Technical Note

Determination of the Small-Field Output Factor for 6 MV Photon Beam Using EGSnrc Monte Carlo

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Abstract

Accuracy of ionization chamber (IC) to measure the scatter output factor (S_{cp}) of a linear accelerator (linac) is crucial, especially in small field (<4 cm × 4 cm). The common IC volume of 0.6 cc is not adequate for small-field measurement and not all radiotherapy centers can afford to purchase additional IC due to the additional cost. This study aimed to determine the efficiency of the EGSnrc Monte Carlo (MC) to calculate the S_{cp} for various field sizes including small field in Elekta Synergy (Agility multileaf collimator) linac. The BEAMnrc and DOSXYZnrc user codes were used to simulate a 6 MV linac model for various field sizes and calculate the radiation dose output in water phantom. The modeled linac treatment head was validated by comparing the percentage depth dose (PDD), beam profile, and beam quality (Tissue Phantom Ratio $(TPR)_{20,10}$) with the IC measurement. The validated linac model was simulated to calculate the S_{cp} consisting of collimator scatter factor (S_c) and phantom scatter factor (S_p). The PDD and beam profile of the simulated field sizes were within a good agreement of ±2% compared with the measured data. The $TPR_{20,10}$ value was 0.675 for field size 10 cm × 10 cm. The S_{cp}, S_c, and S_p simulated values were close to the IC measurement within ±2% difference. The simulation for S_c and S_p in 3 cm × 3 cm field size was calculated to be 0.955 and 0.884, respectively. In conclusion, this study validated the efficiency of the MC simulation as a promising tool for the S_{cp} calculation including small-field size for linac.

Keywords: Collimator scatter factor, phantom scatter factor, linear accelerator

Received on: 16-05-2022 **Review completed on:** 04-07-2022 **Accepted on:** 20-07-2022 **Published on:** 08-11-2022

Introduction

Radiotherapy is a treatment used to cure patients with benign and malignant cancer by irradiating accurate radiation dose to the tumor while minimizing unnecessary dose to the surrounding healthy tissues and organs.[1-3] According to the International Atomic Energy Agency publication, there was a 40% curable rate globally by radiotherapy alone or in the combination with surgery or chemotherapy.[4]

The output factor (S_{cp}) is one of the important parameters in the monitor unit (MU) calculation to correct the radiation dose when the field size was changed from the reference field size, 10 cm × 10 cm.[5] The S_{cp} consists of both collimator scatter factor (S_c) and phantom scatter factor (S_p), respectively, where the S_c was measured in air, while, the S_p was measured within a water medium.[6]

The S_{cp} measurement required the usage of an ionization chamber (IC). However, there are issues such as electron contamination and lack of lateral electron equilibrium (LEE) when using the IC for S_{cp} measurement. The IC position at depth lesser than 10 cm during the S_{cp} measurement with photon energy of 6 MV causes electron contamination in the detector volume of the IC.[6-8] Meanwhile, LEE is not established while using the IC with a buildup cap that has an inadequate longitudinal and lateral thickness which is <2 cm during the S_c measurement.[9]

Apart from that, the IC measurement in the small-field size, defined as smaller than 4 cm × 4 cm, is one of the major issues in dose calculation, especially for S_{cp} measurement. Advanced treatment planning such as intensity-modulated radiotherapy, volumetric modulated radiation therapy, and stereotactic treatment requires smaller field sizes, and the inaccuracy of the

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Access this article online

Quick Response Code:

Website: www.jmp.org.in

DOI: 10.4103/jmp.jmp_40_22

How to cite this article: Chuah KW, Abdul Aziz MZ, Jayamani J. Determination of the small-field output factor for 6 MV photon beam using EGSnrc Monte Carlo. J Med Phys 2022;47:301-8.

S_{cp} measurement for the small-field size will give a high impact on the MU calculation.[10-12] There are issues such as volume averaging effect and partial source occlusion in small-field size dose measurement.[11,13,14]

Due to the issues faced during the S_{cp} measurement using the IC, Monte Carlo (MC) simulation can be an alternative way to calculate these values.[15] MC is a numerical method which simulates random walk of radiation beam transport through random number of sampling.[16] This MC simulation is a reliable tool used to model the LINAC treatment head based on the accurate and detailed information of the LINAC geometry and component materials.[17] This MC simulation was suggested to be used in the radiotherapy dose calculation as it has the equal strength as IC to calculate the dose precisely by taking into account the loss of LEE and aspects of electron and photon beam transport, especially in the small-field size and heterogeneous situation.[17,18]

Materials and Methods

Output factor measurement

In this study, Elekta Synergy (Agility multileaf collimator [MLC]) (Elekta, United Kingdom) was used to measure the S_{cp} using IC (PTW-Freiburg, Semiflex IC 31010, sensitive volume of 0.125 cm^3). The S_{cp} was measured for field sizes: 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm in a water phantom (30 cm × 30 cm × 30 cm). The S_{cp} was measured using source-to-surface distance (SSD) of 90 cm on the water phantom and the IC was positioned at 10 cm depth in the water phantom, as shown in Figure 1a. The dose at arbitrary field sizes was normalized to the dose at the reference field size (10 cm × 10 cm) to obtain the S_{cp} value, as shown in Equation 1:

$$S_{cp} = \frac{D_{(water,FS)}}{D_{(water,FS_{ref})}} \qquad \text{(Eq. 1)}$$

where $D_{(water,\ FS)}$ is the dose in arbitrary field size and $D_{(water,\ FSref)}$ is the dose for the reference field size of 10 cm × 10 cm in a water phantom.

Followed by the total scatter (S_{cp}) measurement, the S_c was measured in air by placing the IC together with a 3 mm thickness of acrylic buildup cap at source-to-axis distance of 100 cm, as shown in Figure 1b. The dose at arbitrary field sizes was normalized to the dose at the reference field size, 10 cm × 10 cm to obtain the S_c value, as shown in Equation 2:

$$S_c = \frac{D_{(air,FS)}}{D_{(air,FS_{ref})}} \qquad \text{(Eq. 2)}$$

where $D_{(air,\ FS)}$ is the dose in arbitrary field size and $D_{(air,\ FSref)}$ is the dose for the reference field size of 10 cm × 10 cm in air. Meanwhile, the S_p was determined by dividing the measured S_{cp} with the measured S_c, as shown in Equation 3:

$$S_p = \frac{S_{cp}}{S_c} \qquad \text{(Eq. 3)}$$

The S_{cp}, S_c, and S_p measurements were not performed for the small-field sizes due to limitation of the IC measurement in small field. These measured data were used to validate the simulation outcome.

Linear accelerator modeling using BEAMnrc/EGSnrc

A BEAMnrc/EGSnrc code was used to model the Elekta Synergy (Agility MLC) linac in this study. The LINAC treatment head was modeled based on the technical data and information provided by the manufacturer (Elekta, United Kingdom) with a nondisclosure agreement (NDA) before beginning this study. A total of 9 component modules were used for modeling the linac, and Figure 2 shows the schematic diagram of the simulated linac model. The 700icru. pegsdat file (ASCII text) was used for this simulation, and this file consists of the mass density, atomic number, and electron density of all the materials used in the LINAC model. The field sizes required for the S_{cp} calculation process including 3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm were defined in the BEAMnrc/EGSnrc by adjusting the MLC and jaw position.

This simulation process was run using the initial particle histories of 1 × 10^9 particles, and the phase-space file was positioned at 100 cm from the source to equal the linac beam data measurement setup for the IC measurement. The global electron cutoff (ECUT) and global photon cutoff energy (PCUT) were 0.7 MeV and 0.01 MeV, respectively. The incident electron kinetic energy and FWHM applied were 6.4 MeV and 1 mm, respectively, referring to previous publication.[19] The information about the particle histories including the particle's position, direction, and energy was stored in the phase-space file after the simulation process in BEAMnrc/EGSnrc was completed. Each field size produces a Phase-space file to analyze the S_c, S_{cp} values.

The BEAMDP user code was used to analyze the simulated outcome by using this phase-space file. The particle distribution from the phase-space file of BEAMnrc/EGSnrc in this study was analyzed in X-Y scatter plot option in BEAMDP. The scatter plot was used to validate the field size opening in the modeled linac before proceeding with the dose calculation using DOSXYZnrc/EGSnrc. The spectral distribution from the phase-space file of BEAMnrc/EGSnrc in this study was analyzed in spectral distribution from phase-space data option in BEAMDP.

Dose calculation in DOSXYZnrc/EGSnrc

The phase-space file generated from the BEAMnrc/EGSnrc simulation was used as an input to calculate the dose distribution in a 3D voxelized water phantom in DOSXYZnrc/EGSnrc. The DOSXYZnrc/EGSnrc was used to calculate the 3D absorbed dose distribution for different field sizes in a Cartesian coordinate of virtual water phantom. The water phantom of 30 cm × 30 cm × 30 cm with each voxel size of

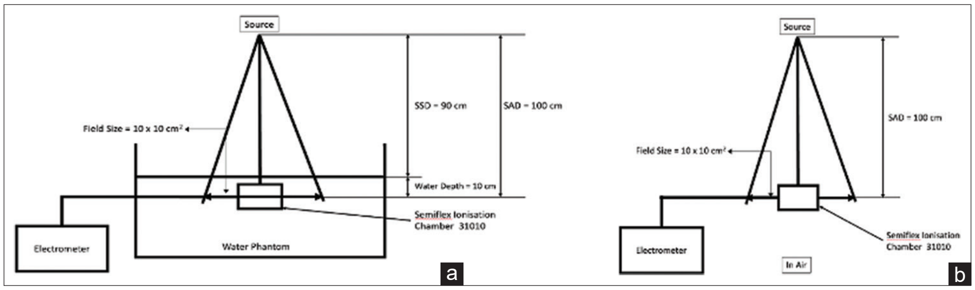

Figure 1: The water phantom and IC positioning for the (a) S_{cp} in water phantom at SAD 100 cm and (b) Sc in air at SAD 100 cm. SAD: Source-to-axis distance, S_c: Collimator scatter factor, S_{cp}: Scatter output factors, IC: Ionization chamber

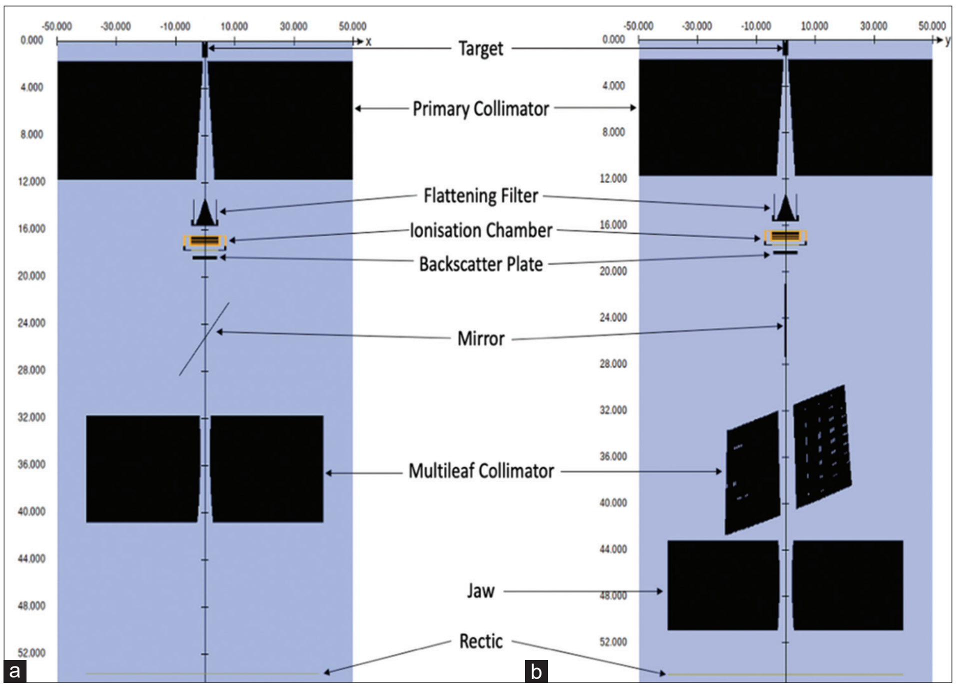

Figure 2: Modeled linac in BEAMnrc/EGSnrc: (a) XZ view, (b) YZ view. linac: Linear accelerator

0.3 cm × 0.3 cm × 0.1 cm, density of 1 g/cm^3, and 700icru. pegsdat file of H2O700ICRU was used in this study. The water phantom was positioned under the linac treatment head at the central axis with the SSD of 100 cm. The x-axis of the water phantom was used to define cross-plane profile, and the y-axis to define in-plane profile, respectively.

The particle histories of 6 × 10^7 particles were applied during this simulation process. The input parameter isource 2 (phase-space source incident from any direction) was applied in DOSXYZnrc/EGSnrc code. The ECUT and PCUT applied were 0.7 MeV and 0.01 MeV, respectively. Photon splitting of 100 and particle recycling of 3 were applied in this simulation and MC simulation for the PDD, beam profile and $TPR_{20,10}$.

LINAC Model Validation

The dose distribution from XZ, YZ, and XY views was retrieved from the STATDOSE application (in-built code in EGSnrc) to plot profile along the simulated particles for each field sizes in water medium. The simulated LINAC model was validated by compare the measured IC readings for PDD, beam profile and TPR 20,10 for the field size 10 cm x 10 cm (TRS 398) and followed the same procedure to validate the field size of 3 cm x 3 cm , 5 cm x 5 cm, 15 cm x 15 cm and 20 cm x 20 cm , respectively. The deviation between the measured data using IC with the calculated data using MC simulation was calculated by using the following equation:

$$Percentage\,difference(\%) = \frac{D_{MC} - D_{IC}}{D_{IC}} \times 100\% \qquad \text{(Eq. 4)}$$

where D_{MC} is the MC simulated dose and D_{IC} is the dose measurement by the IC. The LINAC model was validated by calculate the percentage difference between the IC measured and MC simulation for the PDD, beam profile and TPR20,10. The AAPM TG -105 protocol proposed the tolerance range of < 2% difference between the IC and MC readings.[11]

Calculation of output factor using DOSXYZnrc/EGSnrc

The validated linac model was used to calculate the S_{cp} in the DOSXYZnrc/EGSnrc. The same parameters were used in BEAMnrc/EGSnrc except for the phase-space file position was changed to 90 cm from the source to match the Scp setup for the IC measurement. Furthermore, the same parameters were used in DOSXYZnrc/EGSnrc except for the distance from the phase-space file to isocenter was changed to 10 cm depth. The S_{cp} for 3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm field sizes was simulated in the DOSXYZnrc/EGSnrc and was calculated by using Equation 1.

Calculation of collimator scatter factor using DOSXYZnrc/EGSnrc

The validated linac model was used to perform the S_c calculation in DOSXYZnrc/EGSnrc. The same parameters were used in BEAMnrc/EGSnrc, and the phase-space file position remained at 100 cm from the source to equal the S_c setup for IC measurement. The same parameters were used in DOSXYZnrc/EGSnrc except for the water phantom that was replaced by air (density of 0.001 g/cm3 and 700icru. pegsdat file of AIR700ICRU). The S_c for 3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm field sizes was simulated in the DOSXYZnrc/EGSnrc and was being calculated using Equation 2.

Calculation of phantom scatter factor using DOSXYZnrc/EGSnrc

The S_p was calculated after simulation for S_{cp} and S_c by using Equation 3. The S_p for 3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm field sizes were determined in the MC simulation.

Output factor validation in Monte Carlo simulation

The percentage difference between the measured data using IC and the calculated data using EGSnrc MC simulation for S_{cp}, S_c, and S_p was calculated by using Equation 4. The percentage difference of S_{cp}, S_c, and S_p for the field sizes 3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm was calculated. A good agreement between the measured and calculated data within the tolerance range of ±2% needs to be achieved.

Results and Discussions

LINAC model validation

The field size of the modeled LINAC was validated by the spectral distribution and X-Y scatter plot in the BEAMDP code using the phase-space file for field size of 10 cm × 10 cm. Figure 3a shows the spectral distribution from the modeled linac where the number of fluence simulated in this work adequate to run the simulation for work for 6 MV photon beam. Meanwhile Figure 3b shows the scatter distribution of 6 MV photon beam for the field size of 10 cm x 10 cm at 100 cm from the target. The figure shows the maximum intensity of the scatter particles at range between −5 cm and +5 cm in both X-axis and Y-axis, respectively. This showed the BEAMnrc's phase-space file agreed well with the modeled linac treatment head defined at the field size 10 cm × 10 cm.

The PDD, beam profile, and $TPR_{20,10}$ of the simulation calculate data were further validated by comparing the results from the IC measurement. The PDD from both the IC measurement and MC simulation were superimposed and it was found that the percentage difference was within the tolerance range of ± 2% at depth 1.5 cm, 10 cm, and 20 cm for the simulated field sizes (3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm), as shown in Figure 4.

For the beam profile, the relative radiation dose was decreased as the depth of measurement was increased [Figure 5]. Besides, the beam flatness was improved as the depth of measurement was increased. Moreover, the percentage difference between the IC measurement and MC simulation of beam flatness in cross-plane and in-plane directions achieved a good agreement where the percentage difference was within the tolerance range of ± 2% for the simulated field sizes (3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm) at the depth 10 cm, as shown in Figure 5. However, several beam flatness at 10 cm depth with the percentage difference of more than the tolerance range of ±2% between the calculated and measured data. This may be due to the electron contamination that occurred at the depth smaller than 10 cm. The results did not affect the validation of the linac model as the comparison of the measured and calculated beam profiles was focused at 10 cm water depth according to the IEC protocol.[20,21] Furthermore, in this study, the S_{cp} simulation was executed at 10 cm depth; thus, the calculated S_{cp} was not affected by the beam quality.

Apart from that, the $TPR_{20,10}$ difference between the IC measurement and MC simulation was 1.32% and it was in a good agreement within the tolerance range of ±2%, as shown in Table 1. The PDD, beam profile, and $TPR_{20,10}$ comparison between the IC measurement and MC simulation show that the linac was modeled accurately in the MC simulation for all field sizes.

Output factor calculation in Monte Carlo simulation

Figure 6a shows the S_{cp} of the IC measurement and MC simulation for the field sizes 3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm, respectively. The figure shows that the S_{cp} was increased as the field size was increased. The calculated S_{cp} in the MC simulation was superimposed on the IC measurement with the error bar difference of ± 2% which was in a good agreement within the tolerance range of ± 2%. The highest difference was 0.95% for field size 15 cm × 15 cm. In a previous study, Yani *et al*. found that the calculated S_{cp} in the EGSnrc MC simulation for field size 3 cm × 3 cm, 5 cm × 5 cm, and 10 cm × 10 cm was in the range between 0.86 and 1.00 and the percentage difference between the measured and calculated S_{cp} were within 2%.[22] The S_{cp} measurement and calculation were done at 10 cm water depth in this study to avoid the effect of electron contamination from the Elekta linac treatment head, and the results had proved a good agreement between the measured and calculated S_{cp}.[22,23] Thus, the measured S_{cp} using the IC avoided the issue of electron contamination when

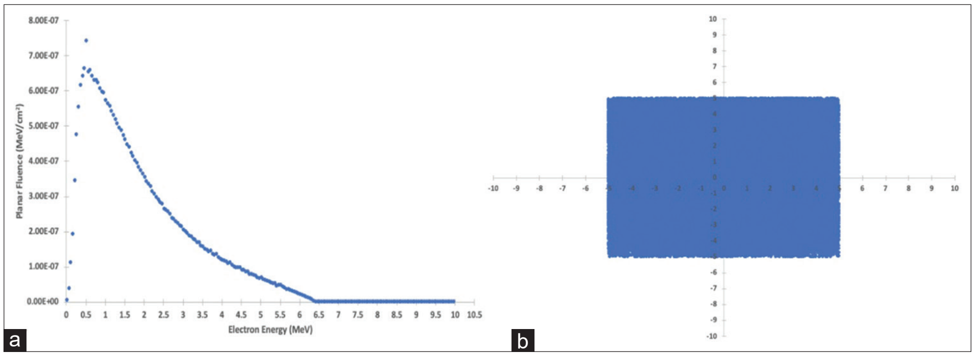

Figure 3: (a) Spectral distribution of 6 MV photon beam at the water phantom surface. The maximum energy absorbed by the water phantom was 6.4 MeV. (b): X-Y scatter plot of 6 MV photon beam for the field size 10 cm × 10 cm at 100 cm distance from the linac's target to the surface of the water phantom. linac: Linear accelerator

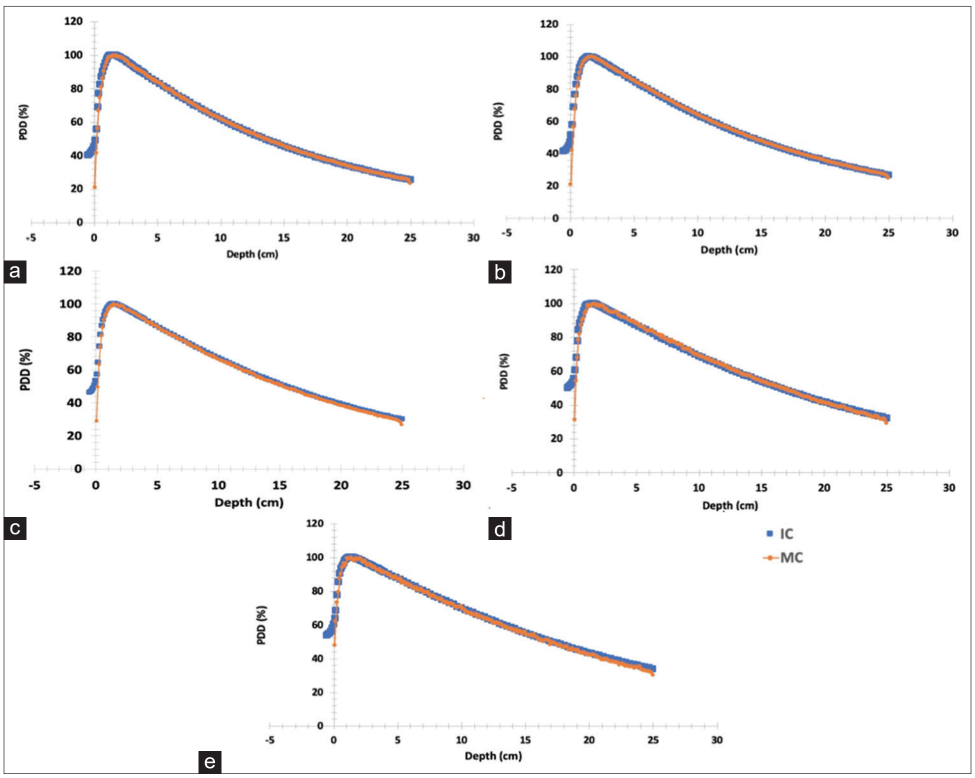

Figure 4: The PDD versus depth for field sizes (a) 3 cm × 3 cm, (b) 5 cm × 5 cm, (c) 10 cm × 10 cm, (d) 15 cm × 15 cm, and (e) 20 cm × 20 cm between the IC measurement and MC simulation for Elekta Synergy (Agility MLC) linac. IC: Ionization chamber, MC: Monte Carlo, PDD: Percentage depth dose, linac: Linear accelerator, MLC: Multileaf collimator

Table 1: The beam quality, tissue–phantom ratio, $TPR_{20,10}$ comparison between the ionization chamber measurement and Monte Carlo simulation for 6 MV photon beam in Elekta Synergy linear accelerator

Field size (cm^2)	$TPR_{20,10}$		Percentage difference (%)
	IC measurement	MC simulation	
10×10	0.684	0.675	1.32

IC: Ionization chamber, TPR: tissue–phantom ratio, MC: Monte Carlo

the IC was placed at 10 cm depth. Apart from that, the MC simulation acted as an alternative method to calculate the S_{cp} as it can overcome the issue of electron contamination during the simulation process.

Figure 6b shows the S_c of the IC measurement and MC simulation for field sizes 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm, meanwhile the S_c value for the field size 3 cm × 3 cm (shaded area) from the MC simulation alone as there was no IC measurement due to IC limitation. The figure shows that the S_c increased as the field size was increased. The calculated S_c in the MC simulation was compared against the IC measurement with the error bar difference of ±2% which was in a good agreement within the

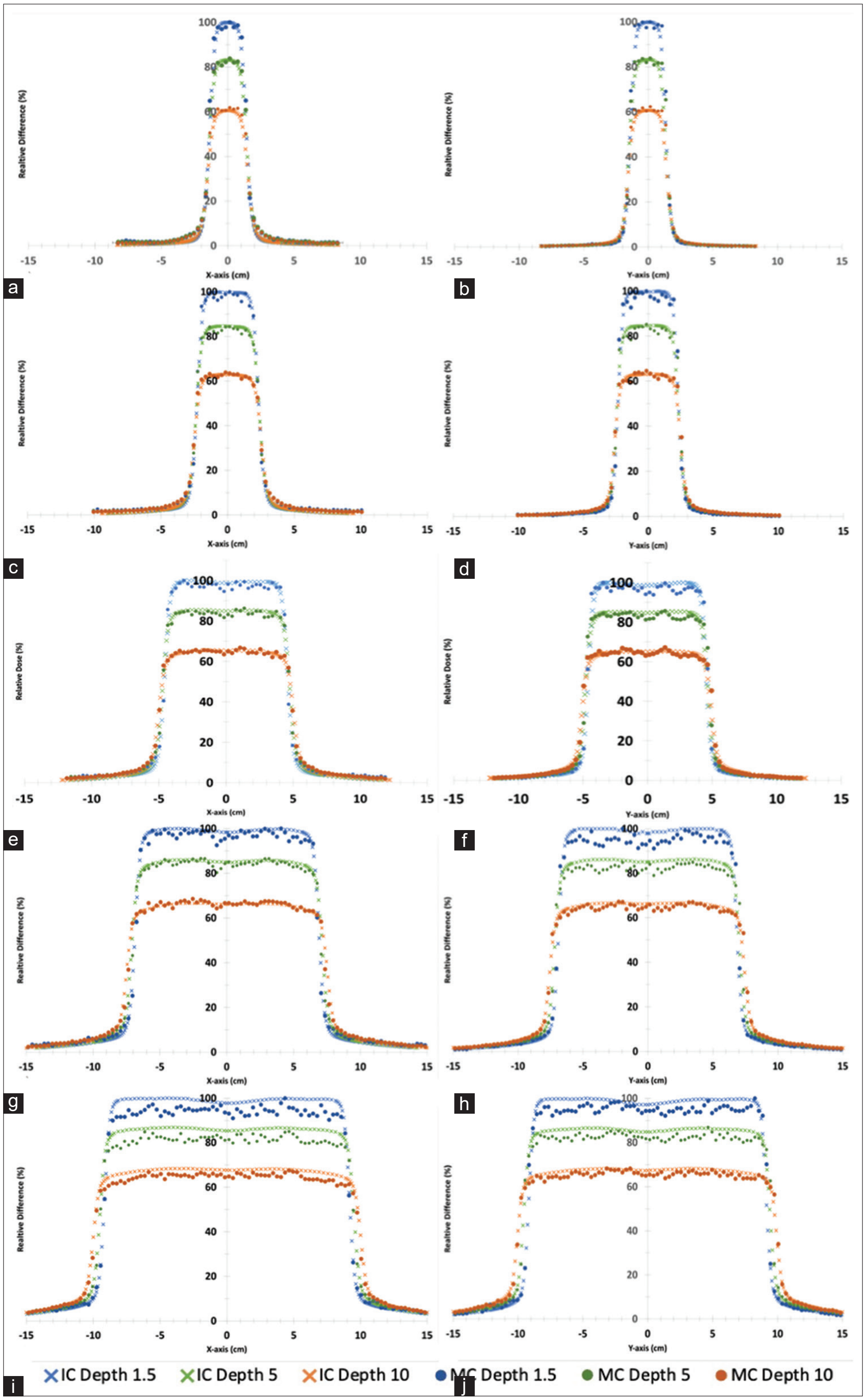

Figure 5: The relative dose in beam profile between IC measurement and MC simulation: (a) cross-plane and (b) in-plane for field size 3 cm × 3 cm; (c) cross-plane and (d) in-plane for field size 5 cm × 5 cm; (e) cross-plane and (f) in-plane for field size 10 cm × 10 cm; (g) cross-plane and (h) in-plane for field size 15 cm × 15 cm; (i) cross-plane and (j) in-plane for field size 20 cm × 20 cm. IC: Ionization chamber, MC: Monte Carlo

tolerance range of ±2%. The highest difference was 0.68% for field size 20 cm × 20 cm.

Based on this simulation work, the calculated S_c for the field size 3 cm × 3 cm was 0.955. There was a lack of data

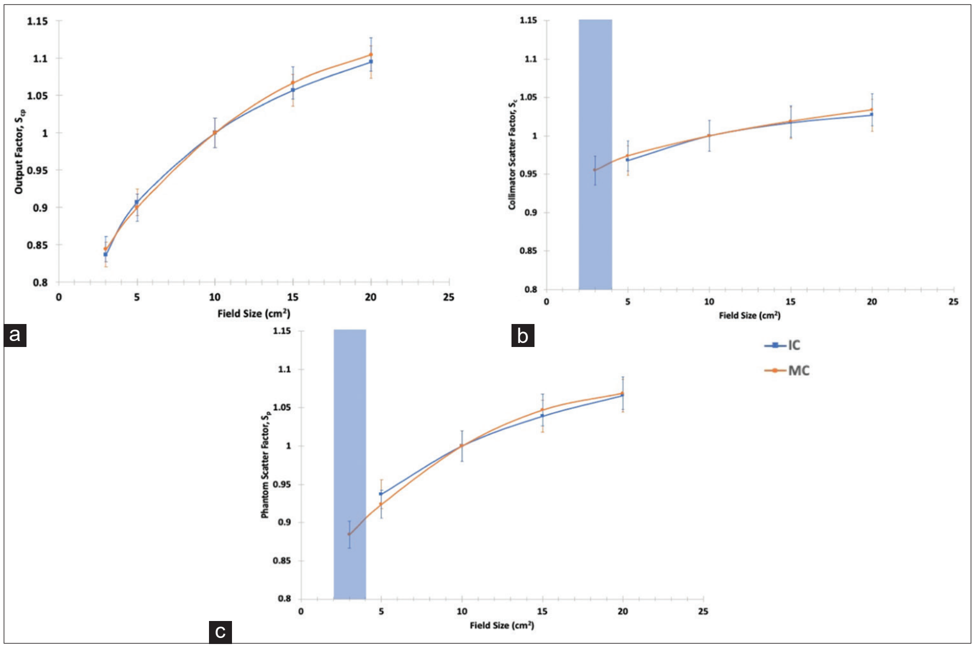

Figure 6: (a) The S_{cp}, (b) S_c, and (c) S_p of IC measurement and MC simulation for field size 3 cm × 3 cm, 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm, respectively. The error bar indicated ± 2% difference. S_c: Collimator scatter factor, S_p: Phantom scatter factor, S_{cp}: Scatter output factor, IC: Ionization chamber, MC: Monte Carlo

in small-field size using IC as the application of 3 mm thick buildup cap in the IC during the S_c measurement might not guarantee a LEE condition. A study by Fogliata *et al*. found that the percentage difference of measured S_c by using IC with a 2 mm thickness buildup cap calculated S_c by using the PENELOPE MC code for field size were within 1% difference and proved that the MC code able to provide accurate values within the tolerance range of 2% difference.[9] They also found that the application of an adequate thickness of buildup cap with a minimum 2 cm thickness in the IC was important to avoid the lack of LEE that occurred in the IC during the S_c measurement.[9,13] With the help of MC simulation, such issue can be avoided as the MC simulation can overcome the lack of LEE when calculating the S_c. Thus, the MC simulation acts as an alternative to calculate S_c when the thickness of buildup cap of the IC is not adequate to measure the S_c.

Figure 6c shows the S_p of the IC measurement and MC simulation for field sizes 5 cm × 5 cm, 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm, and for field size 3 cm x 3 cm, the S_p value from the MC simulation only. The figure shows that the S_p increased as the field size was increased. The calculated S_p in the MC simulation was compared against the IC measurement with the error bar difference of ± 2% which was in a good agreement within the tolerance range of ± 2%. The highest difference was 1.39% for field size 5 cm × 5 cm. Based on this simulation work, the calculated S_p for the field size 3 cm × 3 cm was 0.884. In a previous study, Davoudi *et al*. had showed a good agreement between measured S_p using the IC and calculated S_p using the EGSnrc MC simulation for field sizes 10 cm × 10 cm, 15 cm × 15 cm, and 20 cm × 20 cm with the maximum percentage difference of 0.83% where the percentage difference was within the tolerance range of ± 2%. MC simulation was suggested to calculate the S_p directly to avoid the inaccuracy in measurement by using the IC.[24]

In small-field dosimetry, there was lacking of values from the IC measurement from our center. Since S_c and S_p for field size 3 cm × 3 cm were not measurable, they were calculated from the MC simulation in this study and the values were 0.955 and 0.884, respectively. The results shown were valid because previous studies mentioned that the MC simulation was often being used as a benchmark in dose calculation algorithm, especially in small-field dosimetry due to the ability of MC simulation to eliminate the uncertainties of the IC measurement such as lack of LEE, volume averaging effect, and partial source occlusion during simulation process.[9,13,24] A study by Yani *et al*. proved that the calculated S_{cp} by the EGSnrc MC simulation was in good agreement with the IC-measured S_{cp} in small-field size 3 cm × 3 cm with the percentage difference between the measured and calculated S_{cp} of 1.8% which was within the tolerance range of 2%. Apart from that, Aitelcadi *et al*. proved that the calculated Sc by the MC simulation was in a good agreement with the measured Sc by the IC in small-field size 3 cm × 3 cm with the percentage difference of 0.6%.[12] A study by Fogliata et al. and Davoudi et al.validated the calculated Sc for the field size of 4 cm × 4 cm within ± 1% difference.[8,23] These studies proved that the MC simulation can act as an alternative way to calculate the Scp in small-field dosimetry.

Conclusion

The aim of this study was to determine the small-field S_{cp} of the Elekta Synergy (Agility MLC) linac by using the

EGSnrc MC. The calculated S_{cp} in MC simulation was able to be determined accurately despite external factors that affected the IC measurement such as IC position, buildup cap thickness, and small-field dosimetry, still showing a good agreement between the measured and calculated S_{cp} with the variation within the tolerance range of ±2%. The calculated S_c and S_p for field size 3 cm × 3 cm in this study were 0.955 and 0.884, respectively. Thus, the study showed that the determination of S_{cp} for small- and large-field sizes can be performed efficiently by using the EGSnrc MC simulation.

Acknowledgments

We would like to thank Elekta Limited from the UK and Madam Rosemary for assisting in providing detailed information on the Elekta Synergy Agility used in the Monte Carlo simulation work. This work was also supported by the Universiti Sains Malaysia [304/PPSK/6315497].

Financial support and sponsorship

This work was supported by the Universiti Sains Malaysia [304/PPSK/6315497].

Conflicts of interest

There are no conflicts of interest.

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