accurately using the MC method.[6]

In the literature, EGS/BEAMnrc, PENELOPE, and MCNP codes were frequently used to obtain the OFs, PDDs, or dose profiles.[4–7] The small number of GEANT4 studies have been published, in contrast to other MC codes, motivated this study was done. This study aims to widely demonstrate the energy and field size-related differences between cylindrical ionization chambers commonly used in the clinical applications of the radiation therapy to avoid inaccurate measurement of the OFs. The OFs were calculated by using GEANT4 simulations for five different photon beams with the field sizes ranging from 0.6x0.6 cm² to 30x30 cm². OFs calculated by GEANT4 simulations were compared to those OFs measured by three different cylindrical ionization chambers with the Varian Truebeam STx treatment machine. The cylindrical ionization chambers, which are commonly preferred in clinical applications of point dose measurements, were particularly chosen. Besides the studies that have been investigated in the literature, an extended investigation of the OF comparisons for both flattened (6 MV, 10 MV, 15 MV) and flattening filter-free (6 MV, 10 MV) beams were reported in means of this study. GEANT4 (for Geometry And Tracking),[8] which has been developed for use in CERN (Conseil Européen pour la Recherche Nucléaire) applications, was preferred for MC simulations throughout the study.

The validation of GEANT4 simulations was performed within a good agreement by comparing calculated and measured PDDs, inplane, and crossplane profiles. The energy and the field size-related responses of three different cylindrical ionization chambers were examined for the varied energies and the field sizes that declared above and the results are reported in this study.

MATERIALS AND METHODS

We note that this study does not aim to find correction factors required to use in small field dosimetry. The goal is that making contribution to the literature-expanded assessment of energy and field size-related responses of the most common detector types frequently used in radiation therapy by means of GEANT4.

Treatment Unit

The real-time measurements were performed on a Varian TrueBeam STx medical linear accelerator (Varian Medical Systems, Palo Alto, CA) with commissioned X-ray beams of 6 MV, 6 MV-FFF (Flattening Filter Free), 10 MV, 10 MV-FFF, and 15 MV. The accelerator collimator contains 2 pairs of Jaws made by using tungsten alloy (95% W, T-21014, class 3) in X and Y dimensions and a High Definition (HD) 120 Multi-Leaf Collimator (MLC), which consisting of 120 pairs of tungsten alloy (95% W, T-21014, class 3) leaves. The outer leaves of HD 120 MLC have 14 pairs on either

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Table 1 Basic specification of ionization chamber detectors used in this study

Commercial model	Detector type	Chamber-sensitive material	Chamber-sensitive dimensions (mm)	Volume (cm³)	Maximum dose per pulse	Wall of chamber material
PTW 30013	Farmer ion chamber	Air	Radius: 3.05 Length: 23 Total wall: 0.565	0.600	≥99.5% saturation for 0.46 mGy	PMMA & graphite
PTW 34010	Semiflex ion chamber	Air	Radius: 2.75 Length: 6.5 Total wall: 0.780	0.125	≥99.5% saturation for 0.5 mGy	PMMA & graphite
PTW 31006	Pinpoint ion chamber	Air	Radius: 1 mm Length: 5 mm Total wall: 0.850	0.015	≥99.5% saturation for 4.8 mGy	PMMA & graphite

Table 2 $FWHM_{min}$ of ionization chamber detectors used in this study

Photon energy	$FWHM_{min}$ cone area (PTW 30013)	$FWHM_{min}$ square field size (PTW 30013)	$FWHM_{min}$ cone area (PTW 34010)	$FWHM_{min}$ square field size (PTW 34010)	$FWHM_{min}$ cone area (PTW 31006)	$FWHM_{min}$ square field size (PTW 31006)
6X	18.15 cm²	4.3 cm	7.93 cm²	2.8 cm	7.24 cm²	2.7 cm
6X FFF	13.99 cm²	3.7 cm	5.28 cm²	2.3 cm	4.71 cm²	2.2 cm
10X	28.23 cm²	5.3 cm	14.98 cm²	3.9 cm	14.01 cm²	3.7 cm
10X FFF	23.41 cm²	4.8 cm	11.53 cm²	3.4 cm	10.68 cm²	3.3 cm
15X	31.97 cm²	5.7 cm	17.73 cm²	4.2 cm	16.68 cm²	4.1 cm

side with 5 mm-projected width on the isocenter. The HD 120 MLC has central leaves of 32 pairs with 2.5 mm-projected width on the isocenter. The collimator can be adjusted with the variable width over field sizes of 22×40 cm² and 40×40 cm² with and without HD 120 MLC, respectively.

Detectors

Three different cylindrical ionization chambers, which are 0.6 cc Farmer (PTW 30013, Germany), 0.125 cc Semiflex (PTW 34010, Germany), and 0.015 cc PinPoint (PTW 31006, Germany) were used. The basic characteristics of the ionization chambers are shown in Table 1. The readings were obtained using PTW Unidos Webline electrometer at +400 V. All ionization chambers were calibrated with electrometer by the Secondary Standards Dosimetry Laboratory. Water equivalent RW3 slab phantoms (Sun Nuclear RW3 (Goettingen White Water)) with dimensions of 30x30x1 cm³ and motorized remote-controlled 3D water phantom (PTW MP3 Water Phantom) were used for the acquisition of the real-time measurements.

The lack of lateral charged particle equilibrium (r_{LCPE}) is induced If the full width-half maximum or the radius of the photon beam is smaller than the maxi-

mum range of secondary electrons that have to contributed to dose deposition.[9] A formula explained in the International Atomic Energy Agency (IAEA) Technical Reports Series (TRS) No.483 defines the relationship between photon energy and r_{LCPE} in small-field dosimetry. The minimum field sizes that the cylindrical ionization chambers used in this study can be used to measure the dose deposition without the need for any correction are tabulated in Table 2. The calculated square fields given in Table 2 were at source-axis distance of 100 cm.

The OF Measurements

The point doses were acquired on a Varian TrueBeam STx medical linear accelerator with 6 MV, 6 MV-FFF, 10 MV, 10 MV-FFF, and 15 MV. Real-time measurements were performed in water-equivalent slab phantoms at a depth of 10 cm on the central axis (CAX) of the field sizes with source-surface (phantom surface) distance (SSD) of 100 cm by delivering 100 MU. The orientation of the ionization chambers was perpendicular to the CAX. During these measurements of OFs, Varian TrueBeam STx medical linear accelerator was operated at Dose Rate (DR) of 400 MU/min. As described in IAEA TRS No. 398, a depth of 10 cm is
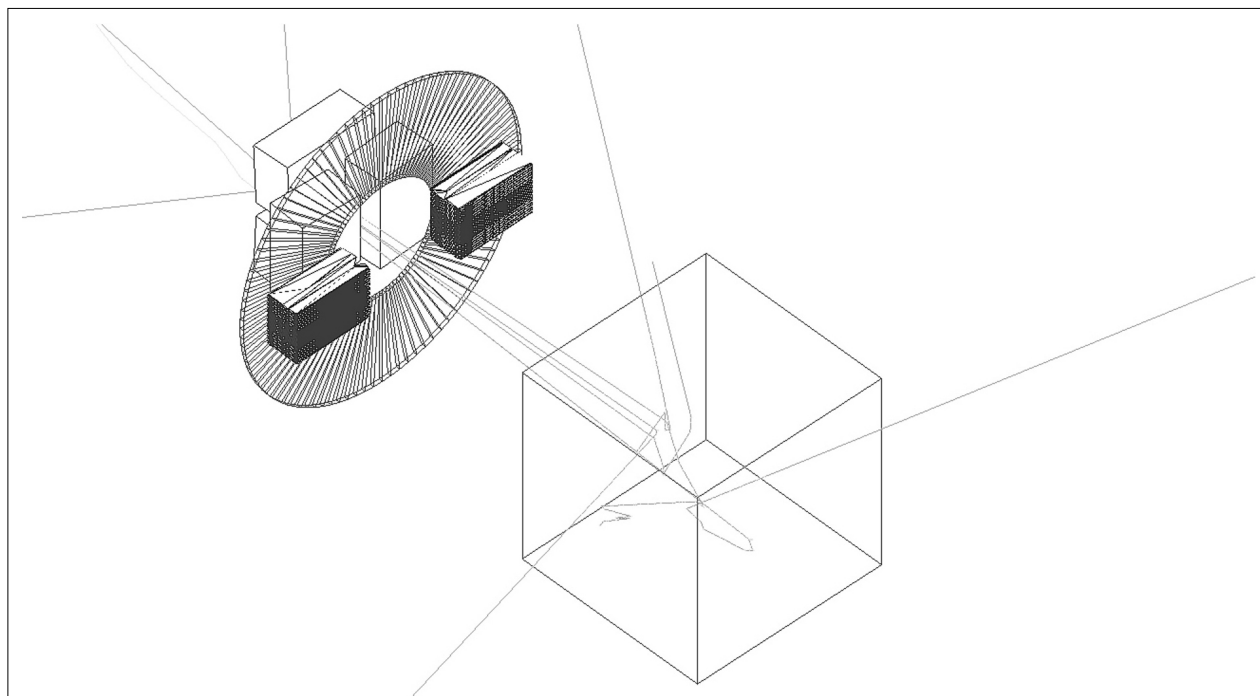
Fig. 1. The simulation geometry in GEANT4.

recommended, particularly to eliminate the contamination of secondary electrons from collimators of the linear accelerator.[1] The varied field sizes adjusted by X-Y jaws of 0.6×0.6, 1×1, 2×2, 3×3, 4×4, 5×5, 8×8, 10×10, 15×15, 20×20, 25×25, and 30×30 cm² projected on the isocenter were used for 6 MV, 6 MV-FFF, 10 MV, 10 MV-FFF, and 15 MV, respectively. The HD 120 MLC was retracted to the park position during the data acquisition. Farmer, semiflex, and pinpoint ionization chambers operated at +400 V were used in real-time measurements. The acquired data of point doses were normalized to readings of 10×10 cm² for all energies separately to determine OFs.

Monte Carlo Simulations

GEANT4 simulation application based on the MC algorithm and C++ programming language was used to model the Varian TrueBeam STx medical linear accelerator. GEANT4 is a toolkit used for simulating the passage of particles through matter that includes all the functionalities such as building complex geometry, expanded physics models, tracking, and hits. It has been used in applications related to particle physics, nuclear physics, accelerator design, space engineering, and medical physics. Many medical physicists working on particle interactions use GEANT4 simulation application for complex geometry design and suitable physics list selection. In GEANT4, there are diverse physics

models on the interactions of particles with the matter with a broad energy range.[10]

The simulation was performed on Linux CentOS version 7 using the GEANT4 v.10.7.2 application built on C++ advanced programming language. The computer that consists of Intel® Xeon E5-2630 v3 processor, 32 GB RAM was used in MC calculations. Through the GEANT4 multi-thread feature, 32 threads of CPU were run in parallel during the MC simulations.

IAEA formatted phase-space files[11] produced by Varian Medical Systems[12] using GEANT4 were used as the generator of photon beams of 6 MV, 6 MV-FFF, 10 MV, 10 MV-FFF, and 15 MV. Photons, electrons, and positrons used in phase-space were scored on a planar surface with 6.5×6.5 cm² at 26.7 cm below the source. The field size of phase space projected on isocenter was 48.6×48.6 cm². Many phase-space files were merged to avoid latent variance problem and also to obtain better statistics on the particle distribution.[13,14] A total of 36.9×10⁹, 26.6×10⁹, 21.3×10⁹, 13.3×10⁹, and 24.6×10⁹ original histories were simulated for 6 MV, 6 MV-FFF, 10 MV, 10 MV-FFF, and 15 MV, respectively.

The X-Y Jaws, HD 120 MLCs, Baseplate, and water phantom were modeled below the phase-space. The simulated materials of the accelerator and the phantom used in GEANT4 were provided by the National Institute of Standards and Technology. The geometric dimensions and the positions of the X-Y Jaws, HD
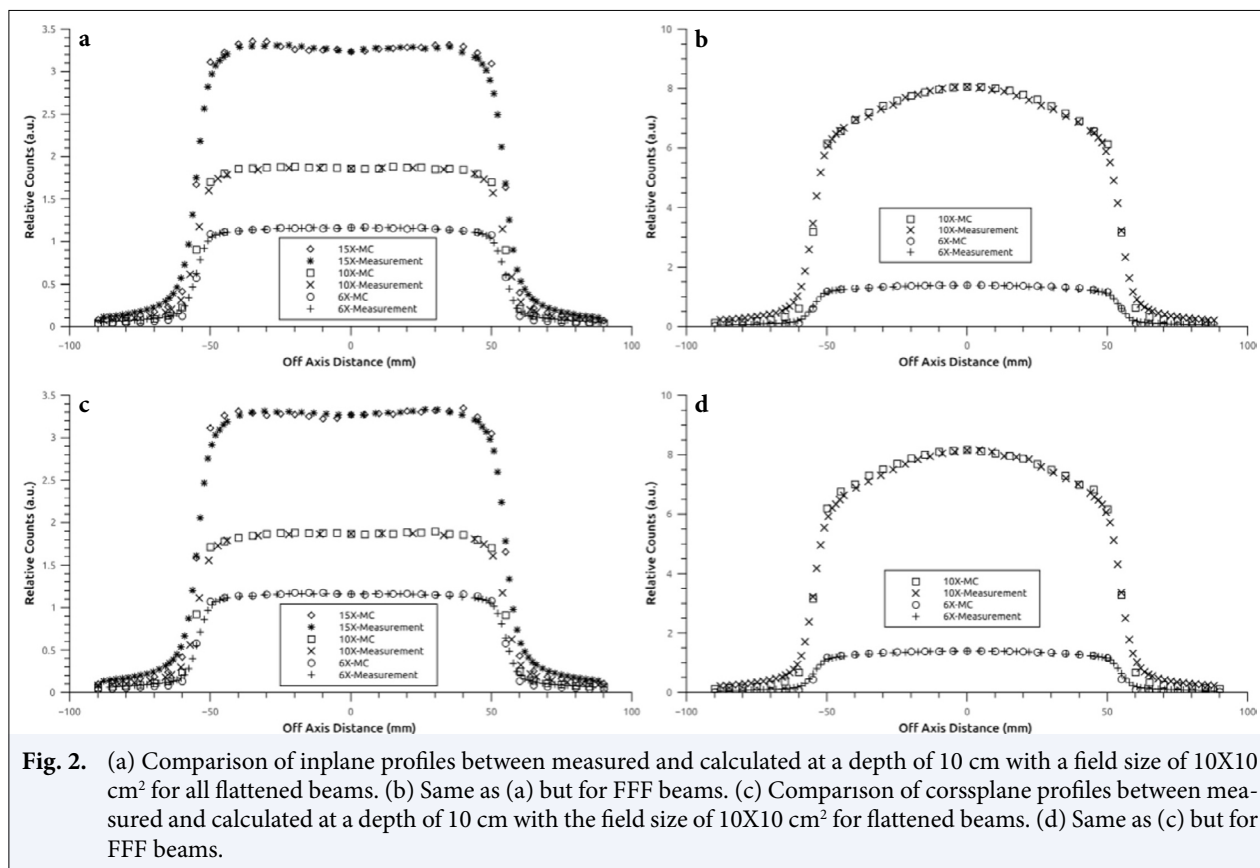
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Fig. 2. (a) Comparison of inplane profiles between measured and calculated at a depth of 10 cm with a field size of 10X10 cm² for all flattened beams. (b) Same as (a) but for FFF beams. (c) Comparıson of corssplane profiles between measured and calculated at a depth of 10 cm with the field size of 10X10 cm² for flattened beams. (d) Same as (c) but for FFF beams.

Table 3 Set-cut values of range and energy for simulated materials

Simulated material	Range cuts			Energy cuts		
	Gamma (γ)	Electron (e⁻)	Positron (e⁺)	Gamma (γ)	Electron (e⁻)	Positron (e⁺)
Air	1 mm	1 mm	1 mm	990 eV	990 eV	990 eV
Wolfram (MLC) (95%)	1 mm	1 mm	1 mm	104.618 keV	2.145 MeV	1.992 MeV
Wolfram (Jaws) (95%)	1 mm	1 mm	1 mm	106.569 keV	2.309 MeV	2.130 MeV
Water	1 mm	1 mm	1 mm	2.940 keV	351.877 keV	342.545 keV

MLC: Multi-leaf collimator

120 MLCs, and Baseplate were obtained from Varian Medical Systems. Varian Medical Systems also provided the movement trajectory of X-Y Jaws and MLCs. The 3D water phantom modeled at the dimensions of 40×40×40 cm³ was placed at the SSD of 100 cm. The general design of the accelerator used in this GEANT4 study is shown in Figure 1.

The G4EmStandardPhysics (Option 4) electromagnetic physics package that consists of many particles (photons, electrons, positrons, etc.) was used utilizing GEANT4 electromagnetic physics library. G4EmStandardPhysics (Option 4) is the most accurate elec-

tromagnetic physics package in terms of the particle energies used in this study. The set-cut values defined by GEANT4 as default were used and these values are tabulated in Table 3. During the GEANT4 simulations, "HepJamesRandom" pseudo-random number generator[15] was used to choose which particle to be consecutively produced. No variance reduction techniques were used in this study.

The 3D water phantom designed in the simulation was divided into voxels of 5×5×5 mm³ and 1×1×5 mm³ as mesh structures. The voxel size of 5×5×5 mm³ was chosen due to Semiflex's sensitive volume size for the
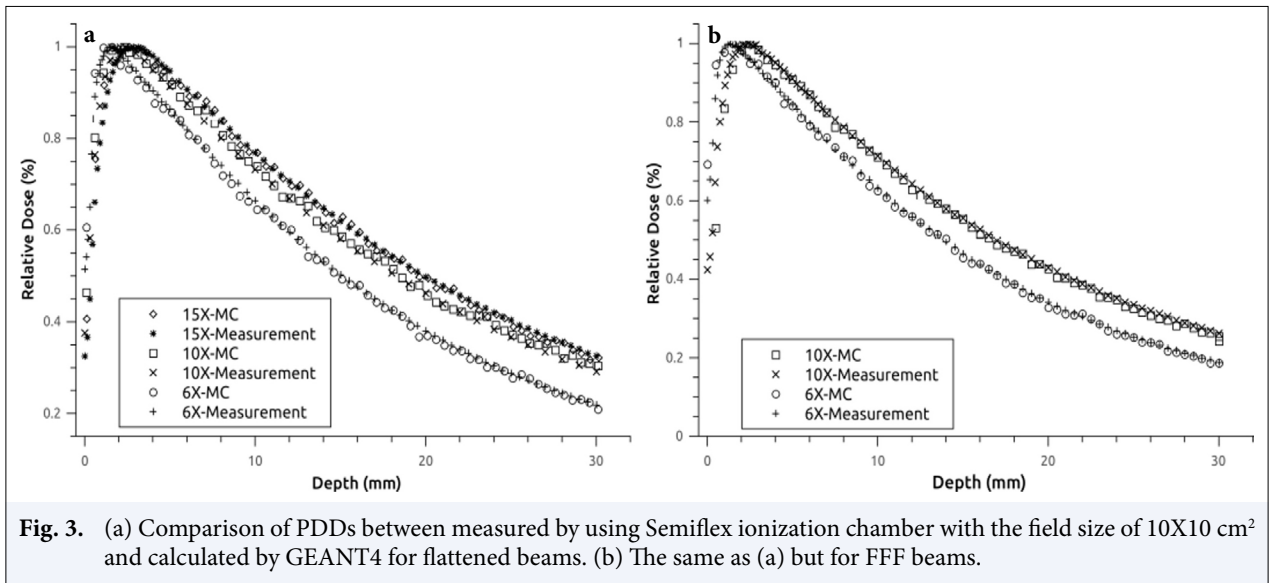
Fig. 3. (a) Comparison of PDDs between measured by using Semiflex ionization chamber with the field size of 10X10 cm^2 and calculated by GEANT4 for flattened beams. (b) The same as (a) but for FFF beams.
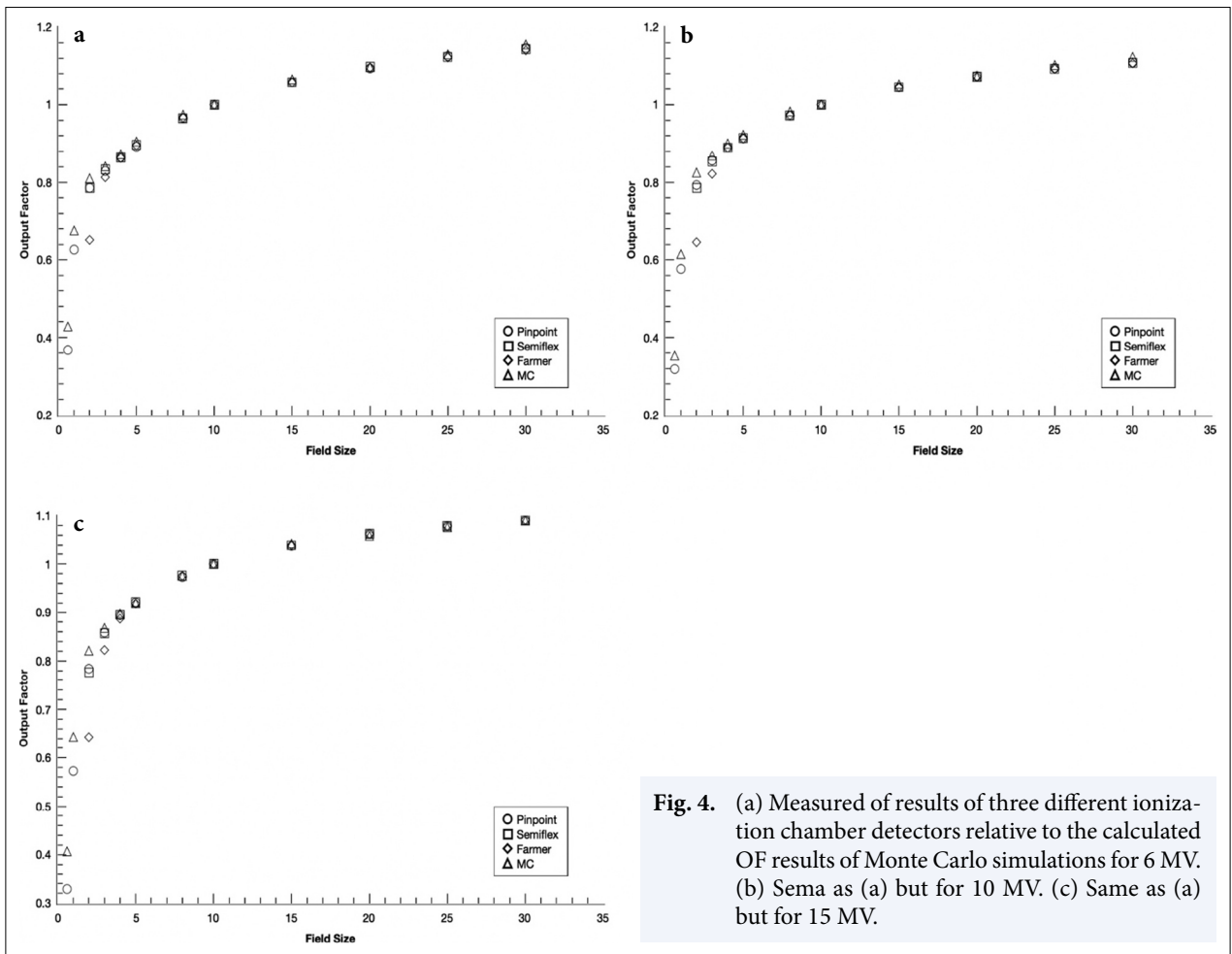
Fig. 4. (a) Measured of results of three different ionization chamber detectors relative to the calculated OF results of Monte Carlo simulations for 6 MV. (b) Sema as (a) but for 10 MV. (c) Same as (a) but for 15 MV.

validation of the simulation model. The voxel size of 1×1×5 mm^3 mesh geometry was used for the calcula-

tions of the OFs. Dose scoring was performed in the medium of water. Primitive dose scorers were assigned

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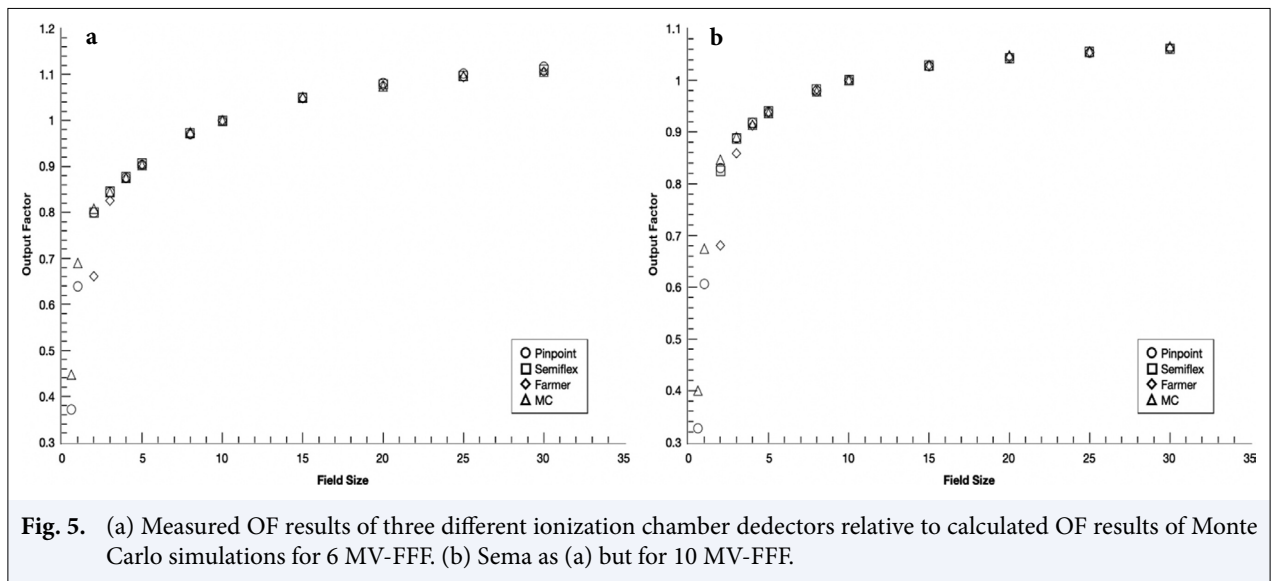A Monte Carlo Study: Ionization Chamber Comparisons Using the Concept of Output Factor

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Fig. 5. (a) Measured OF results of three different ionization chamber dedectors relative to calculated OF results of Monte Carlo simulations for 6 MV-FFF. (b) Sema as (a) but for 10 MV-FFF.

to these meshes to store the dose deposition released by the particles. The dose deposition scored by primitive scorers was printed out as the format of 3D dose and analyzed using in-house codes written in Matlab.[16]

RESULTS

Verification of Monte Carlo Simulations

GEANT4 simulations were performed by defining variable field sizes for all energies to validate the simulation model of the Varian TrueBeam STx with actual measurements. Voxelized 3D water phantom was used to acquire PDDs, inplane, and crossplane profiles for the validation of the GEANT4 simulation model. The 3D water phantom and semifex ionization chamber were used to verify PDDs, inplane, and crossplane profiles of 6 MV, 6 MV-FFF, 10 MV, 10 MV-FFF, and 15 MV with MC calculations. Verification of the dose profiles was done by field size of 10×10 cm² at a depth of 10 cm with SSD of 100 cm. PDD validations were accomplished with a field size of 10×10 cm².

Figure 2 shows comparisons between calculated and measured profiles at a depth of 10 cm with a field size of 10×10 cm². Calculated values were normalized to the CAX and D_{max} of measured profiles of inplane-crossplane and PDD, respectively. The Trapezoidal Rule technique was used to calculate percentage differences between calculated and measured inplane-crossplane and PDD profiles. inplane and crossplane profiles measured by the Semiflex ionization chamber in the 3D water phantom were agreed well with profiles calculated by GEANT4.

The maximum differences of 1.4%, 1.5%, 0.5%, 0.8%, and 0.8% were achieved between the calculated and measured profiles of inplane-crossplane of 6 MV, 6 MV-FFF, 10 MV, 10 MV-FFF, and 15 MV, respectively. The largest deviation of agreement between calculated and measured profiles was at the penumbra (80–20%) and end of the penumbra regions (<20%). The sharpness of the real-time inplane-crossplane profiles might be lost at the edge of the field sizes due to Semiflex air cavity volume and its continuous collection during data acquisition. Also, the real-time measurements were affected by different factors, namely the disturbance in the electron transportation within the detector, the energy and DR dependencies of the detector, and the finite size of the detector.[17]

PDDs calculated by GEANT4 were in 0.9%, 0.1%, 0.7%, 0.7%, and 0.05% agreement with PDDs measured by Semiflex with the field size of 10×10 cm² for 6 MV, 6 MV-FFF, 10 MV, 10 MV-FFF, and 15 MV, respectively. Tissue–Phantom Ratio (TPR$_{20,10}$) was calculated to determine the quality of energy differences between the measured and calculated. TPR$_{20,10}$ values calculated by GEANT4 were in 0.7%, 0.6%, 1.3%, 0.6%, and 1.2% agreement with the field size of 10x10 cm² for 6 MV, 6 MV-FFF, 10 MV, 10 MV-FFF, and 15 MV, respectively. The comparison of PDDs can be seen in Figure 3.

As shown in Figures 2 and 3, the comparison results of PDDs, inplane, and crossplane profiles show that the phase-space data and the simulation model of the Varian TrueBeam STx machine used in the GEANT4 simulation are consistent with the actual Varian TrueBeam STx machine used in this study.
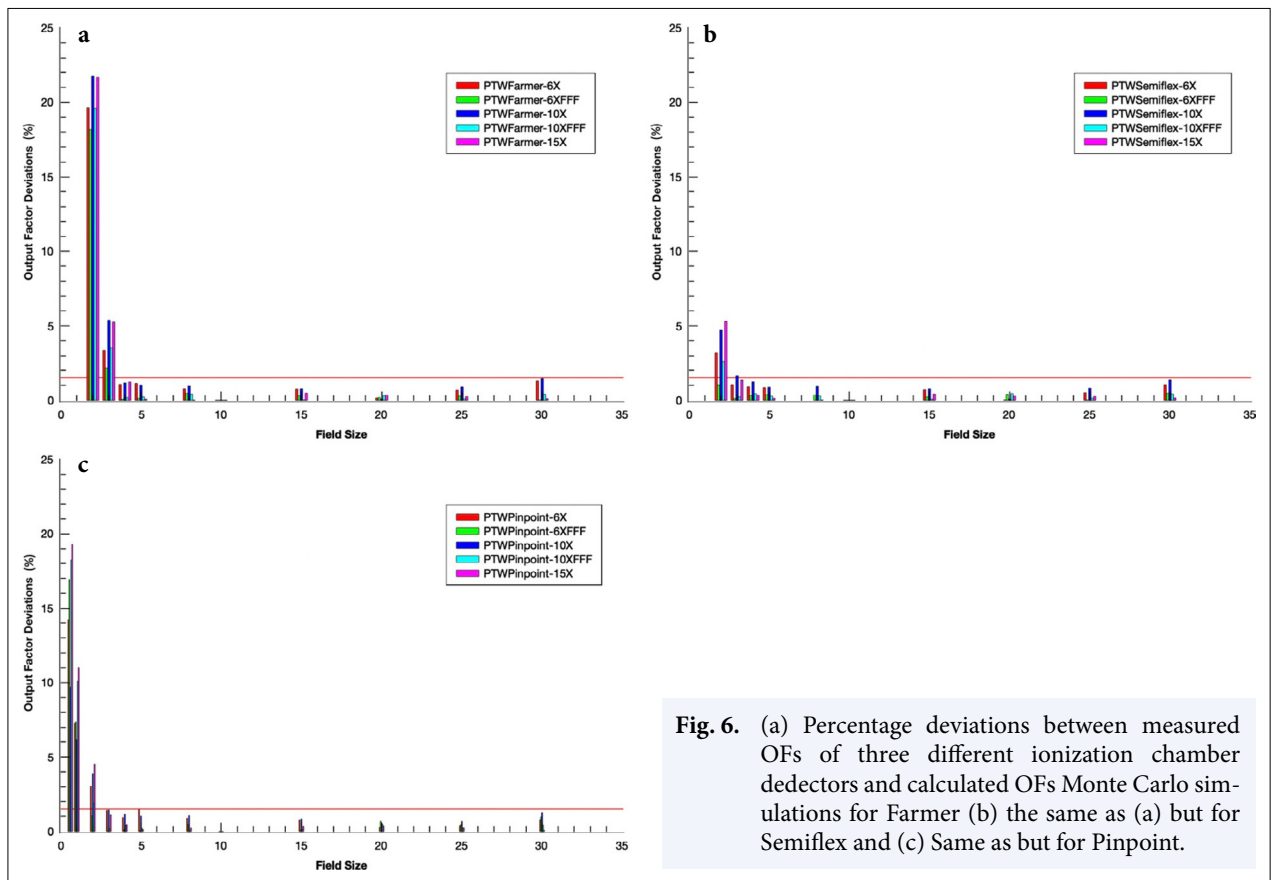
Fig. 6. (a) Percentage deviations between measured OFs of three different ionization chamber dedectors and calculated OFs Monte Carlo simulations for Farmer (b) the same as (a) but for Semiflex and (c) Same as but for Pinpoint.

Table 4 Percentage differences in measured OFs of three different ionization chambers relative to calculated OFs by GE-ANT4 for flattened beams. Here a, b, and c stand for Farmer, Semiflex, and Pinpoint, respectively

Field sizes (cm)	6 MV			10 MV			15 MV		
	a)	b)	c)	a)	b)	c)	a)	b)	c)
0.6			14.21			9.69			19.28
1			7.26			6.16			11
2	19.63	3.19	3.04	21.78	4.74	3.89	21.70	5.31	4.53
3	3.34	1.06	1.42	5.39	1.67	1.45	5.26	1.37	1.11
4	1.07	0.90	0.93	1.18	1.25	1.17	1.23	0.35	0.44
5	1.14	0.84	1.47	1.02	0.88	1.03	0.07	0.13	0.14
8	0.76	0.85	0.88	0.97	0.93	1.06	0.00	0.01	0.24
10	0	0	0	0	0	0	0	0	0
15	0.75	0.72	0.78	0.77	0.76	0.83	0.49	0.42	0.34
20	0.16	0.02	0.28	0.08	0.09	0.18	0.35	0.28	0.35
25	0.69	0.52	0.38	0.89	0.80	0.70	0.24	0.26	0.25
30	1.31	1.06	0.79	1.45	1.38	1.28	0.11	0.16	0.09

OF: Output factor

Comparison of the OFs

The comparison results of OFs between measured by three different ionization chambers and calculated by GEANT4 simulations are shown in Figures 4 and 5. The results are also shown in Tables 4 and 5 as tabulated. In addition, OFs and the statistical errors in the GEANT4 simulations are given in Tables 6 and 7 as tabulated. The relative deviations in the OF mea-

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Table 5 Percentage differences in measured OFs of three different ionization chambers relative to calculated OFs by GE-ANT4 for FFF beams. Here a, b, and c stand for Farmer, Semiflex, and Pinpoint, respectively

Field sizes (cm)	6 MV-FFF			10 MV-FFF		
	a)	b)	c)	a)	b)	c)
0.6			16.94			18.24
1			7.34			10.11
2	18.17	1.04	1.03	19.58	2.60	1.89
3	2.15	0.12	0.04	3.54	0.22	0.18
4	0.07	0.32	0.10	0.17	0.44	0.39
5	0.13	0.38	0.06	0.22	0.29	0.22
8	0.47	0.36	0.44	0.42	0.29	0.03
10	0	0	0	0	0	0
15	0.30	0.22	0.10	0.03	0.08	0.14
20	0.18	0.40	0.70	0.32	0.46	0.44
25	0.30	0.02	0.42	0.10	0.14	0.22
30	0.02	0.48	0.96	0.41	0.43	0.41

OF: Output factor

surements for the field sizes between 4×4 cm² and 30×30 cm² present good agreement within 1.5%. The Farmer ionization chamber had the maximum deviation of 5.5% and 22% for the field sizes of 3×3 cm² and 2×2 cm², respectively. Semiflex and Pinpoint ionization chambers were in the agreement within 2% and 5.5% for 3×3 cm² and 2×2 cm², respectively. Pinpoint ionization chamber was kept using to acquire dose deposition for smaller fields than 2x2 cm² due to its smaller sensitive volume and its results had the deviations of 11% and 19% at field sizes of 1×1 cm² and 0.6×0.6 cm², respectively. The number of the relative deviations of the OFs of the ionization chambers can be seen in Figure 6.

DISCUSSION AND CONCLUSION

A geometrical model of a Varian TrueBeam STx medical linear accelerator has been designed by using GEANT4 simulation software and validated by comparing differences between calculated PDDs and profiles with the real-time measurements. The calculated OFs were compared with three different cylindrical ionization chambers to investigate detector's responses depending on the field size and photon beam energy. This study yields that it is important to pay attention to detector selection. The three different sizes of detectors used in this study were particularly selected because they are most basic chamber types frequently preferred by the users. These detectors to be used to obtain OFs should be selected properly.

It is known that the lack of lateral electronic equilibrium can cause errors in dose measurements, especially for the fields smaller than the sensitive volume of the detector. As Tyler et al.[18] and Azangwe et al.[19] reported that if the ionization chamber size is larger than the uniform region of the field size, the underestimation of the dose at the center of the axis of the beam is measured with differences up to 20–30% due to the detector size. The results declared in this study for the fields smaller than 4×4 cm² show that the percentage differences in OFs between measured and calculated increase up to 22% regarding sensitive volume of the ionization chamber.

Haryanto et al.[4] reported that the Pinpoint ionization chamber detector reads a slightly higher dose due to over-response of this detector to low-energy scatter for the larger field sizes. Martens et al.[20] also present that the Pinpoint ionization chamber has an unwanted signal that can be increased as large as 2.5% at CAX because of irradiated cable length. Nevertheless, no such an impact of the Pinpoint detector was observed in this study.

The formula expressed in IAEA TRS No.483 leads us to the minimum square fields regarding the photon energy are required without loss of LCPE during point dose acquisition should be approximately between field sizes of 3.7×3.7 cm² – 5.7×5.7 cm², 2.3×2.3 cm² – 4.2×4.2 cm² and 2.2×2.2 cm² – 4.1×4.1 cm² for Farmer, Semiflex, and Pinpoint, respectively. However, the results in this study show that Farmer could measure dose deposition reliably until the field size of 4×4 cm²

Table 6 OFs for flattened beams. Here a, b, c and d stand for Farmer, Semiflex, Pinpoint and MC, respectively. Statistical errors of the GEANT4 Simulations are given with MC

Field sizes (cm)	6 MV a)	6 MV b)	6 MV c)	6 MV d)	10 MV a)	10 MV b)	10 MV c)	10 MV d)	15 MV a)	15 MV b)	15 MV c)	15 MV d)
0.6			0.37	0.43 (0.048)			0.32	0.35 (0.049)			0.33	0.41 (0.042)
1			0.63	0.68 (0.038)			0.58	0.61 (0.037)			0.57	0.64 (0.033)
2	0.65	0.78	0.79	0.81 (0.034)	0.65	0.79	0.79	0.83 (0.031)	0.64	0.78	0.78	0.82 (0.028)
3	0.81	0.83	0.83	0.84 (0.033)	0.82	0.85	0.86	0.87 (0.030)	0.82	0.86	0.86	0.87 (0.027)
4	0.86	0.86	0.86	0.87 (0.032)	0.89	0.89	0.89	0.90 (0.029)	0.89	0.90	0.89	0.90 (0.026)
5	0.89	0.90	0.89	0.91 (0.030)	0.91	0.91	0.91	0.92 (0.028)	0.92	0.92	0.92	0.92 (0.026)
8	0.97	0.97	0.97	0.97 (0.029)	0.97	0.97	0.97	0.98 (0.027)	0.98	0.98	0.97	0.98 (0.024)
10	1	1	1	1 (0.027)	1	1	1	1 (0.026)	1	1	1	1 (0.024)
15	1.06	1.06	1.06	1.07 (0.025)	1.04	1.04	1.04	1.05 (0.024)	1.04	1.04	1.04	1.03 (0.022)
20	1.10	1.10	1.09	1.10 (0.023)	1.07	1.07	1.07	1.07 (0.023)	1.06	1.06	1.06	1.06 (0.021)
25	1.12	1.12	1.13	1.13 (0.017)	1.09	1.09	1.09	1.10 (0.022)	1.08	1.08	1.08	1.08 (0.021)
30	1.14	1.14	1.15	1.16 (0.017)	1.11	1.11	1.11	1.12 (0.021)	1.09	1.09	1.09	1.09 (0.020)

OF: Output factor

for all photon energies. In addition, the Farmer ionization chamber can be ignored for the fields smaller than 4×4 cm^2 due to its sensitive volume. Semiflex and Pinpoint chambers could be used to measure the dose deposition until a field size of 3×3 cm^2. Nevertheless, Semiflex and Pinpoint chambers were observed to have poor performance at the field sizes smaller than 3x3 cm^2. Furthermore, the deviations in Pinpoint chamber were up to 5%, 11%, and 19% without any correction applied at field sizes of 2×2 cm^2, 1×1 cm^2, and 0.6×0.6 cm^2, respectively. Papaconstadopoulos et al.[21] found that the uncertainties of 1.3% in OFs could be observed because of the jaw-defined field sizes, particularly for small fields. Even though the uncertainties in small field OFs calculated by GEANT4 simulations in this study would be combined with the uncertainties of 1.3% caused by jaw positioning, the deviations are not small enough to use Pinpoint detector for the field sizes of 1×1 cm^2 and 0.6×0.6 cm^2 depending to photon energy. As tabulated in the Tables 4 and 5, the percentage differences in OFs increased by increasing the value of TPR$_{20,10}$. Although the correction factors tabulated in IAEA TRS No. 483 are the same for the energies of 6 MV, 6 MV-FFF, 10 MV, and 10 MV-FFF and the field sizes varied between 3×3 cm^2 and 1.5×1.5 cm^2, the results in this study show that percentage differences in OFs differ according to TPR$_{20,10}$. Therefore, it is strongly recommended to investigate the correction factor in more detail by considering the photon energy for Semiflex and Pinpoint ionization chambers if they are used during OF measurements with field sizes equal to or smaller than 3×3 cm^2.

The ionization chambers used in this study perform well within 1.5% agreement at all photon energies for the field sizes between 4×4 cm^2 and 30×30 cm^2. Moreover, Semiflex and Pinpoint chambers were in 2% agreement up to the field size of 3×3 cm^2. To obtain accurate OFs for the field sizes smaller than 3×3 cm^2 require smaller sensitive volume of detector rather than the three different cylindrical-type ionization chambers used in this study.

Limitations of This Study
The number of particles used in this study was limited. More particles are needed for use in simulations to acquire dose deposition more precisely particularly for small voxel sizes. Because the number of particles that interact in the voxel decreases with decreasing voxel size and it causes larger statistical errors in calculations.

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Table 7 OFs for FFF beams. Here a, b, c and d stand for Farmer, Semiflex, Pinpoint and MC, respectively. Statistical errors of the GEANT4 Simulations are given with MC

Field sizes (cm)	6 MV-FFF				10 MV-FFF			
	a)	b)	c)	d)	a)	b)	c)	d)
0.6			0.37	0.45 (0.036)			0.33	0.40 (0.030)
1			0.64	0.69 (0.029)			0.61	0.67 (0.023)
2	0.66	0.80	0.80	0.81 (0.026)	0.68	0.82	0.83	0.85 (0.020)
3	0.83	0.84	0.84	0.84 (0.025)	0.86	0.89	0.89	0.89 (0.019)
4	0.87	0.88	0.88	0.87 (0.024)	0.91	0.92	0.92	0.91 (0.019)
5	0.90	0.91	0.90	0.90 (0.023)	0.94	0.94	0.94	0.94 (0.018)
8	0.97	0.97	0.97	0.97 (0.021)	0.98	0.98	0.98	0.98 (0.017)
10	1	1	1	1 (0.021)	1	1	1	1 (0.017)
15	1.05	1.05	1.05	1.05 (0.019)	1.03	1.03	1.03	1.03 (0.016)
20	1.08	1.08	1.08	1.07 (0.018)	1.04	1.04	1.04	1.05 (0.015)
25	1.09	1.10	1.10	1.10 (0.017)	1.05	1.05	1.05	1.06 (0.015)
30	1.11	1.11	1.12	1.11 (0.017)	1.06	1.06	1.06	1.07 (0.015)

OF: Output factor; MC: Monte Carlo

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