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Original Article

Calculation of the X-Ray Spectrum of a Mammography System with Various Voltages and Different Anode-Filter Combinations Using MCNP Code

Lida Gholamkar[1], Mahdi Sadeghi[2], Ali Asghar Mowlavi[3,4*], Mitra Athari[1]

Abstract

Introduction
One of the best methods in the diagnosis and control of breast cancer is mammography. The importance of mammography is directly related to its value in the detection of breast cancer in the early stages, which leads to a more effective treatment. The purpose of this article was to calculate the X-ray spectrum in a mammography system with Monte Carlo codes, including MCNPX and MCNP5.

Materials and Methods
The device, simulated using the MCNP code, was Planmed Nuance digital mammography device (Planmed Oy, Finland), equipped with an amorphous selenium detector. Different anode/filter materials, such as molybdenum-rhodium (Mo-Rh), molybdenum-molybdenum (Mo-Mo), tungsten-tin (W-Sn), tungsten-silver (W-Ag), tungsten-palladium (W-Pd), tungsten-aluminum (W-Al), tungsten-molybdenum (W-Mo), molybdenum-aluminum (Mo-Al), tungsten-rhodium (W-Rh), rhodium-aluminum (Rh-Al), and rhodium-rhodium (Rh-Rh), were simulated in this study. The voltage range of the X-ray tube was between 24 and 34 kV with a 2 kV interval.

Results
The charts of changing photon flux versus energy were plotted for different types of anode-filter combinations. The comparison with the findings reported by others indicated acceptable consistency. Also, the X-ray spectra, obtained from MCNP5 and MCNPX codes for W-Ag and W-Rh combinations, were compared. We compared the present results with the reported data of MCNP4C and IPEM report No. 78 for Mo-Mo, Mo-Rh, and W-Al combinations.

Conclusion
The MCNPX calculation outcomes showed acceptable results in a low-energy X-ray beam range (10-35 keV). The obtained simulated spectra for different anode/filter combinations were in good conformity with the finding of previous research.

Keywords: Anodes, Filters, Full-field digital mammography system, MCNP code, Monte Carlo Method, X-ray spectrum

1. *Department of Medical Radiation Engineering, Science and Research branch, Islamic Azad University, Tehran, Iran,*
2. *Medical Physics Department, School of Medicine, Iran University of Medical Sciences, Tehran, Iran*
3. *Physics Department, School of Sciences, Hakim Sabzevari University, Sabzevar, Iran.*
4. *ICTP, Associate federation Scheme, Medical Physics Field, Trieste, Italy.*

*Corresponding author: Tel: 0098-51-4410 2521; Fax: 0098-51-4410 3170; Email: amowlavi@hsu.ac.ir

1. Introduction

X-ray mammography is one of the most important advances in the field of diagnosis and control of breast cancer. The importance of mammography is directly related to its value in detecting and diagnosing cancer in the early stages, leading to a more effective treatment [1]. In many countries, breast cancer is one of the most common types of cancer and the main cause of mortality among women, aged 35-54 years. According to the statistics of the National Cancer Institute in the United States, one out of every eight women suffers from breast cancer [2, 3]. Unfortunately, the prevalence of this cancer has grown rapidly in Iran, thus highlighting the importance of timely detection of the disease.

Due to the use of a low kilo-voltage in mammography (generally in the range of 25-32 kV), the bulk of low-energy photons is absorbed by the surface tissue layers, and only a very small portion may reach the deeper layers of the body; therefore, the absorbed dose and risk of unwanted effects increase. Since breast is a sensitive organ, removing this part of the beams before reaching the patient's body is essential. This important task is accomplished by filters employed in mammography devices [4].

The presence of a filter alters the shape of the X-ray spectrum, moving it towards higher energies and harder beams [5]; in addition, filters can affect the contrast of medical images. In order to increase the image contrast, metals such as molybdenum (Mo), rhodium (Rh), silver (Ag), and aluminum (Al), which reduce the X-ray photon flux after k-edge energy, are used as filters [5]. The output window of the X-ray tube is made of beryllium (Be; with a thickness of 0.63 mm), which is the in-built filter of the mammography system.

In most traditional mammography systems, anode–filter combinations of Mo-Mo, Mo-Rh, and Rh-Rh are used. However, in new digital models, tungsten-silver (W-Ag), Rh-Al, and W-Rh combinations are often applied. According to the literature [4-7], the later combinations can reduce the patient dose up to 50%.

More than two decades ago, Fewell et al. measured the X-ray spectrum with different target/filter combinations and published several measured spectra [8-10]. Since the experimental measurement of the X-ray spectrum is time-consuming and difficult, different methods for spectrum prediction have been presented [11-13]. These methods can be divided into three categories: empirical, semi-empirical, and Monte Carlo models[14].

Most empirical and semi-empirical models have preset target-filter combinations, thus hindering the analysis of the effect of newly developed material compositions on the quality of the resulting X-ray spectra. Sophisticated Monte Carlo modeling has been adopted as an alternative to overcome the abovementioned limitations. Nevertheless, the prediction of the X-ray spectra using the Monte Carlo method is time-consuming, compared to empirical and semi-empirical models [14].

There are numerous Monte-Carlo codes, which allow the simulation of electron-photon transport, and as a result, the spectra of X-ray sources [15]. The computational Monte Carlo codes, such as MCNP or GEANT, is highly powerful tools for the simulation of X-ray spectra with different target-filter combinations, produced by the X-ray tube in mammograms [12].

In this regard, Ay et al. and Mowlavi calculated the X-ray spectra for some anode-filters, using the MCNP4C code. Mowlavi calculated the spectrum for Rh-Rh, W-Rh, Mo-Al, Mo-Mo, Mo-Rh, and Rh-Al combinations in the energy range of 0-28 keV [12], while Ay et al. calculated the spectra for Mo-Mo, Mo-Rh, and W-Al combinations in the energy range of 0-30 keV [14].

In this study, calculation of the X-ray spectrum in the mammography system was performed with the help of Monte Carlo calculations, i.e., computerized simulation codes, MCNPX2.6.0 and MCNP5, for different anode-filter combinations [16]; the tube voltage range was 24-34 kV with a 2 kV interval. Overall, by using the MCNP code, it is possible to transport electrons, photons, neutrons, or coupled neutron/photon/electron inside the target and filter with various densities and thicknesses. Also, with the help of special cards, the system geometry is simulated and the flux or dose can be calculated by using different tallies [11, 13].

The shape of the obtained X-ray spectrum depends on factors such as anode and filter material, angle of the electron beam irradiation with respect to anode, and tube voltage. In the collision of electrons with anode, the X-ray spectrum shows specific peaks, depending on the anode material [5]. Overall, the simulation techniques can help examine the effects of changes in the anode and filter materials, filter thickness, and tube voltage variations on image contrast and received patient dose before experimentally applying these changes on the tube. Moreover, they can be used to identify the optimal conditions for preparing a clear image, along with a low patient dose.

2. Materials and Methods

The device simulated in this study was a digital mammography system, Planmed Nuance (Planmed Oy, Helsinki, Finland), equipped with an amorphous selenium detector. The device has a tungsten anode and two adjustable Rh and Ag filters with thicknesses of 50 and 75 µm, respectively [17-19]. In this study, the mammography system was simulated with MCNP simulation codes, and the effects of two factors (i.e., the voltage used in the X-ray tube and anode/filter materials) on the X-ray spectrumwere studied.

2.1. MCNP Code

MCNP is a general-purpose Monte Carlo code, which can be used for neutron, photon, electron, or coupled neutron/photon/electron transport in a large energy range. In the MCNP code, three-dimensional coordinates are used to define the geometry of the cell, surface, and interaction environment.

MCNPX2.6.0 is the next generation of Monte Carlo transport code series, which was first introduced by the Los Alamos National Laboratory in 2008, following the release of MCNPX2.5.0 and MCNP4C codes. Improvement of physics-based simulation models, extension of neutron, proton, and photonuclear libraries to 150 MeV, and formulation of new variance reduction and data analysis techniques are the most considerable characteristics of this code; in fact, this code is compatible with MCNP5 [16].

According to Figure 1, the anode was considered as a wedge which mono-energetic electrons collided with to produce the X-ray spectrum. In this study, the angle of electron–anode collision was 10°, and the filter had a cuboid shape with a 60×40×1 mm dimension, located at a 12 cm distance from the origin. The X-ray spectrum was calculated for a tube voltage range of 24-34 kV, which is an appropriate interval for mammography and imaging of breast tissues with F5:P tally (i.e., flux at ring detector tally) at a distance of 60 cm from the X-ray source.

The radius of the detector was 2 cm, and the detector was located parallel to the filter surface. For 400 million NPS (number of source-particle histories run in the problem) of electrons, the statistical error was below 2%. We used any variance reduction method in our calculations, and all photon interactions were simulated. The input file, written with the MCNPX2.6.0 code, was run in MCNP5 for W-Ag and W-Rh combinations at 28 and 30 kV tube voltages, and the X-ray spectra were calculated. The running time ranged between 1000 and 1500 min.

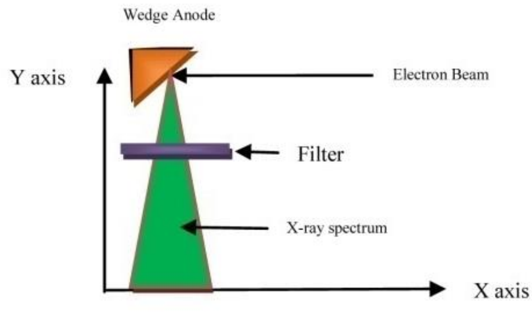


Figure 1. The simple geometry of anode-filter combinations, electron beam path, and X-ray spectrum for the input of MCNP code

2.2. Tungsten anode spectral model using interpolating cubic splines (TASMICS)

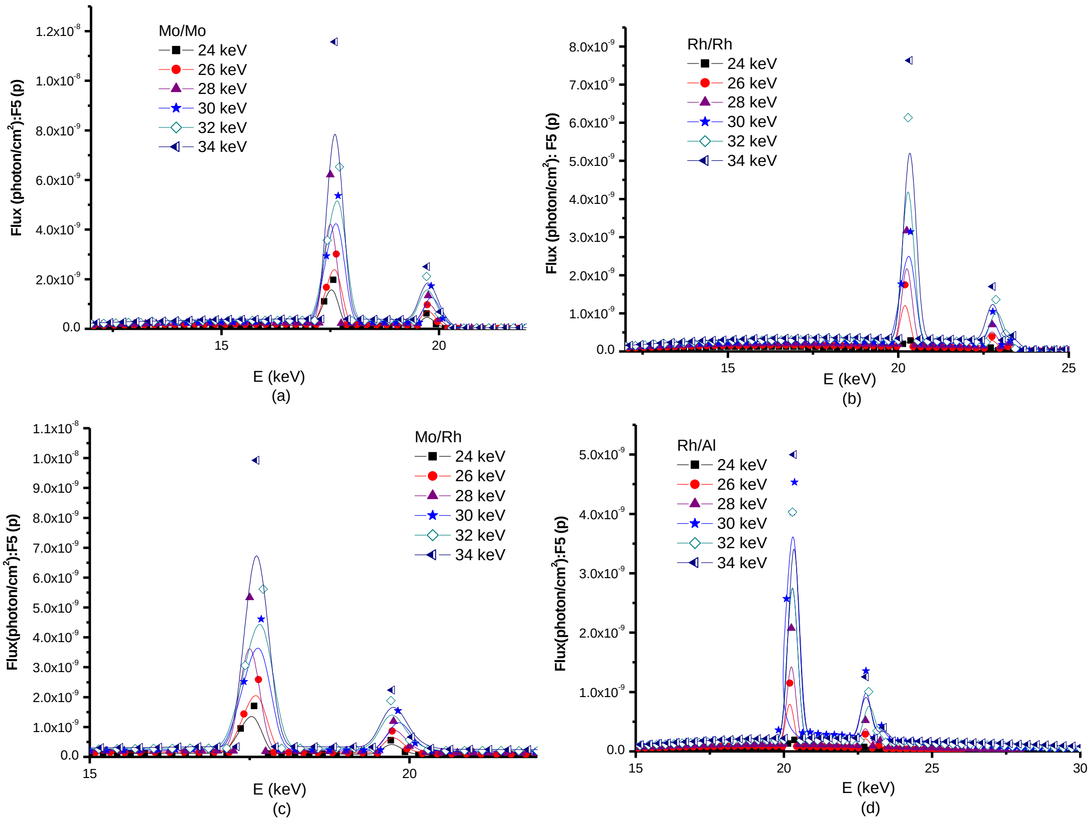
TASMICS model is a computerized program, which can easily produce the X-ray spectrum of tungsten. This spread sheet is a tool used to produce tungsten X-ray spectra with 1 keV energy resolution, ranging from 20 to 640 keV. The database of X-ray spectra is based on the interpolating cubic splines of tungsten anode X-ray spectra, simulated in the Monte Carlo code.

The tungsten anode spectral model using interpolation cubic spline is given the acronym, TASMICS [20]. The exact method used to produce these spectra can be found in the literature [20]. This model can predict the X-ray spectra for different anode-filter combinations with various thicknesses and tube voltages. By applying this code, W-Ag and W-Rh spectra at 28 and 32 kV tube voltages were calculated.

3. Results

The X-ray spectra were calculated by drawing the photon flux changes in terms of energy, as shown in Figure 2 (a-k) for different voltages. To compare the output of MCNPX2.6.0 and MCNP5, the X-ray spectra for W-Ag and W-Rh anode-filter combinations in two 28 and 30 kV voltages were calculated and plotted, as shown in Figure 3; the obtained results showed a high level of conformity. To validate the results, it is essential to compare our findings with previous research. The spectra obtained by Boone et al. with TASMICS model [20] for W-Ag and W-Rh combinations at 28 and 32 kV tube voltages were compared with the present results, as demonstrated in Figure 4.

By using the data reported by Ay et al. for W and Mo anodes, we plotted the X-ray spectrum at 30 kV. Ay et al. had used MCNP4C and IPEM report No. 78 data [11]. As shown in Figure 5, we compared the X-ray spectra produced in this study and the data reported by Ay et al. and IPEM report No. 78 for Mo-Mo, Mo-Rh, and W-Al combinations at 30 kV tube voltage.



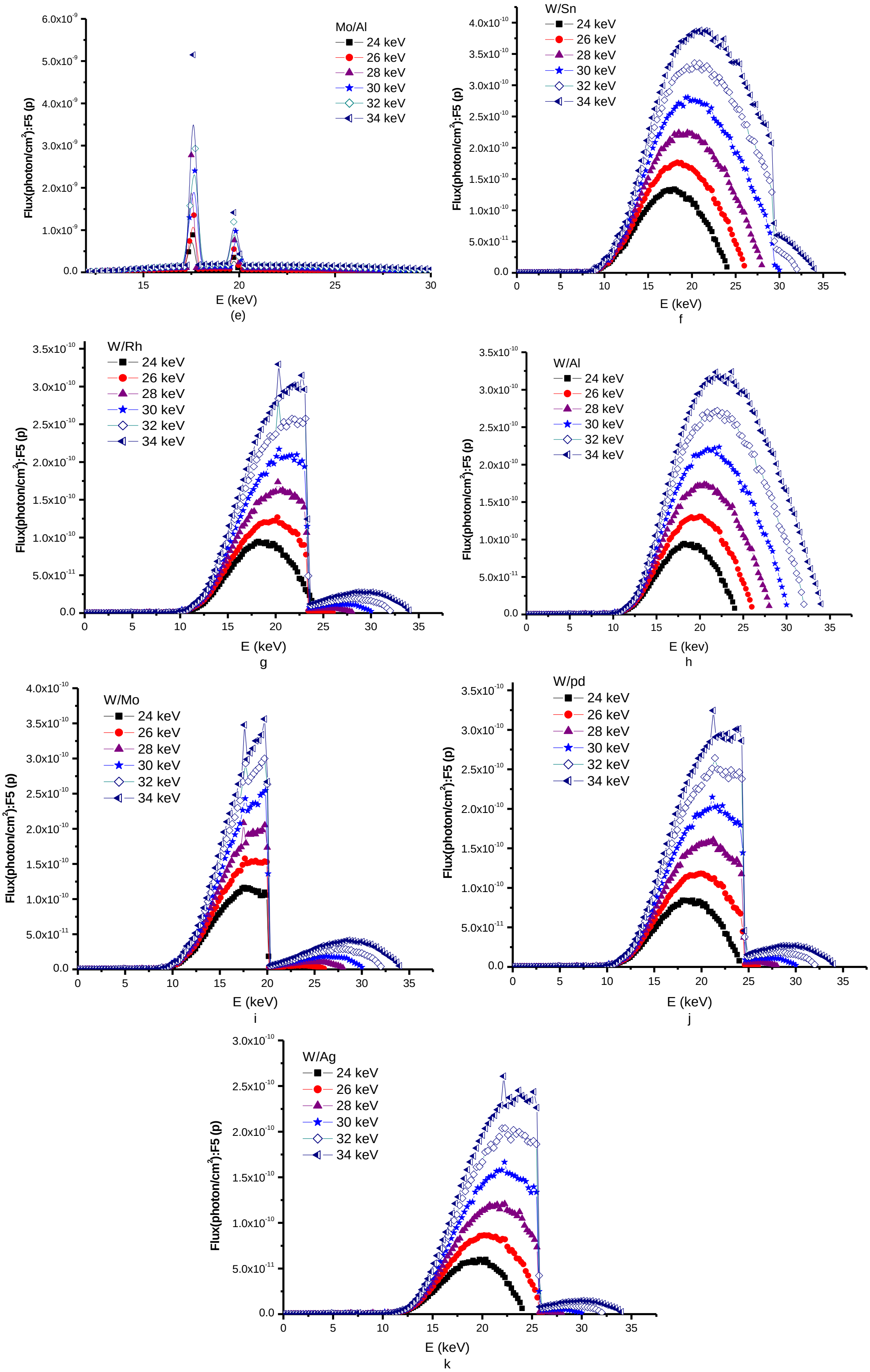


Figure 2. The X-ray spectra for different anode/filter combinations: a (Mo-Mo), b (Rh-Rh), c (Mo-Rh), d (Rh-Al), e (Mo-Al), f (W-Sn), g (W-Rh), h (W-Al), i (W-Mo), j (W-Pd), and k (W-Ag) with 24-34 keV electrons, produced by MCNPX2.6.0

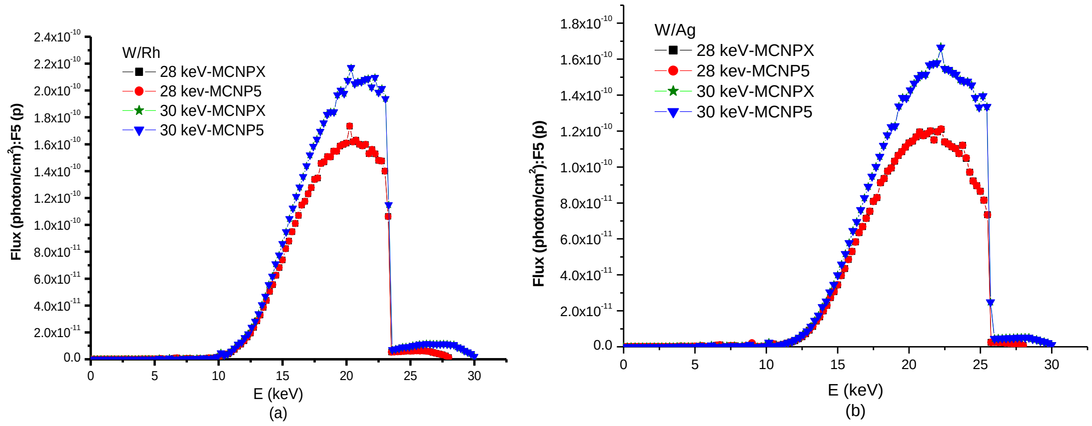


Figure 3. Comparison of X-ray spectra produced by MCNPX2.6.0 and MCNP5 for W-Rh (a) and W-Ag (b) combinations with 28 and 30 keV electrons

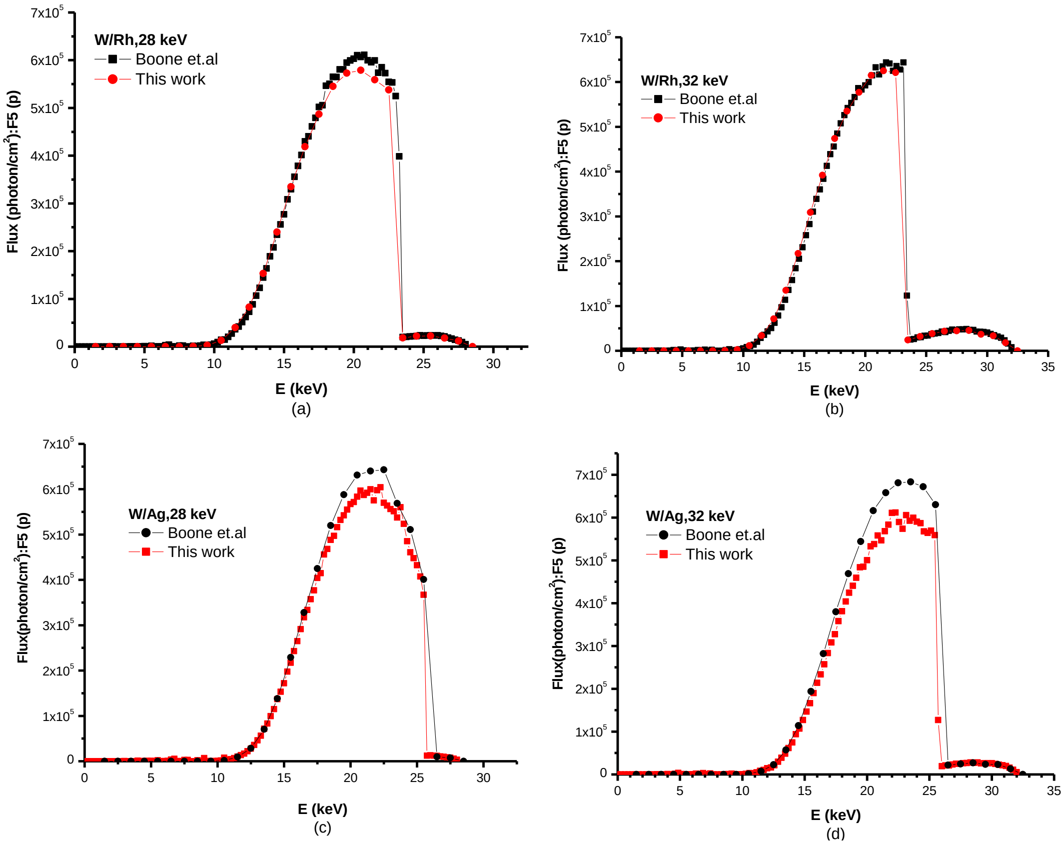
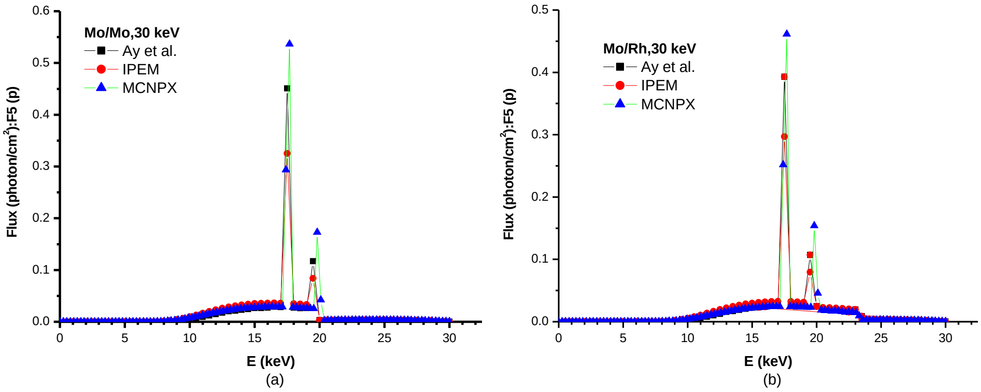


Figure 4. Comparison of X-ray spectra produced in the present study and the data reported by Boone et al. for W-Rh (a, b) and W-Ag (c, d) combinations with 28 and 32 keV electrons



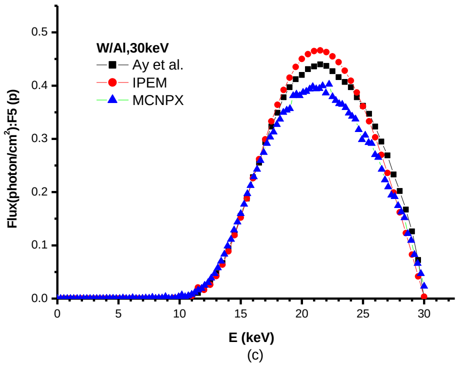


Figure 5. Comparison of X-ray spectra produced in the present study and the data reported by Ay et al. and IPEM report No. 78 for (a) Mo-Mo (b) Mo-Rh, and (c) W-Al combinations at 30 kV tube voltage

4. Discussion

Comparison of diagrams in Figure 2 indicates that by increasing the tube voltage, the produced photon flux is increased, the spectrum broadens, and its peak shifts towards higher energies. Since the tube current is proportional to the squared voltage ($I \propto V^2$), the increase in the current affects the photon flux [5]. Figures related to W anode are broader than Mo and are not sharp. The spectrum related to W-Ag and W-Rh in 28 and 30 keV energies are drawn in Figure 3 for both MCNPX2.6.0 and MCNP5 codes. As expected, since both codes have the same physical principles [16], similar results can be seen in their outputs, and the spectra related to each anode/filter combination are completely overlapped.

The shape analysis of the calculated mammography X-ray spectra with MCNPX2.6.0 and MCNP5 shows that from 15 keV energy onwards (after 10 keV for W anode), the X-ray photon exerts its effect in breast imaging where photonswith a lower energy only increase the dose. In a study by Dance and Thilander, dose calculation in different anode filters showed that Mo-Rh, W-Rh, Rh-Rh, and Rh-Al combinations, if used in appropriate voltages, would produce lower doses, compared to Mo-Mo and could even reduce the patient dose up to 50% [4, 6].

According to Figure 4, it can be seen that the shape of the spectrum, obtained from the MCNPX2.6.0 code and TASMICS, has an acceptable consistency. The photon flux of the data obtained by Boone et al. was slightly higher than the present study, which is due to the application of different methods for writing the input file of MCNPX and TASMICS, system geometry details, and assumptions used in coding [16, 20]. For instance, the X-ray source distance from the filter, filter shape definition, anode shape definition, site of photon flux calculation, and number of given NPS in the input file are different.

In the present study, we considered pure tungsten for the anode. The anode angle was 10 degrees, Be filter thickness was 0.63 mm, and the focal spot distance from the detector was 60 cm. In the TASMICS model, when anode was composed of tungsten (95% by weight) and rhenium (5% by weight), its angle was 12 degrees and contained only 0.8 mm Be filtration. The resulting TASMICS spectra were located at a 1000 mm distance from the anode focal spot [20].

In Figure 5, specific peaks of the X-ray spectra in MCNPX for the Mo anode with Mo and Rh filters showed a difference of about 0.5 keV from the data reported by Ay et al. and IPEM report. In the present study, the photon flux was higher, which is related to how the X-ray spectra were calculated in the codes. The low-energy X-ray intensity (< 19.5 keV), calculated by MCNPX, was greater than that reported by Ay et al. and IPEM data. This is in fact a result of the significant overestimation of the intensity of characteristic X-rays in MCNPX, following the normalization procedure.

The attenuation of Rh filter in 20 keV energy range was higher than the attenuation of the

Mo filter. For tungsten target spectra, the spectrum generated by MCNPX was in good agreement with IPEM and Ay et al. data in the energy range of < 17 keV; however, the intensity of the spectrum in the energy range of 17–30 keV was lower.

5. Conclusion

Although the simulation method with MCNP code included time-consuming calculations and a large amount of input and output data, the calculation outcomes showed acceptable results in low-energy X-ray beams (10-35 keV). Based on the findings, the output of MCNPX2.6.0 and MCNP5 codes were in good agreement. The results showed that the specified spectra and peaks for each anode-filter combination were consistent with the data presented in the literature. There was no statistically significant difference between MCNPX and other published data for Mo and W targets. Finally, according to the present and previous findings, it can be said that use of the MCNPX simulation code facilitates the calculation of X-ray spectrum for different types of anode-filter combinations and all voltages.

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