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MONTE CARLO SIMULATION OF X-RAY SPECTRA IN DIAGNOSTIC RADIOLOGY AND MAMMOGRAPHY USING GEANT4

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ABSTRACT

The open-source object-oriented toolkit GEANT4 was used to simulate x-ray spectra in diagnostic radiology and mammography. The simulations were performed using different combinations of target, filters and tube voltages. All the relevant physical processes were included in the calculations: Compton scattering, photoelectric effect, Rayleigh scattering, bremsstrahlung and ionization. The analyzed energy range is from 10 keV to 150 keV. Both Penelope and Low Energy physical models included in the Low Energy extensions of GEANT4 toolkit were used in this work. Range cuts for electron and gamma were set to 500 nm and 3000 nm, respectively. The simulated x-ray spectra using both physics models were compared with calculated spectra generated by the IPEM report number 78. Results show good agreement for the bremsstrahlung intensity for the spectra with tube voltages 40 kV, 100 kV and 150 kV, while the bremsstrahlung intensity is larger for the simulated spectra with 25 kV and 30 kV. Simulated characteristic peaks present lower intensities all spectra. These discrepancies should be related with the ionization process and/or the atomic relaxation implemented in the code. The cross section tables for electrons used in the simulations should be checked.

1. INTRODUCTION

One of the most important factors to protect the patient from radiation and to optimize medical diagnostic radiology is to understand the relationship between radiation dose and image quality. This aim can be reached with the knowledge of the diagnostic x-ray energy spectra, which provide a complete description of the x-ray beam. Since Kramers' first attempt in 1923, several research groups are working to find an accurate method for predicting x-ray spectra, which would be very useful because experimental measurement of x-ray spectra[1,2] is time consuming and requires special equipment which is available only in some laboratories.

There are three categories of methods for x-ray spectra prediction: empirical models[3], semi-empirical models[4,5] and Monte Carlo[6,7,8] simulations. The main advantage of empirical and semi-empirical models is the low computation time consumption. Otherwise these models make possible only the use of preset target and filter combination. Although, Monte Carlo modeling is the slowest method, it can be easily applied in systems with complex geometries and different materials. This is owned to the fact that Monte Carlo methods permit to simulate the passage of radiation through matter taking into account all the relevant physical process, and all particles (e.g. electrons and photons) can be tracked until they stop. Actually, there are several public domain general-purpose Monte Carlo code such as EGS4 [9], MCNP[10] and GEANT4[11,12].

This work used the GEANT4 version 7.0 code to simulate the diagnostic radiology and mammography x-ray spectra, and compare them with a catalogue of x-ray spectra IPEM report number 78[13] described below. GEANT4 is a relatively new Monte Carlo code originally developed for high-energy physics applications. However its popularity is increasing in other areas, including space and medical applications. The simulation consisted of bombarding the target with an electron beam and then attenuating the emitted radiation with specific filters. The attenuated spectrum was obtained for various target - filters - tube voltage combinations. GEANT4 code provides two different physical models which are indicated for the proposed energy range (10keV – 150 keV). Both are used in this work.

2. MATERIALS AND METHODS

2.1. The GEANT4 Monte Carlo Code

GEANT4 is an open-source object-oriented toolkit developed by an international collaboration which can be used to simulate the passage of particles through matter. The code is written in C++ programming language and provides a complete set of software components for all aspects of the simulation process: descriptions of geometry, involved materials, particles of interests, physical processes, generation of event data and the visualization of the geometry and particle trajectories. The toolkit contains a set of physical models[14] describing how particles interact with materials. The user must specify which physical process must be under consideration in the simulation. GEANT4 includes a set of physical processes to extend the range of validity of electromagnetic interactions down to 250 eV. These extensions come in two packages: Low Energy and Penelope models. Some important physical processes are provided only by these packages: x-ray fluorescence and Auger electron emission. Each kind of particle - gamma, electron and positron - requires production thresholds which should be set by the user. This threshold should be defined as a distance, or range cut-off, which is internally converted to an energy for individual materials[15].

2.2. Simulation of X-ray Spectra Using GEANT4

The simulations consisted of electrons with energies corresponding to the tube voltage impinging on targets with the same material and electron incidence angle of the simulated tube. The energy spectrum of the photons emitted in the solid angle corresponding to the simulated tube was recorded in a data file. A second simulation was performed to provide the filtration of the x-ray. The inherent filtration of the tube as well as additional filtration was simulated by shooting photons, with the energy distribution obtained in the first simulation, on plates made of Be, Al and Mo filters, depending on the required radiation quality. The filtration effect of the air inside the irradiation chamber was also included. The distance between the focal spot and the detection area is 1 m. The distance between the focal spot and the first filter is 10 cm. There is no air attenuation between the filters. The effect of the focal spot size is considered negligible, even for the heel effect [6]. The photon energy is recorded for each photon that crosses the detection region, which consists of a volume filled with air. The geometry of the simulation is shown in Fig. 1.

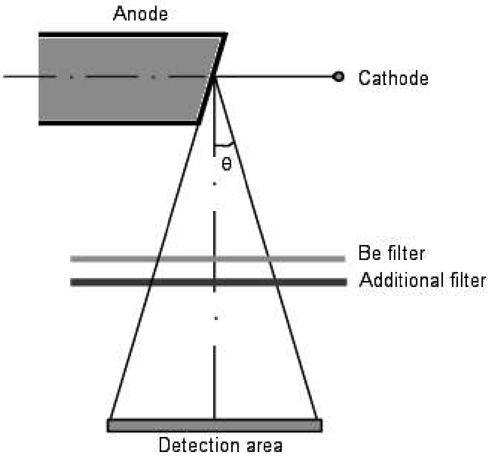

Figure 1. Geometry used for computational simulation of x-ray spectra.

Table 1 shows the different investigated parameters. The simulations were performed using the Low Energy and Penelope physical models. The following processes were included in the simulations: Compton scattering, photoelectric effect, Rayleigh scattering, bremsstrahlung and ionization. The range cuts for electron and gamma were set to 500 nm and 3000 nm, respectively. Energy cuts for secondary particles were chosen to be 250 eV. These values must be carefully chosen because computation time and quality of results depend strongly on them.

Table 1. Parameters combinations for the x-ray spectra simulated using GEANT4

Tube Voltage (kV)	Target Material / Angle	Filter (mm)
25	Mo / 17 º	0.5 Be + 0.03 Mo
30	Mo / 17 º	0.5 Be + 0.03 Mo
40	W / 22 º	4 Be + 2.5 Al
100	W / 22 º	4 Be + 2.5 Al
150	W / 22 º	4 Be + 2.5 Al

2.3. IPEM Report 78

The electronic version of the data book includes a spectrum processing software, which allows the generation of spectra for a variety of target and filter materials over the diagnostic radiology and mammography energy range. This version is based on semi-empirical model for computing x-ray spectra of Birch and Marshall[4] and uses XCOM photon cross-section library of Berger and Hubell[16]. The IPEM report number 78 was used as reference to compare with the GEANT4 simulations because of its popularity and wide availability.

3. RESULTS AND DISCUSSION

Figures 2 to 6 show the comparisons between the GEANT4 simulations and the IPEM report 78 calculated spectra, according to the beam characteristics detailed in Table 1.

Both Penelope and Low Energy physical models present similar results for all the proposed situations. Since the spectra have normalized areas, overestimation in the intensity of one type of physical process causes underestimation in the intensity of other processes. Because of this, the bremsstrahlung accordance can only be verified in the spectra without characteristic peaks (figure 4).

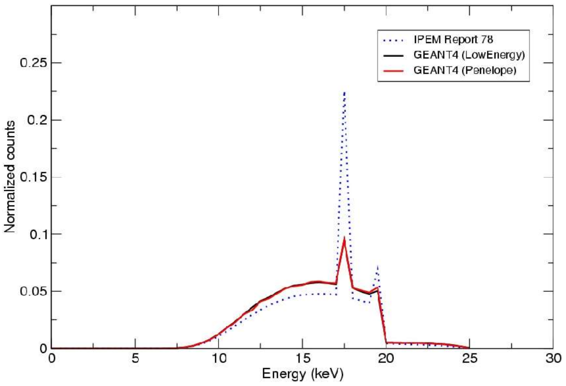

Figure 2. Two simulated x-ray spectra compared with a calculated spectrum[3]. Characteristics: tube voltage: 25 kV, molybdenum target at 17 degrees; filters: 0.5 mm beryllium and 0.03 mm molybdenum.

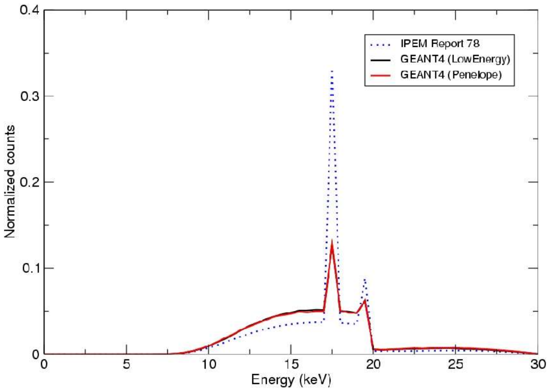

Figure 3. Two simulated x-ray spectra compared with a calculated spectrum[3]. Characteristics: tube voltage: 30 kV, molybdenum target at 17 degrees; filters: 0.5 mm beryllium and 0.03 mm molybdenum.

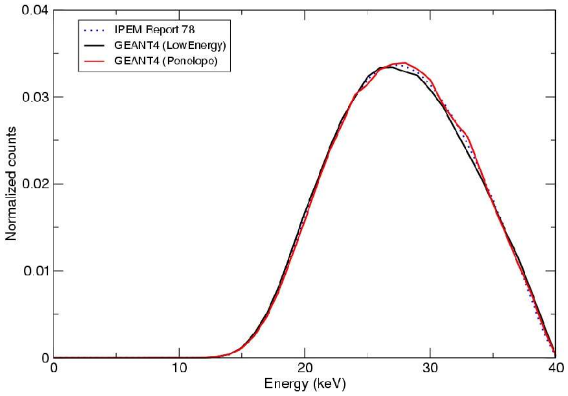

Figure 4. Two simulated x-ray spectra compared with a calculated spectrum[3]. Characteristics: tube voltage: 40 kV, tungsten target at 22 degrees; filters: 4.0 mm beryllium and 2.5 mm aluminum.

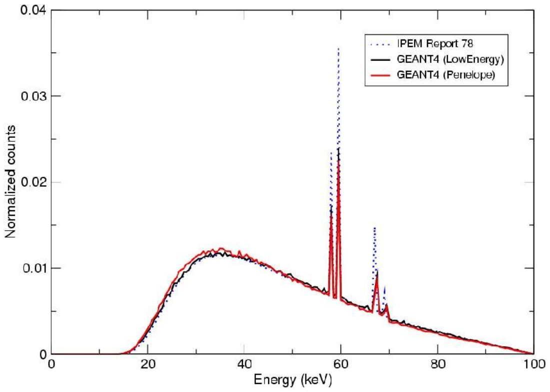

Figure 5. Two simulated x-ray spectra compared with a calculated spectrum[3]. Characteristics: tube voltage: 100 kV, tungsten target at 22 degrees; filters: 4.0 mm beryllium and 2.5 mm aluminum.

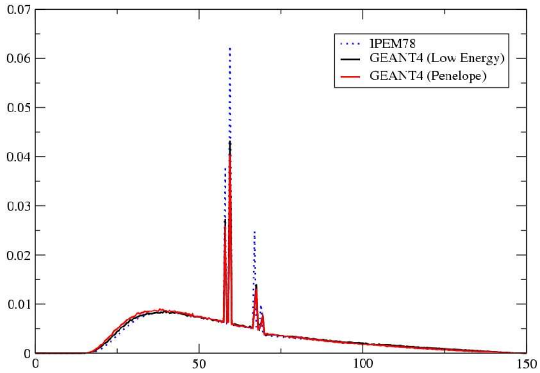

Figure 6. Two simulated x-ray spectra compared with a calculated spectrum[3]. Characteristics: tube voltage: 150 kV, tungsten target at 22 degrees; filters: 4.0 mm beryllium and 2.5 mm aluminum.

Results show very good agreement of the bremsstrahlung intensity for the spectra with tube voltages 40 kV and a reasonable accordance for 100 kV and 150 kV. A higher bremsstrahlung intensity was noticed for the simulated spectra with 25 kV and 30 kV. Characteristic peaks are lower in the simulated spectra for all the simulations where they are present. These results point to a low than expected proportion between the characteristic photons and the bremsstrahlung photons. Quantitative and more precise study about the origin of this discrepancy becomes necessary, since it was also observed in simulations with other Monte Carlo codes[17,18].

4. CONCLUSIONS

Object-oriented toolkit GEANT4 was used to simulate x-ray spectra in diagnostic radiology and mammography. Simulated spectra were compared with a catalogue of x-ray spectra. Discrepancies between the intensities of characteristic and bremsstrahlung photons were observed. These results indicate problems that should be related with the ionization process and/or the atomic relaxation implemented in the code. Cross section tables for electrons used in the simulations should be checked to consider the possibility of improving the results in the investigated energy range. Code developers were communicated about our results and we hope to help with improvements in the Low Energy extension of the GEANT4. Quantitative and more detailed evaluations are in progress. As soon as the electron transport code and its respective cross section tables are revised, GEANT4 can become a powerful tool to simulate typical x-ray tubes used in diagnostic radiology.

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