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Monte Carlo simulation of X-ray spectra and evaluation of filter effect using MCNP4C and FLUKA code

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ABSTRACT

The general-purpose MCNP4C and FLUKA codes were used for simulating X-ray spectra. The electrons were transported until they slow down and stop in the target. Both bremsstrahlung and characteristic X-ray production were considered in this work. Tungsten/aluminum combination was used as target/filter in the simulation. The results of two codes were generated in 80, 100, 120 and 140 kV and compared with each other. In order to survey filter effect on X-ray spectra, the attenuation coefficient of filter was calculated in 120 kV. More details of filter effect have been investigated. The results of MCNP4C and FLUKA are comparable in the range of bremsstrahlung spectra, but there are some differences between them especially in specific X-ray peaks. Since the specific peaks have not significant role on image quality, both FLUKA and MCNP4C codes are fairly appropriate for production of X-ray spectra and evaluating image quality, absorbed dose and improvement in filter design.

1. Introduction

X-ray machines are one of the most important facilities which are utilized in radiography and radiotherapy. Knowledge of the X-ray energy spectrum of a diagnostic X-ray tube is essential for evaluating image quality and absorbed dose to the patient (Sanborg et al., 1994). X-ray spectra have been determined by measuring the X-ray output experimentally. Experimental measurement of X-ray spectra requires special equipment which is available only in a limited number of laboratories (Fewell and Shuping, 1978; Fewell et al., 1981; Antonuk et al., 1997; Wilkinson et al., 2001). Fewell et al. measured X-ray spectra with different target/filter combinations for over two decades and have published several measured spectra (Fewell and Shuping, 1978; Fewell et al., 1981). However, the measurement of X-ray spectra is impractical for a clinical X-ray machine and specialized equipment is required which is available only in some laboratories. Different methods have been developed for numerically prediction of X-ray spectra. These can be divided into three categories: empirical models (Fewell and Shuping, 1978; Fewell et al., 1981; Boone et al., 1997; Boone and Seibert, 1997), semi-empirical models (Boone, 1988; Birch and Marshall, 1979; Tucker et al., 1991; Blough et al., 1998) and Monte Carlo modeling (Kulkarni and Supe, 1984; Acosta et al., 1998; Bhat et al., 1999; Verhaegen et al., 1999; Ng et al., 2000; Ben Omrane et al., 2003; Verhaegen and Castellano, 2002). Although, purely empirical and semi-empirical models remain the fastest methods for X-ray spectra prediction, the models proposed so far still have limitations which prevent their adoption for a large range of applications (Ay et al., 2004a). The use of the Monte Carlo method to simulate radiation transport has become the most accurate means of predicting the X-ray spectra even in complex geometries owing to more accurate physics modeling. Moreover, the method tracks the evolution of all secondary particles (and their descendants) generated by primary electrons. For the purpose of Monte Carlo simulation of X-ray spectrum, some authors have used self-written or in house developed computer codes (Kulkarni and Supe, 1984; O'Meara et al., 1998), while others have used public domain general-purpose Monte Carlo codes such as EGS4 (Bhat et al., 1998, 1999; Ben Omrane et al., 2003), MCNP (Verhaegen et al., 1999; Mercier et al., 2000) and ITS (Ng et al., 2000). Nevertheless, the prediction of X-ray spectra using the Monte Carlo method is time consuming compared to empirical and semi-empirical models. Few works are available on X-ray spectra production, using general-purpose Monte Carlo codes especially new codes like FLUKA. On the other hand, these codes have many advance features that can be used for more complicated problems, like simulating CT images of complex phantom geometries and dosimetric calculations. Indeed these codes have many variance reduction capabilities, which can be used for time consuming simulations such as dose calculation

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in fluoroscopy. The first step for testifying the multipurpose codes in such problems is to estimate their accuracy on X-ray spectra production.

In our previous work, MCNP4C Monte Carlo code has been used to simulate the diagnostic radiology and mammography X-ray tube (Ay et al., 2004b). In this work, we used FLUKA Monte Carlo code to produce X-ray spectra and we compared it with MCNP4C and experimental results. The effect of Al filter on X-ray spectra has been investigated in more detail.

2. Material and methods

2.1. The MCNP4C code

MCNP4C is a general-purpose three-dimensional Monte Carlo code that can be used for neutron, photon and electron or coupled neutron/photon/electron transport (Briesmeister, 2000). For photon transport, the code takes into account incoherent and coherent scattering, the possibility of fluorescent emission after photoelectric absorption and bremsstrahlung. The continuous slowing down approximation energy loss model is used for electron transport. To follow an electron through a significant energy loss, the MCNP4C code breaks the electron's path into many steps. These steps are chosen to be long enough (with valid multiple scattering theories) to encompass many collisions but short enough so that the mean energy loss in any one step is small (to ensure that approximations necessary for multiple scattering theories are satisfied). Except for the energy loss and straggling calculation, the detailed simulation of the electron history takes place in the sampling of the substeps. The Goudsmit–Saunderson theory is used to sample from the distribution of angular deflections, in a way that the direction of the electron can change at the end of each substep. For electron transport, MCNP4C addresses the sampling of bremsstrahlung photons at each electron substep. The table of production probabilities is used to determine whether a bremsstrahlung photon will be created (Hughes, 1997). The el03 database also includes characteristic *k* X-ray production probabilities. The el03 evaluation is derived from the ITS 3.0 code system (Halbleib et al., 1992).

2.2. The FLUKA code

FLUKA uses an original multiple Coulomb scattering transport algorithm for electrons, which gives the correct lateral displacement even near the boundaries (Ferrari et al., 1991). In each step of the multiple scattering algorithms, the discrete event cross sections of the continuous energy loss are considered. The bremsstrahlung differential cross sections of Seltzer and Berger (Ferrari et al., 1991; Seltzer and Berger, 1985, 1986) have been extended, and the angular distribution of bremsstrahlung photons is sampled accurately. The Landau–Pomeranchuk–Migdal suppression effect (Landau and Pomeranchuk, 1953; Migdal, 1956, 1957; Landau and Pomeranchuk, 1965) and the Ter-Mikaelyan (1954) polarization effect in the soft part of the bremsstrahlung spectrum are also implemented. The present lowest transport limit for electrons is 1 keV. Although in high-*Z* materials the Moli'ere multiple scattering model becomes unreliable below 20–30 keV, a single-scattering option is available which allows to obtain satisfactory results in any material also in this low-energy range. The characteristic X-rays in FLUKA are optionally activated either by the default physics selected for the simulation or by the card EMFFLUO. The FLUKA code will take into account all detailed interactions of six *K* and *L* single subshells. The fluodt.dat includes the cross sections of characteristic X-rays and other data, required for low-energy electron–photon transport (Fasso et al., 2003).

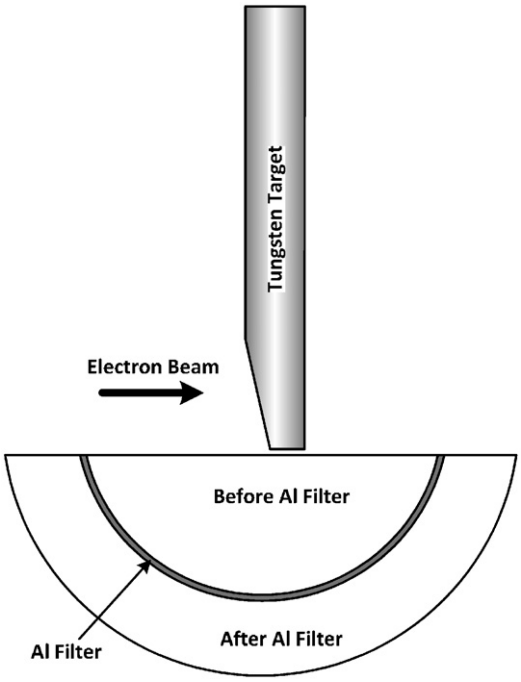

Fig. 1. Geometry of X-ray tube.

2.3. The specification of X-ray tube

The geometry of X-ray tube has been implemented accurately in the simulation. The angle of electron's departure from the cathode is precisely considered in order to get 1.2 mm focal spot. The anode is made from tungsten with an angle of 12°. The aluminum filter thickness is 1.2 mm (Fig. 1). When the electron beam hits the tungsten target, X-ray photons are generated. The energy of electron beam was chosen to be 80, 100, 120 and 140 keV. The electrons and photons have been transported inside the target and filter and the bremsstrahlung and specific X-ray spectrum have been produced. The spectra of these photons have been calculated by track length method in both Monte Carlo codes.

2.4. The effect of Al filter

In order to evaluate the effect of Al filter, the X-ray spectrum is calculated before and after the Al filter by both codes. For this purpose the X-ray spectrum of 120 kV has been treated as a point source in the center of spherical Al filter. With this method the calculation time has been reduced to several minutes. In order to scrutinize the Al filter effect in more detail, photon sources with energies from 10 to 140 keV with 10 keV steps has been considered. The values of collided and uncollided photons as well as total penetrating photons have been calculated with both codes.

3. Results and discussions

One of the most important parameters influencing the quality of X-ray spectrum is filtration. The produced X-ray profiles before and after the filter using FLUKA code are shown in Figs. 2–3. The corresponding results of MCNP simulation are similar to the FLUKA results. The X-ray spectra show continuous and characteristic X-rays spectra of tungsten. The effect of Al filter in