Original Articles/นิพนธ์ต้นฉบับ

# Monte Carlo Multiple-source Model for 6 mV Photon Beams from Varian Clinac iX Linear Accelerator

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## Abstract

**Objective:** The aim of this study was to build a multiple source model for a 6 MV Photon beam from the Varian Clinac iX linear accelerator (at the Department of Radiology, Ramathibodi Hospital).

**Material and Method:** Beam Data Processer (BEAMDP) was used to analyze the phase space data from the EGSnrc(Electron-Gamma Shower National Research Council of Canada)/BEAMnrc code and obtain the parameters for beam representation. A DOSXYZnrc code was used to calculate dose distribution in a 3D rectangular voxel. The simuation compose of two unknown parameters, energy and full width at half maximum (FWHM). These parameters were determined by using an iterative process and a comparison with the percentage depth dose and the beam profile from the measurement. The five-source model were comprised of a point sub-source for target, circular planar sub-source for primary collimator and flattening filter, rectangular planar sub source for electron, and positron. The characteristics of beams such as relative intensity, field planar fluence distribution and energy distribution from original phase space were derived by using the BEAMDP code.

**Result:** The initial parameter found an energy of 6.5 MeV and radial intensity distribution with a width of 0.6 mm FWHM. Most of the depth dose and beam profile between our source model and the measurement showed good agreement within ±2 % for field size of 5 x 5, 10x10, 15 x 15 and 20 x 20 $cm^2$ except of the 30 x 30 $cm^2$ field size at 100 cm SSD. The relative point dose of the source model in homogeneous phantom deviated within ±1% and ±2% between the original phase space and the measurement respectively. The source model was shown to reduce disk space requirement and CPU time, while the statistical uncertainty of dose calculation was the same as the full Monte Carlo simulation.

**Conclusion:** Our source model accurately simulates the dosimetric characteristics of a photon beam for all field size, except for 30 x 30 $cm^2$.

**Key words:** Monte Carlo Simulation/ Multiple Source Model/ BEAMDP

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## Introduction

For the process of treatment planning in radiotherapy, the accuracy of dose calculation method that derived to a patient is very important. Since radiation therapy is generally a complex process and must carefully perform to deliver enough radiation to the tumor to destroy it without irradiating normal tissue to a dose that will lead to serious complications[1] which is the aim of radiotherapy.

In the past, there are many developing algorithms for dose calculation. The general requirement for dose calculation algorithm is accuracy, speed and general aspect[2] The most accurate method in dose calculation is believed to be the Monte Carlo simulation.[3] This method is based on a random number sampling cooperating with a physics interaction to simulate the transport of representative particle through a medium. The Monte Carlo method can simulate the fate of particle and record many quantities data of interest along its trajectory.

The limitation of Monte Carlo simulation is required the need of large disk space and long computing time to get agreeable level of accuracy. In some case, it may take several days for calculating dose. So, that is the reason why Monte Carlo is sometimes not suitable for clinical dose calculation in radiotherapy.

The techniques have been developed to help improving the calculation efficiency is multiple source model. BEAMDP (BEAM Data Processor) is required by the multiple source model. It is used to analyze the full phase space in order to calculate the beam representation. The source model has been executed in EGSnrc user code such as BEAMnrc, DOSXYZnrc. It can model a simulated beam with 10% or less particles than that of required by the traditional Monte Carlo simulation, without losing the accuracy of the dose calculation.[4] Using the multiple source model is therefore saving CPU time for dose computing and disk space for data storage.

At present, Ramathibodi Hospital had installed the Varian Clinac iX linear accelerator and expected to use it for the main of radiotherapy. Because there has not been any study that shows the accuracy of the source model for the Varian Clinac iX linear accelerator by using Monte Carlo simulation. Additionally Iljamäki L. and Siljamäki S.[5] stated that the beam properties may differ between individual accelerators even of the same manufacturer and model because of the adjustment of beam delivery system during the on-site installation. In this work, we will study the suitability of Monte Carlo dose calculation in Variance Clinac iX linear accelerator located at Ramathibodi Hospital. The main task is to build a multiple source model for 6 MV photon beam from the Varian Clinac iX linear accelerator and to investigate the accuracy of the source model in homogeneous phantom by comparing the results from the full phase space to that of the measurement.

## Material and Method

### 1. Monte Carlo Simulation

#### 1.1 BEAMnrc simulation

The treatment head is simulated by BEAMnrc code. The full models are built from the physical components of Clinac iX linear accelerator: Target, Primary collimator, Vacuum window, Flattening filter, Ionization chamber, Field light mirror, and Jaw. The last component is a slab where all particle history's information is stored at 100 cm from target (SSD=100) and the phase space file is obtained. The specifications of all components obtained from the manufacturer. The global photon and electron cut-off energy were 0.01 MeV and 0.7 MeV, respectively. Latch is set in 0-31 bits. In this study we indicated bit 1-23 bit, as shown in Figure 1, to record particle's history where it's has been and/or has interacted. It's important requirement for the multiple-source model. Range rejection, Transport cutoffs, Directional Bremsstrahl-

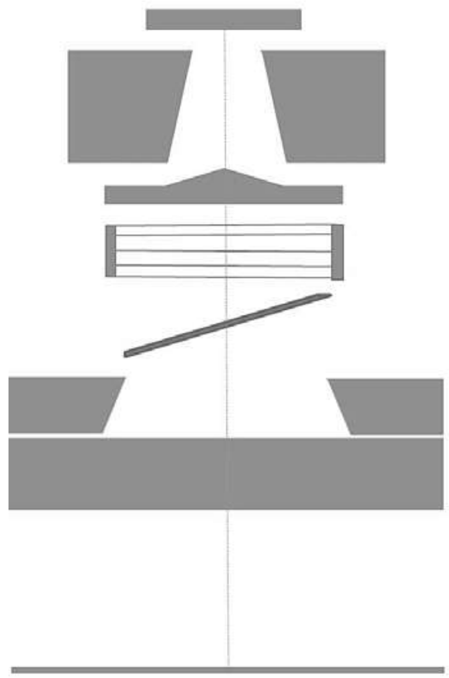


***Figure 1*** *Schematic diagram of the geometries illustrating for Varian Clinac iX linear accelerator in photon mode with associated Latch bit. (The image is not scale)*

ung splitting and Russian roulette are used for increase efficiency of Monte Carlo simulation. The source input parameter is "ISOURC=19: Parallel Circular Beam with 2-D Guassian X-Y Distribution" to specific charge and type of source of incident particles. The simulation is an iterative process. Optimal initial electron beam are defined by varying energy and full-width at half maximum (FWHM) of the spatial Gaussian distribution in order to match the measurement data. We selected those five energies that were 5.8, 6.0, 6.3, 6.5 and 6.7 MeV. The FWHM were 0.4, 0.6, 0.8, 1.0, 1.3 and 1.7 mm. Incident particle is on $10x10^6$ for 30x30 $cm^2$ in field size. The field size of 30x30 $cm^2$ was selected because the radial intensity of initial electron beam is known to be more sensitive to the beam profile of large field size than small field size.[6]

For generating the phase space files, we follow the following four steps;

1. Model the Linear accelerator by indicating component module with specified physical geometric component from the manufacturer.

2. Define the optimal initial electron beam by varying the energy and FWHM. The input data are saved in 'egsinp' file.

3. Build and compile accelerator.

4. Execute to run the BEAMnrc simulation. The output of phase space is saved in '.egsphsp1' file. For the next, phase space file from BEAMnrc simulation were used as an input source file to calculate dose distribution in DOSXYZnrc code.

Dose calculation data was compared with the measured data to fit in criteria. The least value of difference was selected for the initial parameter. The flowchart shows the iterative process as in figure 4.5

### 1.2 DOSXYZnrc simulations

For dose calculation, DOSXYZnrc code has been used. It simulates the particle that transports and scores the deposited energy in the voxels of the phantom. Material and density can be specified for each voxel. A standard batching technique was used for statistical analysis. To determine the uncertainty, a history-by-history basis is done by grouping scored quantities (i.e., energy deposited). For phase space source, the quantities were grouped by primary history then the incident particles will trace back to primary history. The output of DOSXYZnrc file is shown in ".egslst", ".3ddose" and ".pardose".[7] The 3ddose file stores the calculated dose for all voxel in terms of dose per incident history with corresponding uncertainty.

Central axis depth dose curve and beam profile were measured in the Blue phantom. In the simulation, we have divided the water phantom into a group of voxels ranging from 0.5 $cm^3$ to 1 $cm^3$ in x,y,z direction depends on the energy and the field size. Depth dose curves were simulated at the central axis with the voxel of 1x1x0.5 $cm^3$ in build up region and the voxel of 1x1x1 $cm^3$ in any depth. Beam profile is simulated in a group of voxel about 0.5x1x1 $cm^3$ in penumbra region and the voxel of 1x1x1 $cm^3$ in the central and umbra region. ISOURCE = 2: Phase-Space Source Incident from Any Direction is calculated dose from original phase space files and ISOURCE = 4: Beam Characterization Model Incident from Any Direction is calculated dose from multiple source model.[7] When the number of available particles is less than required, the recycling is needed. The recycling is typically 3 times for dose calculation from the phase space file. However, the recycling is inapplicable for the source model. Because of the effect of electron contamination is impressive in depth of 10 cm, the beam profiles are calculated at 10 cm depth.

### 1.3 BEAMDP simulations

BEAMDP is an interactive program that developed for the OMEGA project. It can be used to derive the data by analyze the original phase space that required for representation and reconstruction of the electron beam of multiple-source model.[8]

The fact that supports an idea of beam characterization is particle from different components of an accelerator have significantly different energy, angular and special distribution, while the particle from the same component have similar characteristics in term of energies and incident directions. So, Particles may be treated as coming from different sub-sources if they are from different component of an accelerator. In the same component, energy range and incident direction of particles have very similar characteristics, which their positions at the scoring plane are independent.[4] A multiple-source model is created by BEAMDP code. BEAMDP is used to analyze the full phase space data from BEAM simulation that contains a type of particle, direction, position, energy, weight, and LATCH. LATCH bit setting is necessary to derive the information of particles such as the region numbers where it is created or last scattered for a photon. LATCH option 3 (set by interactions) was recommend for beam characterization model.

The method to design a source model for beam re-construction is shown in Figure 2 First, each component of Linac treatment head are simulated with associated LATCH bit setting by EGSnrc/BEAMnrc code. Geometry of sub-source model is specified by user. Full phase-space data (at scoring plane, SSD = 100 CM) are analyzed to derive relative intensity, spectral and planar fluence distribution by BEAMDP code. The phase space reconstruction from an output file of BEAMDP is done in the BEAMnrc or DOSXYZnrc code. Reconstruction beam are compared with the measurement to test algorithm on source model. In this study, the five-source model is used, which consists of a point source for target, circular planar source for primary collimator and flattening filter and two rectangular planar source for electron and positron. The square field with square regions of equal area for the planar fluence distribution was used in all sub-sources. Energy distributions for each of the energy

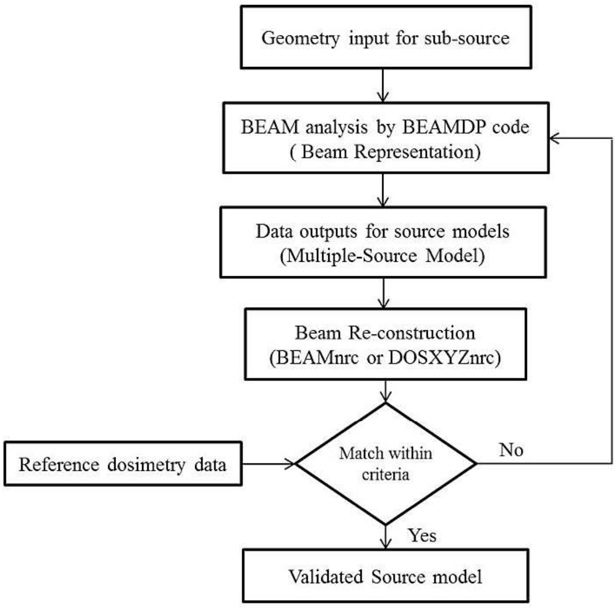


***Figure 2*** *Flow chart for iterative process in BEAMDP code simulation*

region are generated using BEAMDP. The treatment field dimensions are given by the user. The maximum number of energy bin allowed is 200 which can be changed by editing the beamdp.mortan program.

## 2. Verification of the Varian CLINAC iX Linear Accelerator

To verify the source model, we divided into two parts. First, the comparisons of Depth Dose curve and Beam Profile of multiple source model with measurement. The measurement of depth dose and beam profile database of Varian Clinac iX Linear Accelerator at Ramathibodi Hospital were collected by medical physics team. The percent depth dose and beam profile were measured using PFD3G photon diode detector in Blue phantom. It's used for optimized the Monte Carlo parameter by comparing between simulation data and measurement. In our study, the depth dose curve and beam profile were compared in term of field size, 5x5, 10x10, 15x15, 20x20 and 30x30 cm$^2$ at 100 cm SSD, respectively. Second, verify an accuracy of Multiple-source model by comparison relative dose distribution with measurement in a water phantom. We are used FC65-G ionization chamber for measurement in one dimension water phantom. The reference field size is 10x10 cm$^2$ for any central axis depth at 100 cm SAD and 20x20 cm$^2$ for dose lateral at 10 cm depth. The interesting points are set into 6 positions. At position 1 is the point (0, 0, 5), 2 is the point (0, 0, 10), 3 is the point (-5, 0, 10), 4 is the point (+5, 0, 10), 5 is the point (0, 0, 15) and 6 is the point (0, 0, 20) in (X, Y, Z) direction. (as shown in Figure 3)

### 2.3 Acceptance Criteria

For patient dose calculation, the goal of the source model is agree with measurement within $\pm$2% [22] and statistic uncertainty achieved in each voxels was less than $\pm$1%.

The comparison between source model and the measurement is done by calculating the percentage difference. It is define as

$$Percent\ Difference = \frac{|Simulation - Measurement|}{Measurement} \times 100\%$$

The storage space requirement and CPU time were compared by the fraction of the dose calcula-

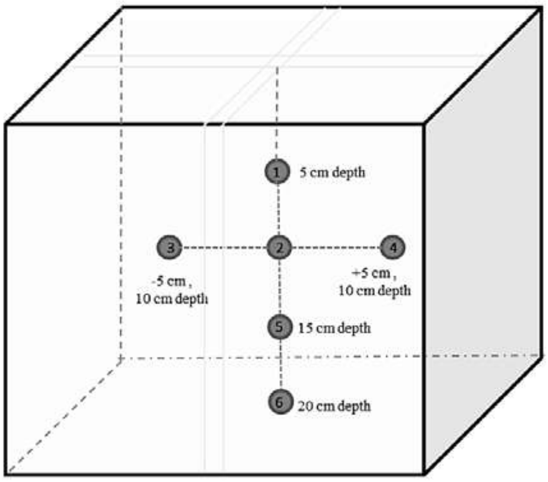


***Figure 3*** *The interesting point in 1D water phantom*

tion required for original phase space and the source model. The unit of disk space and CPU time was showed in byte and second respectively.

## Results

### 1. The optimal parameters of initial electron beam on target

The initial electron beam parameters were estimated in the BEAMnrc/EGSnrc code. The energy of initial electron beam was found to be 6.5 MeV with 0.6 mm FWHM of radial intensity distribution. These initial parameters gave the minimum dose difference of depth dose and beam profile between simulation and measurement for the 30x30 $cm^2$ field size. The depth doses were read from 3 to 20 cm depth at 100 cm SSD in standard water phantom. They were normalized to 10 cm depth. These depths were chosen to defend any influence in dose at build up region for high energy photon beam.[9] The value of percentage difference using dose profiles comparison in the range within the field region (+0 to +15 cm) to transfer an accurate dose relevant inside patient. The average percent difference of beam profile obtained from the full phase space and the measurement was less than our accepted criteria (within $\pm$2%). They gave the similar result in the relative output factor, however, it was underestimated for 30x30 $cm^2$ field size.

There were many factors of incompetence to simulate accuracy model such as the component densities, the physical geometry of the flattening filter from manufacturer's specification and transport method applied by MC code. In addition the incident angle distribution was not used in this work. By adjusting these parameters, the simulated beam profile could be shaped to matching with the beam profile from the measurement.[9] Additionally, the energy distribution of incident electron was ignored as well. It was found to be necessary in some machines.[10]

### 2 Multiple-Source model

#### 2.1 Five-source model

Using the BEAMDP code, analysis of the original phase space data revealed that most of photons were originated from the target while the photons created at the primary collimator and flattening filter were negligible, as presented in Figure 4.

Figure 5 shows the photon's energy spectra for our 6 MV photon beam with 30x30 $cm^2$ field size obtained from the full Monte Carlo simulation and from our five-source model. Both spectra were nor-

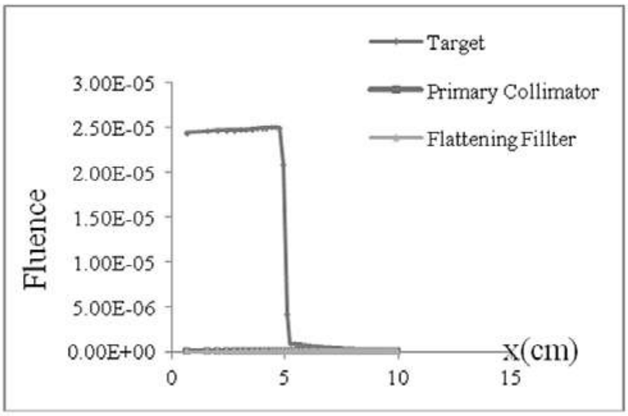


***Figure 4*** *Planar fluence distribution of 6 MV photon beam of target, primary collimator and flattening filter for 30x30 cm$^2$ field size.*

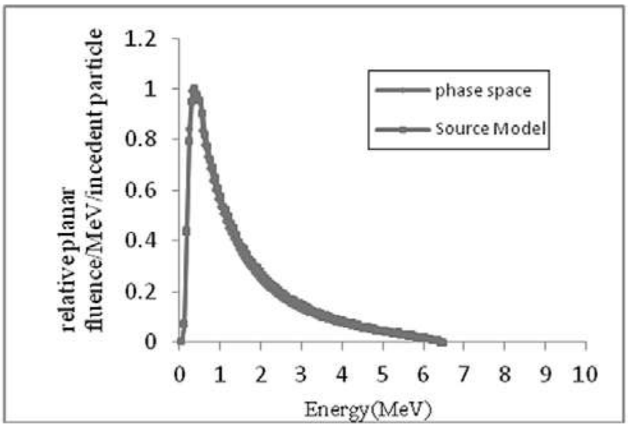


***Figure 5*** *Comparison of 6 MV photon beam energy spectrum between source model and original phase space file for 30x30 cm$^2$ field size.*

**Table 1** The percent difference of central axis depth dose and dose profile between our source model and the measurement for field size of 5x5, 10x10, 15x15, 20x20 and 30x30 cm$^2$, at 100 cm SSD.

| Field Size (cm$^2$) | Average percent difference (%) ± SD | |
|---|---|---|
| | Depth dose | Beam profile |
| 5×5 | 0.21 ± 0.24 | 0.93 ± 1.52 |
| 10×10 | 0.88 ± 0.40 | 0.84 ± 0.74 |
| 15×15 | 0.64 ± 0.43 | 1.35 ± 0.96 |
| 20×20 | 0.76 ± 0.83 | 1.07 ± 1.17 |
| 30×30 | 1.54 ± 0.26 | 2.59 ± 1.82 |

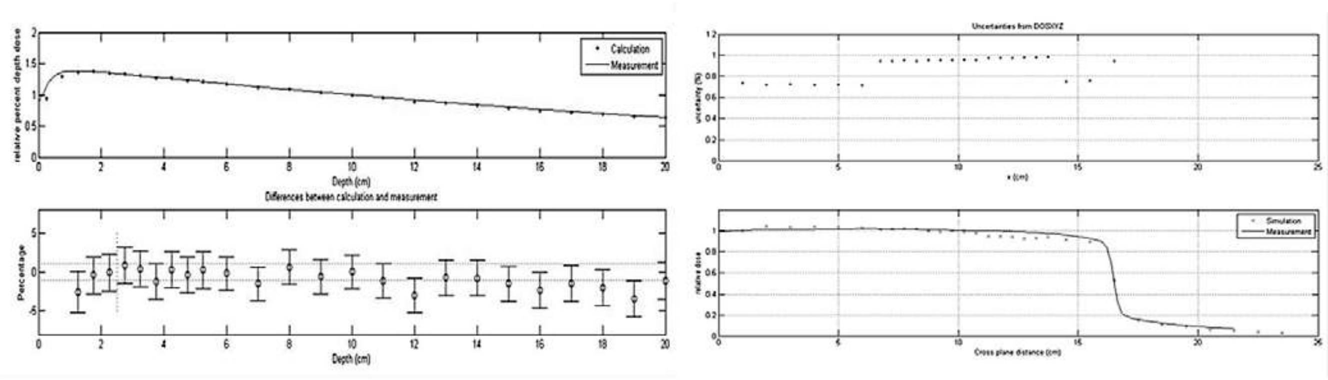


***Figure 6*** *Comparison between central axis depth dose curves and beam profile calculated using Multiple-source model and the measurement. The energy of initial electron beam is 6.5 MeV and the FWHM of initial electron beam of 0.6 mm. The field size is 30x30 cm$^2$.*

malized by its maximum fluence. The most probable energy of both spectra is about 0.37 MeV

### 2.2 Comparison of depth dose curve and beam profile

The multiple-source model was reconstructed and can be applied by DOSXYZnrc for 3-D dose calculation. The calculation of depth dose curve and dose profile from source model was compared with measurement for the field size of 5x5, 10x10, 15x15, 20x20 and 30x30 cm$^2$, 100 cm SSD as present in Figure 6. The depth dose curves were all normalize at 10 cm depth. The depth-dose comparison was done from the depth of 3.0 cm to 20.0 cm and the profile was compared from the beam center to just before the beam penumbra. The results show that the central axis depth dose between calculated and measured was in good agreement (the percentage difference is within 2%) in all field size. Agreement in beam profile between calculation and measurement was within 2 % in all field size, except for 30x30 cm$^2$, as shown in Table 1. The reason of this discrepancy could be due to the analysis of the original full phase space in large field size (30x30 cm$^2$), so it may be affected to the source model. An uncertainty of depth dose curve was varied with field size. This is due to an increase in number of bins for planar fluence distribution specified by user. However, all uncertainties in each voxel are within 1%.

### 2.3 Comparison the original phase space and the measurement in homogeneous phantom

To verify the accuracy of the source model in homogeneous phantom, five points were specified for measured and calculated point dose, see in Figure 5.8. Relative central axis depth dose were used at depth of 5, 10, 15 and 20 cm for 10x10 cm$^2$, 100 cm SAD. The relative lateral dose were used at (-5, 10) and (+5, 10) for 20x20 cm$^2$, 100 cm SAD. Table 5.8 shows the comparison of relative dose of source model with original phase space and the measurement in water phantom at 100 cm SAD. It shows very good agreement with $\pm$1% by comparison of source model with original phase space. Good agreement (within 2%) calculated between the source model and the measurement.

### 2.4 Time and disk storage

For CPU time and disk storage requirement, to obtain the same statistical uncertainty (within $\pm$1), the disk storage used in the multiple source model is less than the original phase space file by a factor of about 50,000 and 90,000 for 10x10 cm$^2$ and 30x30 cm$^2$ field size, respectively. The calculation time without accumulated the process of dose calculation

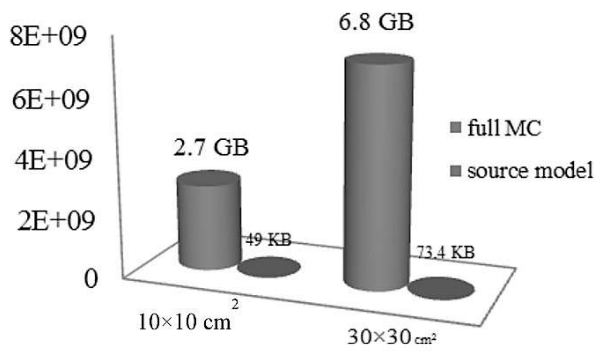


*Figure 7* *The comparison of storage space requirement between full Monte Carlo simulation and our source model for field size of 10x10 cm² and 30x30 cm², 6 MV photon beam.*

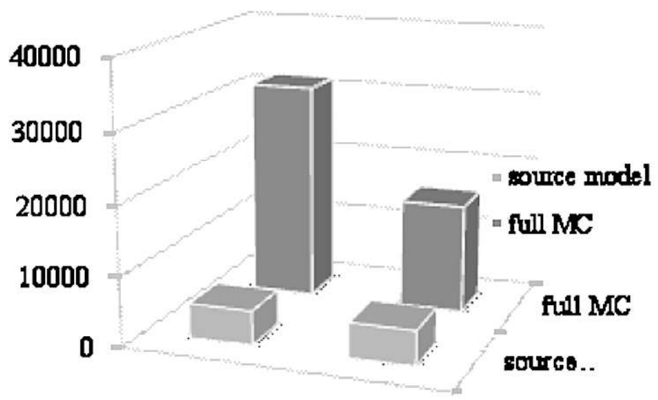


*Figure 8* *The comparison of CPU time usage between full Monte Carlo simulation and our source model for field size of 10x10 cm² and 30x30 cm², 6 MV photon beam.*

can reduce by a factor about of 6 or 3 for 10x10 cm² and 30x30 cm² field size, respectively. The chart on Figure 7 and Figure 8 compared size of data storage and time between full Monte Carlo simulation and source model for field size of 10x10 cm² and 30x30 cm², respectively.

## Conclusion

Our source model showed good agreement of the depth dose and beam profile with the measured data for the field size of 5x5, 10x10, 15x15, and 20x20 cm² at 100 cm SSD. The difference was found to be within 2% while it was slightly higher for the 30x30 cm² field size. The relative point dose of the source model in homogeneous phantom deviated within 1% and 2% from that of the original phase space and measurement, respectively. The source model can reduce the disk space requirement, significantly, and CPU time while the accuracy of dose calculation is acceptable.

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Original Articles/นิพนธ์ต้นฉบับ

# แบบจำลองมอนติคาร์โลแบบหลายแหล่งกำเนิดสำหรับลำรังสีโฟตอน 6 เมกกะโวลต์ จากเครื่องเร่งอนุภาคแวร์เรียนไคลแน็คไอเอ็กซ์

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## บทคัดย่อ

**วัตถุประสงค์:** สร้างแบบจำลองหลายแหล่งกำเนิดของลำรังสีโฟตอนพลังงาน 6 เมกกะโวลต์ ด้วยเทคนิคมอนติคาร์โลสำหรับเครื่องเร่งอนุภาคแวร์เรียนไคลแน็คไอเอ็กซ์ ซึ่งติดตั้งอยู่ที่ภาควิชารังสีวิทยา โรงพยาบาลรามาธิบดี

**วิธีวิจัย:** แบบจำลองหลายแหล่งกำเนิดสร้างโดยโปรแกรมรหัส BEAMDP ใช้วิเคราะห์ข้อมูลเฟสเปสจากการสร้างแบบจำลองส่วนหัวของเครื่องเร่งอนุภาคแบบด้วยโปรแกรมรหัส EGSnrc/BEAM และคำนวณปริมาณรังสีดูดกลืนในแฟนทอมน้ำโดยโปรแกรมรหัส EGSnrc/DOSXYZ พารามิเตอร์ไม่ทราบค่าสำหรับแบบจำลองแบบเฟสสเปสคือ ค่าพลังงานและการกระจายตัวของลำรังสีอิเล็กตรอนที่ตกกระทบเอกซเรย์ ทั้งสองค่าหาได้จากการเปรียบเทียบ Percentage depth dose และ Beam profile ระหว่างการจำลองกับการวัดจริง แบบจำลองแบบหลายแหล่งกำเนิด ถูกกำหนดให้มี 5 แหล่งกำเนิดสำหรับ target, Primary collimator, Flattening filter, electron และ positron. โปรแกรมรหัส BEAMDP จะวิเคราะห์ลักษณะลำรังสีจากแบบจำลองแบบเฟสสเปสและสร้างลำรังสีแทนลำรังสีแทนที่ได้จะถูกสร้างลำรังสีขึ้นมาใหม่ จากนั้นเปรียบเทียบกับการจำลองแบบเฟสสเปสเพื่อตรวจสอบอัลกอริทึมของลำรังสีจากแบบจำลองหลายแหล่งกำเนิด

**ผลการศึกษา:** จากการจำลองแบบเฟสสเปสพบว่าค่าพารามิเตอร์เริ่มต้นของพลังงานมีค่าเท่ากับ 6.5 เมกกะอิเล็กตรอนโวลต์ และค่าการกระจายตัวของลำรังสีอิเล็กตรอนที่ตกกระทบเอกซเรย์มีค่าเท่ากับ 0.6 มิลลิเมตร จากการเปรียบทียบ depth dose และ Beam profile ระหว่างแบบจำลองหลายแหล่งกำเนอดและการวัดจริง ที่ขอบเขตลำรังสีขนาด 5x5, 10x10, 15x15, 20x20 และ 30x30 ตารางเซนติเมตร ระยะจากแหล่งกำเนิดถึงผิวน้ำ 100 เซนติเมตร พบว่า ค่าเปอร์เซ็นต์ความแตกต่างไม่เกิน ±2 เปอร์เซ็นต์ ยกเว้นการเปรียบเทียบที่ขอบเขตลำรังสี 30x30 ตารางเซนติเมตร. ผลการเปรียบเทียบการคำนวณปริมาณรังสีสัมพันธ์ของแบบจำลองหลายแหล่งกำเนิดใน HOMOGENEOUS PHANTOM มีค่าความแตกต่างไม่เกิน ±1 และ ±2 เปอร์เซ็นต์ เมื่อเทียบกับการคำนวณรังสีจากแบบจำลองแบบเฟสสเปสและการวัดจริงตามลำดับ. แบบจำลองหลายแหล่งกำเนิดยังสามารถลดพื้นที่ในการเก็บข้อมูลและเวลาที่ใช้ในการจำลองโดยยังคงความถูกต้องของความไม่แน่นอนในการคำนวณปริมาณรังสีอยู่เช่นเดียวกับการจำลองแบบเฟสสเปส

**สรุปผลการศึกษา:** แบบจำลองแบบหลายแหล่งกำเนิดจากการศึกษานี้สามารถจำลองลักษะลำรังสีโฟตอนได้ความถูกต้องยกเว้นที่ขอบเขตลำรังสี 30x30 ตารางเซนติเมตร

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