REVIEW ARTICLE

A Review of the Recent Monte Carlo (MC) Simulation for Dosimetry in Mammographic Applications

Zaker Salehi[1], Elnaz Balvasi[2], Mohd Zahri Abdul Aziz[3]

[1] Department of Radiation Sciences, Yasuj University of Medical Sciences, Yasuj,Iran
[2] Department of Radiation Sciences, Lorestan University of Medical Sciences, Khoramabad,Iran
[3] Oncological and Radiological Sciences Cluster, Advanced Medical & Dental Institute, Universiti Sains Malaysia, Malaysia

ABSTRACT

The Monte Carlo (MC) method was utilized widely to various problems like an absorbed dose calculation as the method able to apply in a complex geometry such as mammography. Since 1980, the approach was utilized in mammographic dosimetry to calculate the backscatter factor and absorbed dose in breast phantoms because it was considered as the most accurate dose calculation algorithm in several experimental setup. This paper provides a review of the applications of Monte Carlo simulation (MC) for the process dosimetry in mammography. In comparison to experimental measurements, this approach poses a minimum calculation uncertainty (less than 2%), realistic measurement positions, and appropriate for low-energy radiation simulation. The applications of the MC codes in mammography, such as radiation modelling, organ dose calculation, tumor growth analysis, etc., were discussed in this review.

Keywords: Monte Carlo simulation, Mammography, Dosimetry, Dose

Corresponding Author:
Mohd Zahri Abdul Aziz, PhD
Email: mr.zahri@gmail.com, mohdzahri@usm.my
Tel: +604-5622356

INTRODUCTION

Monte Carlo (MC) simulation has been used for various applications in medical physics in the last 50 years (1). The simulation is based on a random sampling and statistical modelling, in order to estimate the mathematical functions and analyze the operations of a complex system. There are various MC codes which have been widely used in the medical physics, such as EGS, EGS4, BEAM, EGSnrc, MCNP and GEANT4 (1). Generally, this method offers several advantages to the medical physics research (2), as it is non-invasive, and its accuracy makes it appropriate for low-energy radiation modelling, for example in mammography. MC simulation in medical radiation was started with EGS (Electron-Gamma Shower) which is later developed as new versions of EGS3 and EGS4. ETRAN is another MC simulator which after being modified was incorporated into MCNP (Monte Carlo N particle) code. MCNP 4b,4c and 5 together with GEANT are recently introduced as MC simulators. This paper reviews the principles of MC simulation, focused on its application in mammography.

MC CODES IN MAMMOGRAPHY

MC codes for radiation simulation

MC simulation has been started since 1980 in order to calculate the backscatter factor and absorbed dose in breast phantoms (2). Doi & Chan quantified rad/roentgen conversion factors for water, fat and a mixture of water-fat using an x-rays generator. The calculated backscatter factors were analyzed by MC calculations with a great accuracy comparing to measurement using dosimeters. In another study, the x-ray interactions in dense and fatty breast phantoms using different imaging detectors and various thicknesses, via MC simulation (3). The energy used in their radiation modelling was 28 kV, which is common for a clinical mammographic procedure and their experimental setup was illustrated in Fig. 1 . In their study, the MC model determined the thickness of the detectors, to achieve an optimal imaging performance (3).

In another research conducted, the frequency of an x-ray scatter signal in mammography and breast tomosynthesis projections were studied. The MC simulation was used to simulate the projection images of each patient breast. These images were analyzed at two different x-ray source positions; 0° and 30° for each patient breast (4). The power-law relationship of the noise power spectrum (NPS) was used to analyze the results obtained from the MC simulation. The study proved that, MC simulation

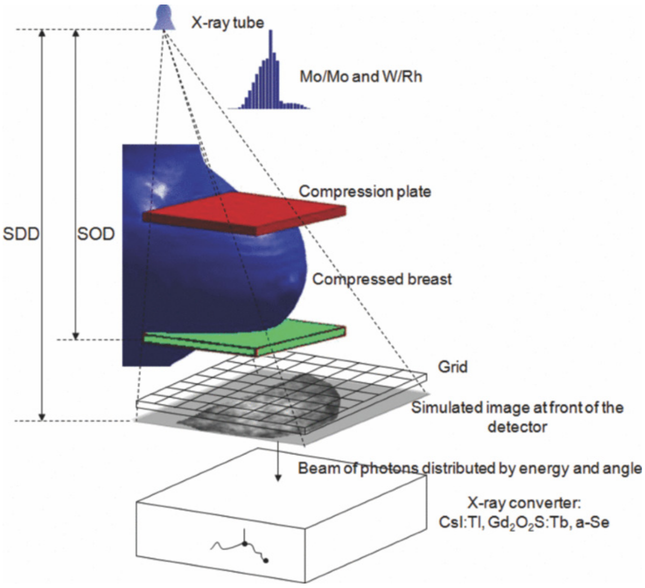

Figure 1: A simulation model of x-ray interactions in a mammographic procedure using different imaging detectors (3)

is a powerful instrument in providing a valuable data for the development of a scatter reduction algorithm in tomosynthesis imaging in comparison to measurement using dosimeters. This is due to the positioning problem and limitation of accessibility in dose measurement using a standard phantom or patient. In this case, MC calculation dose of every position can be easily calculated for every cm thickness in phantom and patient accurately. Some of the researchers, benchmarked photon spectral in mammography energy range using MC simulation instead of dose data. In 2014, an experiment was conducted by David et al., to study the spectra of standard mammography-quality beams using a MC simulations. Si-PIN spectrometer was employed as the dosimeter and the PENELOPE code was the MC simulator. The determination of the half value layers (HVL's) of each beam quality was conducted by using an ionization chamber. The simulated energy spectra of four different mammography energy ranges were compared with the experimental value as in Table I. The relative differences obtained between the simulated and experimental energy spectra were found to be less than 1.5% (5).

Table I: The relative differences (%) between the experimental and simulated mean energies (keV) of various mammographic beam qualities (5).

Quality	kV	Experimental (keV)	Simulated (keV)	Difference (%)
RQR-M1	25	16.30 ± 0.14	16.16 ± 0.20	0.9
RQR-M2	28	16.92 ± 0.15	16.77 ± 0.20	0.9
RQR-M3	30	17.31 ± 0.15	17.15 ± 0.18	0.9
RQR-M4	35	18.30 ± 0.17	18.05 ± 0.22	1.4

Ai, Gao and Yu (2014) introduced a new method to analyze the scattered particles produced in the process of low dose mammography, using MC simulation (6). The main purpose of the study was to reduce the impact of scatter radiation. MC algorithm was used to evaluate the scatter-to-primary ratio (SPR). Since the MC method does not pose additional radiation compared to the actual clinical procedure, a much easier comparison can be done with the hardware-based scatter correction method (6). The upgraded versions of two open source MC codes and MC graphics processing unit, has been developed by Ghammraoui and Badal in 2014. These codes were developed to analyze the effect of molecular interference in coherent x-ray scattering. The study was also conducted to evaluate the probability of characterizing breast composition, in a volume of interest of a whole breast phantom (7).

MC codes, such as, MCNP4b, 4c and MCNPX, have been widely used to simulate the radiation interactions in mammographic applications (8, 18, 20, 22). Leon, Brateman and Wagner (2014) applied MCNPX to evaluate the scatter fraction of a small pencil beam, using a mammographic geometry. The results showed low deviation between simulation and the measured data (8). Malliori et al., (2014) studied the impact on image quality when monochromatic beams were used for lower dose breast tomosynthesis (BT). MC simulation was conducted using two x-ray beams; 28 kVp and monochromatic 19 keV, at different entrance surface air kerma (9). Table II shows the mean glandular dose (MGD) values obtained from the MC codes (9), compared with the experimental data by Boone (2002) (10) and Dance (1990) (11). As indicated in the Table II, the simulated data shows low disparity with the experimental values.

GEANT4 toolkit were used in a research conducted by Vedantham, Shi and Karellas (2014), to investigate the large-angle x-ray scatter at the design energy of 25 keV, using Talbot-Lau interferometry for breast imaging. MC simulations of radiation transport using GEANT4 were carried out by adapting the implementation of C++ program. The transmission efficiencies of the gratings in parallel beam geometry estimated using the MC simulations, were compared with the theoretical calculation. MC simulations using cone beam geometry were also conducted for validation (12). A powerful version of MC named PENELOPE was applied to assess the scattered radiations in a digital mammography (13). Although the simulated area was about 1 mm, the accuracy of simulation was significant (13). 3D MC simulations of the grid geometrical parameters were performed by designing a linear anti-scatter grid on screen-film mammography (SFM) and digital mammography (DM) systems (14). This research was carried out by Khodajou-Chokami and Sohrabpour (2015), to remove the undesirable effects of scattered radiation with the grids.

Table II: ESAK and MGD dose calculations [aexperimental (10, 11); bsimulated (9)]

Phantom	Beam Type	Incident photon fluence (photons per mm²)	ESAK (mGy)	MGD (mGy) comparison estimations [a]	MGDMC (mGy) MC 2D[b]	MGDMC (mGy) MC BT [b]
	28 kVp W/Rh	$8.10x10^5$	0.1828	0.06	0.05	0.05
		$8.10x10^6$	1.8286	0.56	0.53	0.52
		$1.62x10^7$	3.6571	1.11	1.05	1.40
		$2.43x10^7$	5.4857	1.67	1.58	1.57
CT breast phantom	19 keV	$8.10x10^5$	0.1564	0.06	0.05	0.05
		$8.10x10^6$	1.5643	0.57	0.55	0.54
	28 kVp W/Rh	$1.62x10^7$	3.1285	1.13	1.10	1.09
		$2.43x10^7$	4.6928	1.70	1.65	1.64
	19 keV	$1.62x10^7$	3.6571	1.16	1.29	1.27
		$2.43x10^7$	5.4857	1.73	1.93	1.91
		$1.62x10^7$	3.1285	1.17	1.35	1.34
		$2.43x10^7$	4.6928	1.76	2.03	2.00

X-ray simulation in mammography

BEAMnrc is a simulation package inside EGSnrc, has been used for various applications in the last decade, which include, x-ray simulation and modelling of radiological modalities (15-19). Due to the simple interface, this code can be run on various processing platforms, including Windows, with minimal programming effort. Fig. 2 and Fig. 3 illustrate a simulation of an x-ray tube of a mammography unit by BEAMnrc. The model was made with the anode tilted to 13° from the vertical axis held in the place by a copper holder. The beryllium window with 1.2 mm thickness was defined as an additional slab (Fig. 2). The volume above the window was defined as vacuum. In this simulation, the number of particles, also called as 'history' in BEAMnrc, was set to 500 million particles ($5x10^8$) as simulations performed by other researchers (15-19). The maximum allowed time for the CPU to run the simulation was set to 500 hours, to prevent the CPU from shutting down before all the particles have been simulated.

MC CODES TO CALCULATE THE BREAST & GLANDULAR DOSE

For dosimetric assessments and organ dose evaluations of digital breast tomosynthesis (DBT), an MCNPX-based program was developed by Baptista et al. in 2015. Considering the MC results obtained from the organ dose study, the radiation doses were found to be in the range of ± 10 μSv, and comparable to the measured values (15). The study underlined the need to improve the estimation of doses, in DBT examinations for certain organs (20). GEANT4 is also a useful tool to calculate the absorbed dose and analyze the complex optimization of breast dosimetry. In a recent study by Fedon et al. (2015), the code was used to calculate the MGD, which is one of the main dosimetric quantities in mammography. Consequently, the MGD values were evaluated based on the corresponding ESAK (21). Hernandez, Seibert and Boone (2015) used MCNPX 2.6.0 to assess the monoenergetic normalized MGD

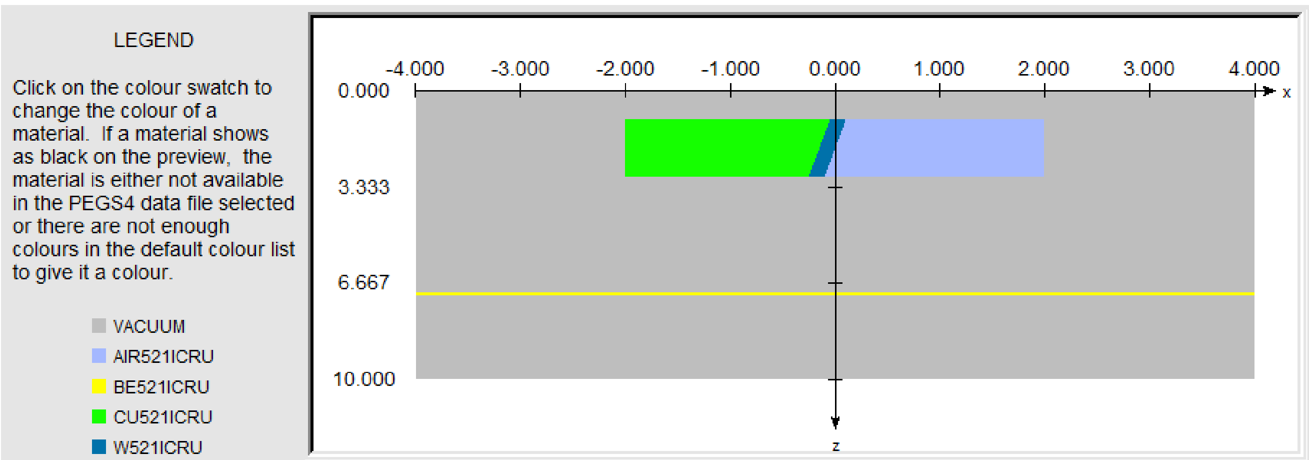

Figure 2: Radiation modelling using BEAMnrc source code. The EGS_Window based on the materials defined in the BEAMnrc program. The materials used for the simulation were beryllium (Be) window, tungsten (W) anode, copper (Cu) holder, air and vacuum.

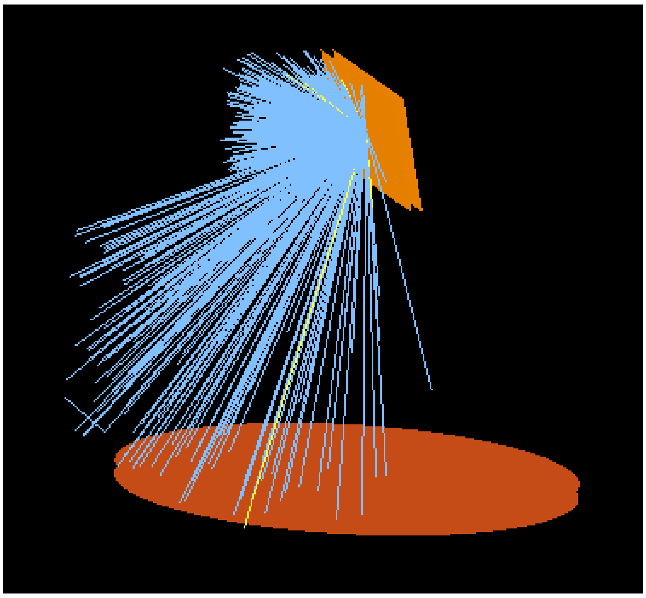

Figure 3: The interaction of electrons with the anode and the emergence of photons from the anode towards the Be window

values in a typical mammographic geometry, when heterogeneous glandular distributions were being considered. The MC calculated breast dose was found to be approximately 30% lesser than the homogeneous counterpart (22).

EGSnrc code together with the MC C++ class library was employed to derive the x-ray spectrum of a digital mammographic beam (23). Tube voltages between 26 and 32 kV (mammographic range) was applied in the study, and the simulation history was set to 50 million particles. The results showed that the uncertainty of the calculated values was less than 3% of the MC simulations, indicating the high accuracy of the MC modelling for low-energy beams. Furthermore, the measured and simulated HVL values, together with the HVL values calculated by the TRS-457, were obtained in the study. Good agreement was observed between the simulated and measured data. Also, considering the values recommended by the TRS-457, the maximum relative difference (%) of the simulated HVL values was found to be 3%, which demonstrates the capability of the MC code to perform precise calculations for mammographic applications. In this study, the glandular dose was determined by using the MCNPX code (23). MCNPX was utilized, in order to generate a monoenergetic glandular dose data (24). The purpose of this study was to calculate the breast dose in tomosynthesis, for arbitrary spectra of the Selenia Dimensions DBT system (24). The MC code was also employed to find the glandular dose distribution, for various thicknesses and glandularities using different x-ray energies (25).

OTHER APPLICATIONS OF MC CODES

The use of MC codes was not only limited to dose calculation. In 2010, a MC model of breast cancer was considered to estimate the tumor size, based on a series of mammographic images (26). In the research, Breast Cancer Screening Simulator (BCSS) model was used to generate the life history, in terms of the tumor growth and clinical progression. A computer-based simulation analysis was used to evaluate the relative impact of the mammographic tumor differentiable and tumor volume doubling time, on the poor screening outcomes in younger women compared with the older women. Finally, the simulated breast cancer model was applied to estimate the median tumor size that was detected on the mammographic image, and the mean tumor volume doubling time (26). In 2010, a computer program for tumor detection based on a mammographic MC model was developed by Forastero et al, 2010. The model was made based on two main sub-models; a model to detect the tumor, and another one to analyze the tumor growth. The model also confirmed the distribution of tumor detection probability, as a function of the tumor size. Furthermore, the frequency and transition probability of various histological types can be obtained, with the use of this established model (27).

MC simulation was also employed to calculate the correction factors of scattered radiation in DBT, based on the DBT geometry (28). Comparison between the calculated and measured results was found to be less than 10% (28). In the study by Daskalaki, Bliznakova and Pallikarakis (2016), MC modelling was employed to evaluate the effect of silicone breasts, towards the contrast of the breast images. Based from the results; It was found that implants thicker than 26 mm can change the view of underground structures during breast imaging (29).

CONCLUSION

MC simulation is feasible for mammographic dosimetric applications. This review summarized the potential of MC codes in mammographic studies which include, radiation (primary and scattered) simulation, MGD calculation and PSF assessment. In improving the accuracy of dose calculations in mammography, MC simulation is the best applicable method, offering accuracy in the dose calculation with no extra dose to the patient, and cost effective. It became possible to calculate MGD or PSF in the same way as measurement in the clinical setting of mammography.

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