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Design of Low-Pass Filter of X-Ray Energy to Improve the Quality of Medical Imaging

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Abstract

Using narrow-spectrum energy bandwidth can be effective on image quality. Because while increasing the possibility of processing the attenuation coefficient, it also provides a reduction in the beam hardening artifact. For this purpose, in this paper, energy absorption filters are used by planning absorption and attenuation curves and sudden changes in attenuation in the interaction of the beam on the edges, as well as considering the operating conditions of existing imaging devices and the best energy required for imaging a specific part of the body. Then, their images were compared with the recorded images without filters and were approved by clinical experts. The samples, on the other hand, were designed with Monte Carlo N-particle radiation transport computer code (MCNP4C), which showed an acceptable agreement with the computational cases.

Keywords: Artifact, Beam hardening, Medical imaging, Monte Carlo N-particle radiation transport computer code (MCNP4C), X-ray filters
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1. Introduction

The quality of the image depends on the process of determining the disease in a particular clinical diagnosis, the model of eye-brain perception in humans and as well as the characteristics of the images [1], so determining the quality of the images is a difficult task. Therefore, describing the characteristics of X-ray images based on measurable components can provide a good indicator for expressing image quality, the most important of which are the degree of spatial resolution, noise and contrast [1-3]. Therefore, in this paper, by designing filters that have the ability to absorb and attenuate higher energy beams and transmit lower energy beams, which eventually leads to a narrower width of the output spectrum. The goal of improving image quality will be followed by increasing the accuracy of all measurable components. Finally, the reduction of beam hardening artifacts [4] has been made possible.

2. Material and Methods

In this paper, the attenuation of the incident beam is considered based on the collision of the beam with the material in its path. In this case, due to the phenomenon of absorption or deflection of photons, reducing the intensity of the beam leads to attenuation of the incident beam, which in addition to the energy of the photons also depends on the number of photons (Equation 1) [5,6]:

$$I = \sum N_i \times E_i \qquad (1)$$

Meanwhile, one of the phenomena that occurs is the photoelectric effect. If the photoelectric effect is the predominant phenomenon, the attenuation of the beam in the environment and finally in the absorption edges of the elements (κ, L, M) will be added [6]. On the other hand, with increasing energy, the rate of transmission also increases. Of course, it should be noted that in some energies that are at the absorption edges of the elements, due to the photoelectric effect, the absorption rate also increases sharply [7]. So, these features form the basis of the design of low-pass filters of X-ray energy. In the meantime, it is necessary to study the effective conditions in the design of low-pass filters. One of these conditions is how the X-ray tube is designed and expression of X-ray tube production function. In this tube, there is a glass bubble that covers the anode and cathode, also the presence of insulating oil around the tube and the tube chamber window all cause the inherent smoothness of the beam [8]. In this case, if the purpose of the beam smoothness is to eliminate low energies, the average energy of the X-ray is increased and the tissue contrast is reduced. On the other hand, if large thicknesses are used, the beam intensity will be reduced and the need for more irradiation time will be inevitable. Therefore, the probability of patient movement and motion artifact increases [9-11]. So what importance in designing conventional filters to eliminate low-energy rays is to choose a material as a filter that absorbs all the low-energy photons and transmit all the high-energy photons in return. Since there is inherently no substance with such a property, by using the natural tendency of some materials to have a photoelectric effect in absorbing the lowest energy photons, these materials can be used as a filter. Therefore, in designing low-pass filters, increasing the ratio of low-energy eliminated rays to high-energy removed rays is important [6,11,12].

From a wide range of materials, choosing “Iodine” as a filter can be a good option. Because iodine filter has less absorption in energies between 20 to 33 kV than other energies. Shown in Figure (1). Therefore, if this filter is placed at the output of X-ray tube with about 50 kVp, energies between 33 to 50 keV will be severely attenuated [12,13].

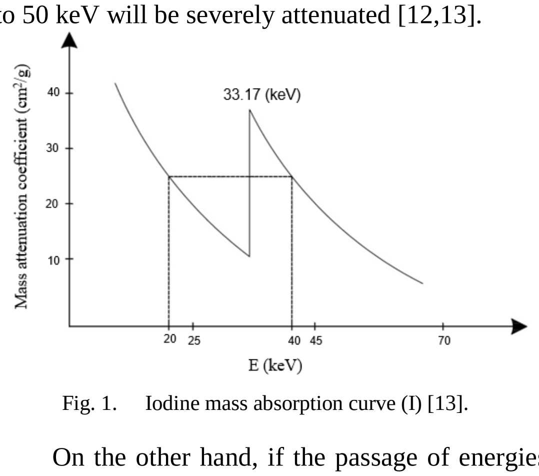

Fig. 1. Iodine mass absorption curve (I) [13].

On the other hand, if the passage of energies between 20 and 30 keV is considered, according to Figure (2), it can be claimed that “Tin” with an absorption edge of 29.2 keV would be a good choice [12,13].

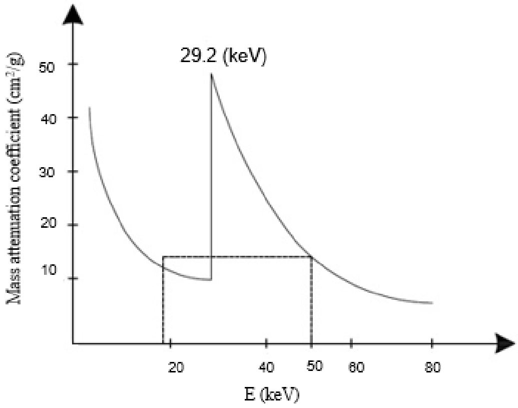

Fig. 2. Tin mass absorption curve (Sn) [13].

3. Experimental setup and Result

In this paper, X-ray source with "Tungsten" rotating anode and focal point of 0.6 mm, 40 kVp and 318 mA is used. The energy spectrum of this X-ray source is shown in Figure (3) [3].

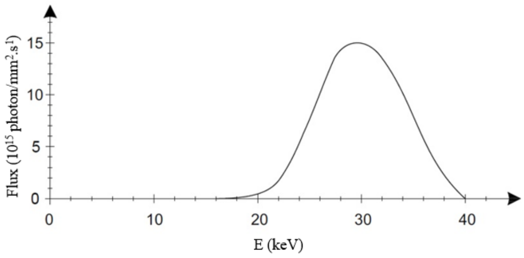

Fig. 3. X-ray source energy spectrum of 40 kVp and 318 mA [3].

Since the goal is to attenuate energies higher than 30 keV, tin can be a good choice because the κ absorption edge in this element is 29.2 keV [13]. Also, another important parameter is choosing the thickness of the filter so that the amount of beam drop after the filter is not so great as to cause quantum noise. For example, if a reduction of up to 30% of the beam intensity at the maximum point of the spectrum is acceptable, according to Equations (2) and (3) below, we can obtain the thickness that causes the maximum reduction [1,3]:

Of course, the amount of acceptable reduction also depends on the operating conditions of the device and the type of imaging [14].

$$I = I_0 e^{-\mu x} \tag{2}$$

$$\frac{I_0 - I}{I_0} = 30\% \quad \rightarrow \quad x = 0.3567/\mu \tag{3}$$

According to Figure (4), the X-ray spectrum is maximal at keV28. Therefore, the μ attenuation coefficient for this energy is obtained from the tin attenuation curve of $\mu(E = 28\,\text{keV}) = 57.5$. Therefore, the appropriate thickness will be as follows.

$$x = 6.2 \times 10^{-3} cm \tag{4}$$

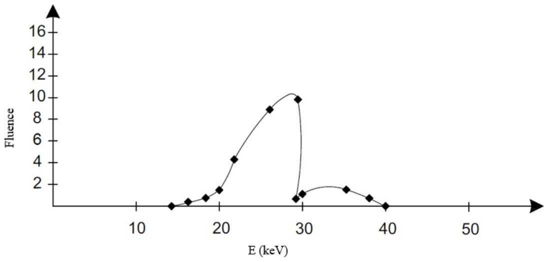

Fig. 4. X-ray spectrum at 28 keV is maximum.

The beam output spectrum of the filter is shown in Figure (5), in which the two X-ray output spectra before and after the filter are compared.

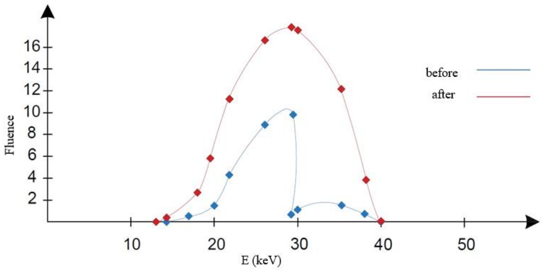

Fig. 5. Comparison of X-ray output spectrum before and after the filter (blue before the beam passes through the filter - red after passing the beam through the filter).

As shown in Figure (5), at energies between 24 keV and 30 keV, the reduction in beam intensity is less than 50%. While at energies above 30 keV, the intensity is about 90%. In addition to the calculations performed from the tin attenuation coefficient curve, the above filter was simulated by MCNP4C and the result is reported in Figure (6):

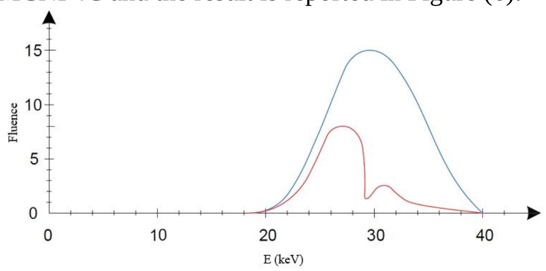

Fig. 6. Filter simulation result by MCNP4C code (red).

In Figure (7), the two spectra of the computational and simulation results have been compared. As it is seen, the simulation also confirms the computational results. In this figure, the scattering at the edges in the spectra obtained from the simulation is due to the statistical nature of the scattering as well as the transfer of some attenuated rays from high energies to low energies (scattering effect) [3,6]. In addition, the loss of simulated energy relative to the computational results at the top of the graph indicates the presence of impurities in the element, which is not considered in the attenuation spectrum of the element.

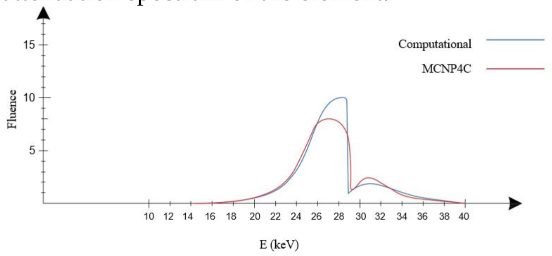

Fig. 7. Comparison of two spectra of computational results (blue) and simulation with MCNP4C code (red).

4. Discussion

One of the important goals in medical imaging is to obtain the best image quality, so that the best clinical diagnosis is possible and, of course, the patient has the least risk in terms of imaging [16]. The method proposed in this paper is to use the technique of absorption edges of elements in low-pass filters of energy, in order to record quality images by reducing the radiation dose [17]. In this method, the thickness of the filters is calculated based on the amount of absorption and energy of the beam in the radiation spectrum. Therefore, in cases where X-ray tubes with high values of kVp are used, because a larger thickness of the filter is required to create a significant percentage of attenuation in the output beam, the tube current (mA) must be increased to compensate for the decrease in intensity. Since the operating point of X-ray lamps is defined in certain milliampere values, these filters can often be useful in low kVp imaging. In addition to the energy of the X-ray tube, the choice of filter type also depends on the target material [1,3,8,17].

At low energies, due to the impressive attenuation difference between soft tissue and bone, better contrast can be observed in the images. For example, in energy 20 keV, the bone attenuation coefficient is six times that of water. While in the energy 100 keV range this ratio will be about one and a half times and will create less contrast. Therefore, the use of high energies is preferred when certain contrasts are desired; Because reducing the absorbed dose by the patient is also important [17,18].

5. Conclusion

In this paper, possible solutions to eliminate high energies in the X-ray spectrum and achieve a narrower energy band in the desired range were investigated. The use of X-ray optics has no clinical application or is very limited due to the high intensity reduction and the need for high-intensity X-ray production resources as well as its high cost. Therefore, the method used in this paper is based on the analysis of material attenuation curves and the sudden increase in attenuation at their κ edges. In this regard, several variables should be considered in the design of filters, which will be defined according to the existing working conditions, type of device, type and thickness of tissue, as well as energy limits for optimizing images. But the material and thickness of filter and the type and thickness of the tissue are factors that can be explained about in general.

Filter material selection depends on the maximum acceptable energy. In this case, in order to remove energies of more than a certain value, the filter material must be selected in such a way that its κ absorption edge is within the energy range. Of course, if there are several materials with this property, its availability and cost-effectiveness should also be considered. Another important factor in choosing the material of the filter is its compatibility with the anode material of the X-ray machine. Matching the two in terms of material causes the beam intensity to be adjusted after passing through the filter. On the other hand, choosing the right filter thickness is also very important because the presence of the filter reduces the output beam intensity and the filter thickness should be selected based on the maximum percentage of output beam intensity reduction. Also, considering that for each X-ray machine, the maximum imposed load is determined by the manufacturer; Therefore, for devices with higher values of maximum load, it is possible to use a thicker filter. It was also shown that for thicker filters, the removal rate of high energies is higher than that of low energies, so as long as the decrease in output intensity does not cause quantum noise, the thickness can be increased.

Since the use of less kVp is suitable in soft tissues, and also due to the greater the thickness of the desired tissue, the degree of attenuation will be greater and it is necessary to use a higher kVp. Therefore, the type and thickness of the filter are important factors in designing a suitable filter.

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