Simulation and comparison of radiology X-ray spectra by MCNP and GEANT4 codes

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ABSTRACT

Monte Carlo method is a very accurate method to optimize medical diagnostic radiology spectra and simulation of radiation transportation. Using MCNP code, radiology and mammography attenuated x-rayspectrawere simulated.The IPEM report number 78 was used as a reference to compare with the GEANT4 and MCNP simulations because of its popularity and wide availability. The results of GEANT4 in 40keV showed a good homogeneity with IPEM report in terms of intensity, whilst the MCNP code in tube voltage 150kVp showed a very good agreement. Whereas theGEANT4outputintensityinallcases was less than the IPEM report, MCNP code showed higher characteristic peak intensity. The MCNP results were obtained with a less error percentage in comparison with IPEM reportexceptatlowenergies. The comparison shows a good agreement between these two codes. MCNP shows a very goodagreement in high tube voltage whereas GEANT4 showsvery goodagreement in low tube voltage.

Key words: Radiology; Mammography; MCNP; GEANT

INTRODUCTION

In recent years, simulation methods have played a very important role in science. Computational simulation of x-ray spectra is one of the important methods for investigation of patient dose and image quality in diagnostic radiology systems [1-3]. Since Kramer's first attempt in 1923, several research groups have been working to find an accurate method for predicting x-ray spectra, would be very useful, because the experimental measurement of x-ray spectra [4, 5] is time- consuming and requires special equipment which is available only in some laboratories. Moreover, using Monte Carlo is a very accurate method for simulation of radiation transportation. Although, Monte Carlo modeling is the slowest method, it can be easily applied in systems with complex geometries and different materials. This owns to the fact that Monte Carlo methods permit to simulate the passage of radiation through different matter [6-8]; taking into account all the relevant physical process, all particles (e.g. electrons and photons) can be tracked until they stop. Actually, there are several public domain general-purpose Monte Carlo codes such as EGS4(Electron Gamma Shower)[9], MCNP(Monte Carlo N Particle)[10] and GEANT4(Geometry and Tracking)[11, 12].The aim of this study is a comparison between very well-known Monte Carlo codes, MCNPand GEANT4, for making a suitable choice in the energy domain of application

MATERIALS AND METHODS

MCNP Code

MCNP is a general-purpose Monte Carlo N–Particle code that can be used for neutron[8], photon[13, 14], electron[15, 16], or coupled neutron/photon/electron transport, including its capability to calculate Eigen values for critical systems. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by the first and second-degree surfaces and the fourth-degree elliptical tori. For photons, the code takes account of incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung. A continuous-slowing-down model is used for electron transportation that includes positrons, k-x rays, and bremsstrahlung, but does not include external or self-induced fields.

IPEM Report 78

There is an electronic data book, based on a semi-empirical model computing x-ray spectra, includes spectrum processing software[17]. This data book generates spectra for a variety of radiological parameters such as different target and filter materials, electron incidence angle and the diagnostic radiology and mammography energy ranges. XCOM photon cross-section library is used in this version. Because of its popularity and wide availability, The IPEM report number 78 [18]was used as a reference comparing with the GEANT4 and MCNP simulations.

Simulation of X-ray Spectra Using MCNP

Molybdenum and Tungsten are employed as a common target in x-ray tube. While tungsten is the most widely used anode material, Molybdenum is used as anode material in mammographic X-ray tubes[19]. Table 2 shows their characteristic peaks. It is very obvious that when the energy of an electron incident on the target exceeds the binding energy of an electron of a target atom, it is energetically possible to eject the electron and ionize the atom. During filling the vacancy with an outer shell electron, a characteristic X-ray photon with energy equal to the difference between the binding energy of the electron shells is released. Because of binding energies are unique, consequently, the emitted X-rays have discrete energies that are characteristic of that element. These discrete energy peaks superimpose oncontinues bremsstrahlung spectrum, as obvious in Figs 2-6 too. Continues spectrum comes from interaction between accelerated electrons emerge through cathode and anode nucleus. This work used the MCNP version 4C code to simulate the diagnostic radiology and mammography attenuated x-ray spectra, for different combinations of target-filter and tube voltage, presented in table 1. The anode angle is defined as the angle of the target surface with respect to the central ray in the X-ray field, as shown in [Figure. 1]. This MCNP simulation utilized detailed physics treatment model and the results were compared with a novel article [20] using GEANT4 version 7.0 lowenergy physical models included in the extensions of GEANT4 toolkit was employed in that work. The IPEM report number 78 was used as a reference [18] to compare with the GEANT4 and MCNP simulations because of its popularity and wide availability. The geometry of the simulation is shown in (Figure. 1). We consider this geometry in both mammography tube and conventional X-ray tube. The main difference is target material (molybdenum versus tungsten). Attenuation of the X-ray beam occurs because the inherent filtration of the tube and added filtration.

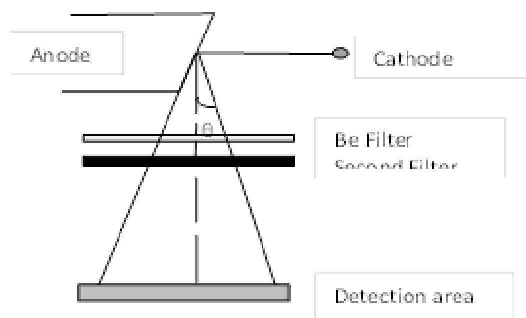

Figure 1. Schematic used for computational simulation of x-ray spectra in both MCNP and GEANT4 codes.

Simulation was done in two programs. In the first program, electrons with energies corresponding to the tube voltage were impinging on targets with the same material and electron incidence angle of the simulated tube. The bremsstrahlung photons passed from inherent Be filtration and these energy spectra of the photons was recorded in a data file. This spectrum was normalized and used as a photon source in the second program. The second simulation was performed to provide the filtration of the x-ray. Depending on the required radiation quality, after passing from Al or Mo filter, the final output was normalized and saved.

Table1. Parameters combinations for the x-ray spectra simulated using MCNP and GEANT4.

Tube Voltage (kVp)	Target Material / Angel (degree)	Filter (mm)
25	Mo / 17	0.5 Be + 0.03 Mo
30	Mo / 17	0.5 Be + 0.03 Mo
40	W / 22	4.0 Be + 2.5 Al
100	W / 22	4.0 Be + 2.5 Al
150	W / 22	4.0 Be + 2.5 Al

Table2. Molybdenum and Tungsten x-ray characteristic

	$K_{\alpha1}$ (keV)	$K_{\alpha2}$ (keV)	$K_{\beta1}$ (keV)
Tungsten	59.32	57.98	67.24
Molybdenum	17.48	17.37	19.61

The filtration effect of the air inside the irradiation chamber was ignored. The distance between the focal spot and the detection area was 1 m. The distance between the focal spot and the first filter was 10 cm. There was no air attenuation between the filters. The effect of the focal spot size was considered negligible, even for the heel effect[3, 19]. Finally, surface current tally, F1, for photons was plotted after passing each 10 statistical checks.

RESULTS

Figures 2 to 6 shows a comparison between MCNP, GEANT4 (low energy modeling) and IPEM report No.78. Also, the tables 3 to 6 obviously show Monte Carlo relative errors to the IPEM report. For better view, we only have considered that part of the X-ray spectra in which characteristic peaks exist, for 100 kV and 150 kV.The corresponding data for this voltage are reported in table 5 and table 6.

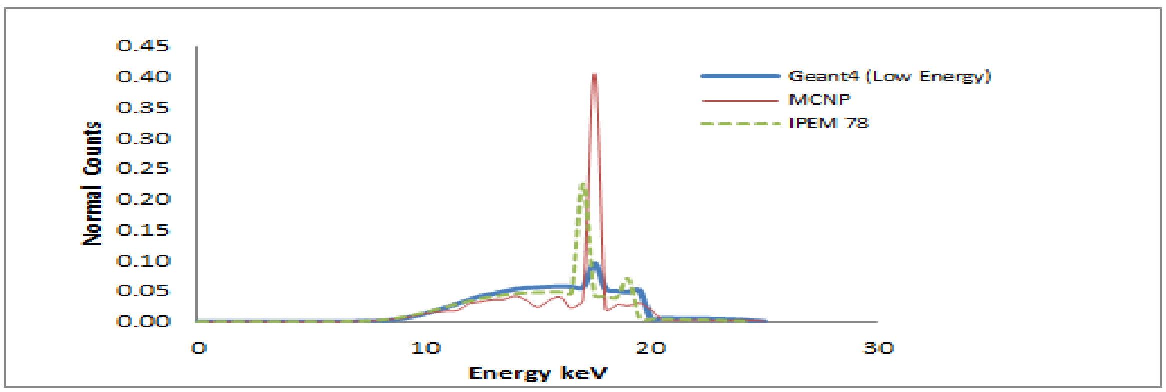

Figure 2. X-ray spectra, tube voltage: 25 kV, Mo target At 17 degrees, filters: 0.5 mm Be and 0.03 mm Mo. Present work (narrow red line), GEANT4 simulation (Bonifacio et al. 2005, thick blue line) and reference data (IPEM78, green dash line).

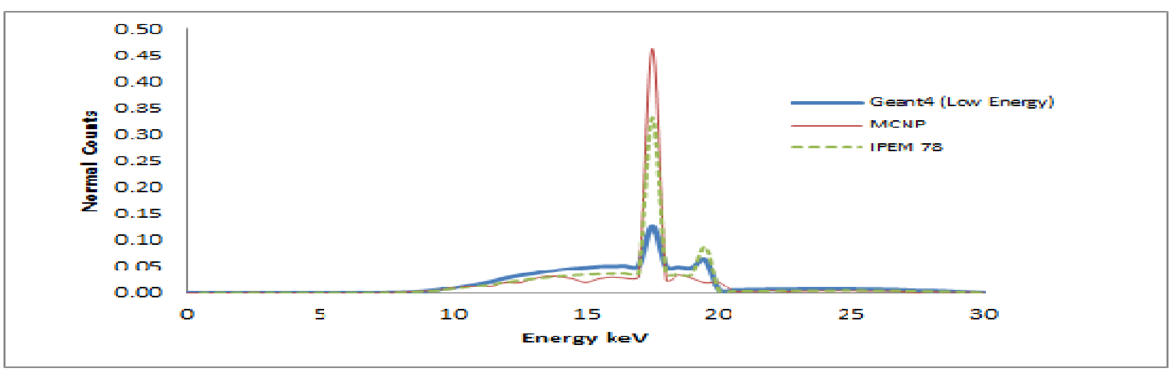

Figure 3. X-ray spectra, tube voltage: 30 kV, Mo target At 17degrees, filters:0.5 mm Be and 0.03 mm Mo. Present work (narrow red line), GEANT4 simulation (Bonifacio et al. 2005, thick blue line) and reference data (IPEM78, green dash line).

Table3. MCNP and GEANT4 relative errors compared with IPEM No.78- for 25kV.

	X-ray characteristic	Low Energy %	MCNP 4C %
IPEM 78	K_α K_β	-57.86 -28.04	+79.84 -86.79

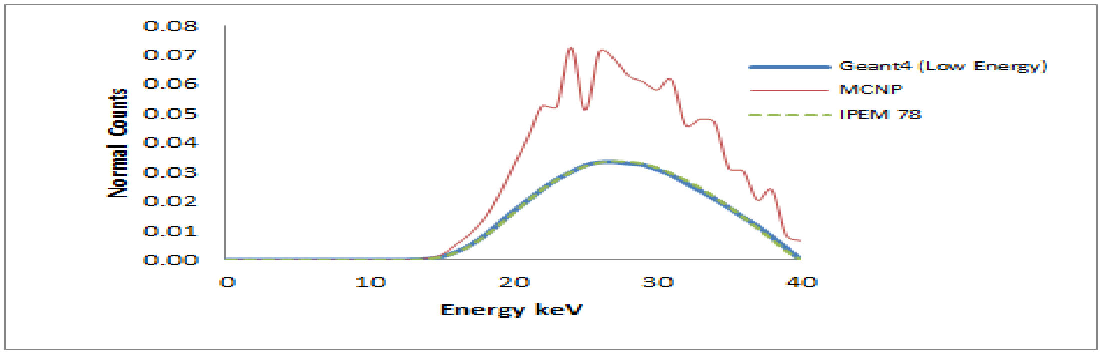

Figure 4. X-ray spectra, tube voltage: 40 kV, W target, At 22degrees, filters:4.0 mm Be and 2.5 mm Al. Present work (narrow red line), GEANT4 simulation (Bonifacio et al. 2005, thick blue line) and reference data (IPEM78, green dash line).

Table4. MCNP and GEANT4 relative errors compared with IPEM No.78- for 30kV.

	X-ray characteristic	Low Energy %	MCNP 4C %
IPEM 78	K_α K_β	-61.81 -28.99	+39.40 No peak

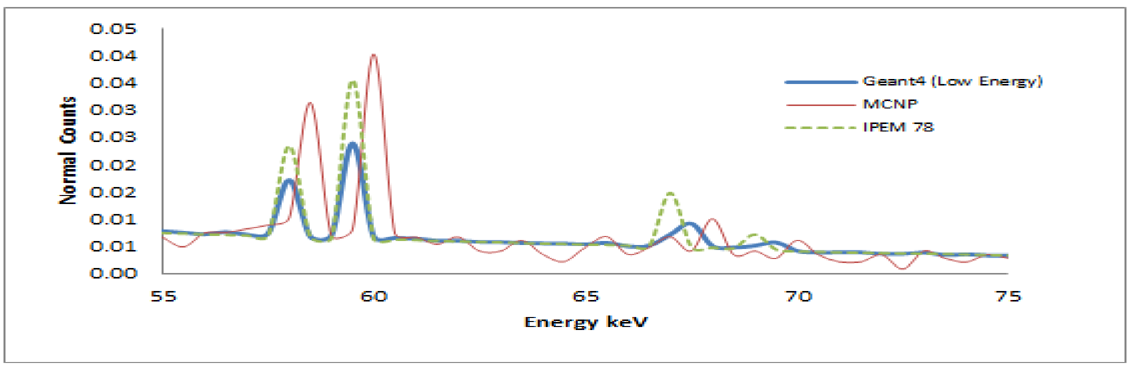

Figure 5. X-ray spectra, tube voltage: 100 kV, W target, At 22 degrees, filters:4.0 mm Be and 2.5 mm Al. for better comprehension, only that part of the X-ray spectra in which characteristic peaks exist, have been considered. Present work (narrow red line), GEANT4 simulation (Bonifacio et al. 2005, thick blue line) and reference data (IPEM78, green dash line).

Table5. MCNP and GEANT4 relative errors compared with IPEM No.78- for 100kV.

	X-ray characteristic	Low Energy %	MCNP 4C %
IPEM 78	$K_{\alpha1}$ $K_{\alpha2}$ $K_{\beta1}$ $K_{\beta2}$	-26.72 -32.74 -37.99 -20.50	+33.80 +13.36 -32.19 -14.86

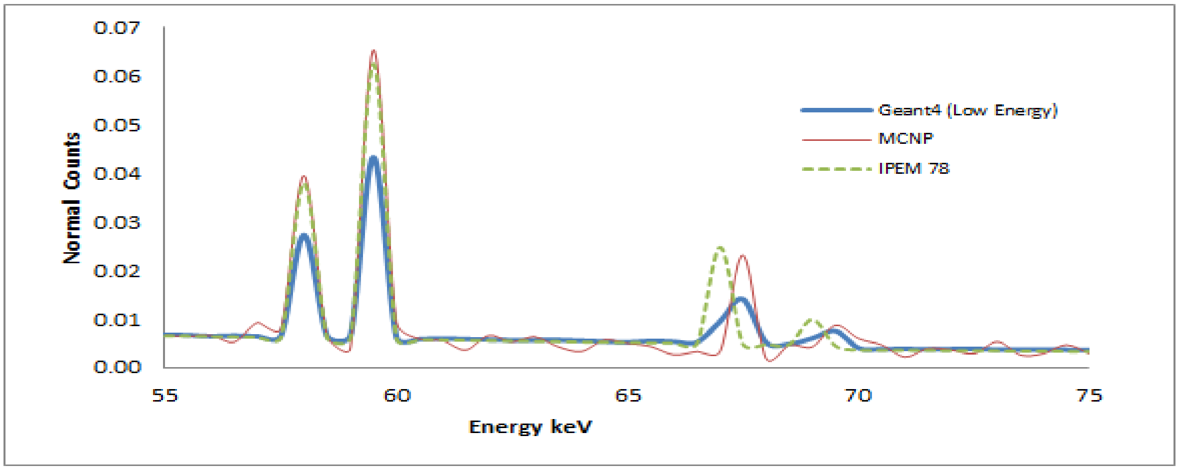

Figure 6. X-ray spectra, tube voltage: 150 kV, W target , At 22 degrees, filters:4.0 mm Be and 2.5 mm Al. for better comprehension, only that part of the X-ray spectra in which characteristic peaks exist, have been considered. Present work (narrow red line), GEANT4 simulation (Bonifacio et al. 2005, thick blue line) and reference data (IPEM78, green dash line).

Table6. MCNP and GEANT4 relative errors compared with IPEM No.78- for 150kV

	X-ray characteristic	Low Energy %	MCNP 4C %
IPEM 78	$K_{\alpha1}$	-28.26	+3.76
	$K_{\alpha2}$	-30.76	+4.56
	$K_{\beta1}$	-43.18	-6.71
	$K_{\beta1}$	-24.24	-12.11

DISCUSSION

In this work, radiological spectra were simulated using MCNP, and using same work with GEANT4 code, comparisons were done. Radiological spectra were simulated withvarious filtration and tube voltage depends on their applications. The Figures. 2 to 6 shows a comparison between MCNP, GEANT4 and IPEM report No.78. Also, the tables 3 to 6 obviously show Monte Carlo relative errors to the IPEM report. In these tables, peaks that have overestimated value relative to the IPEM report, are shown as positive numbers and peaks with lower estimated value relative to the IPEM report, are shown as negative numbers.

It is seen from Figure 2 and table 3, for 25 kV that both MCNP and GEANT4, report characteristic peaks with a higher relative error in contrast with IPEM. Although GEANT4 shows lower intensity compared with IPEM report, MCNP predicts X-ray photon intensity in a higher value.

For 30 kV, it is clearly obvious that, again MCNP shows a higher intensity compared with IPEM report. Lower X-ray characteristic peak (K_{α}) is very obvious in both GEANT4 and MCNP as shown in Figure. 3 and table 4. Unlike GEANT4, MCNP did not report a clear peak for K_{β}. This is a disadvantage for this code. Using suitable variance reduction might be the key of the problem.

Characteristic K- X-ray is emitted only when the electrons impinging on the anode exceed the binding energy of K-shell that is 69.5 kVp for tungsten anode and 20 kVp for molybdenum anode. Simulation of radiological spectrum in 40 kV is presented in Figure. 4. As we expect, we do not have any characteristic peaks in our spectra. The energy of X-ray produced by tube is under the K edge of the tungsten target. GEANT4 shows very good agreement of the bremsstrahlung intensity, but MCNP shows a higher intensity with undesirable fluctuations.

As Figure. 5 and its corresponding table shows, in comparison with GEANT4, MCNP reports characteristic peaks with a lower relative error and higher photon intensity.

Form Figure. 6 and table 6, It is obvious that in this high energy tube voltage, MCNP shows a very goodagreement. Except $K_{\beta2}$ reported at lower relative error in comparison with GEANT4, other characteristic peaks were simulated with relative error lower than 7% or even 5% relative to the IPEM report, WhereasGEANT4 reported the data with more than 30% relative error. Unlike GEANT4, in MCNP, K_{α}characteristic peaks are higher in simulated spectra for all simulations where they are present. Results show MCNP hasa very goodagreement in 150kV and GEANT4 shows a very good agreement in lower tube voltage, 40 kV. Discrepancies between the intensities of characteristic and bremsstrahlung photons were observed. These results indicate problems that should be related to the ionization process and/or the atomic relaxation implemented in the code.

CONCLUSIONS

In this paper, a comparison between MCNP 4C and GEANT4 with IPEM report was made. For diagnostic imaging, electrons from the cathode filament are accelerated towards the anode by a peak voltage ranging from 20-150 kV, so we focused in this energy range. It can be obviously seen from results, the comparison shows a good agreement between these two codes. As we see the more energy tube voltage, the less relative errors, especially for higher energy characteristic peaks are made. MCNP shows a very goodagreement in high tube voltage whereas GEANT4 showsvery goodagreement in low tube voltage.

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