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Impact of Photon Spectra on the Sensitivity of Polymer Gel Dosimetry by X-Ray Computed Tomography

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ABSTRACT

Introduction: The purpose of the current study was to investigate the effect of X-ray spectra on the sensitivity of a polymer gel dosimeter imaged with a conventional computed tomography (CT) scanner.
Material and Methods: The whole process of CT imaging of an irradiated polymer gel was simulated by MCNPX Monte Carlo (MC) code. The imaging of polyacrylamide gel was accomplished by means of a conventional X-ray CT scan machine for different X-ray spectra, including mono-energetic beams and the spectra generated after passing through physical filters, including copper and tin. The MC-scored photon fluence inside simulated detectors was used to reconstruct the axial CT images by MATLAB software. The resultant images were used to derive the dose calibration curve of the gel for different spectra, based on which the highest sensitivity was selected.
Results: Among the calculated gel sensitivities for different beam spectra, the highest increase in average sensitivity was obtained as 23% for the 140 kVp spectrum with copper filter and copper+tin filter. However, the sensitivity of mono-energetic beams showed no considerable variation with the increase of energy from 30 to 140 keV.
Conclusion: As the findings indicated, the optimization of photon spectra by means of a physical filter could increase the sensitivity of polymer gels in gel dosimetry using CT imaging.

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Introduction

Polymer gel dosimeters are water gels containing vinyl monomers, which are sensitive to the high-energy photon beams used in radiation therapy. One of the advantages of polymer gel dosimeters is that their density is very close to unity; as a result, they are radiologically equivalent to the soft tissue in interaction with high-energy photon and electron beams. In other words, the energy absorbed by these dosimeters is equal to the radiation dose transferred to the soft tissue. This property has made this chemical an acceptable material for the radiation dosimetry purposes [1-5].

The response of a polymer gel to radiation is realized through the formation of polymers from monomers. Unlike the commonly used dosimeters, such as ionization chambers and diodes, which measure the dose at a point or plate, polymer gel dosimeters provide dose distribution in a three-dimensional volume with a high-spatial resolution and appropriate accuracy [6-8].

Magnetic resonance imaging (MRI) is a standard method for reading irradiated gel by determining the relaxation time of R_2 inside the 3D volume of the polymer gel [2, 6, 9]. However, there are several reasons urging the radiation scientists to look for other modalities for data acquisition from the irradiated gels. For instance, the lack of access to expensive MRI equipment in radiotherapy centers has limited the use of polymer gel dosimetry. In addition, MRI entails a long imaging time that can last up to 1 h [1, 10].

FIn recent years, some other imaging modalities have been proposed for the readout of latent information in polymer gels. The studies show that the changes due to polymerization occur in other physical parameters, such as optical density [11, 12], linear attenuation coefficient [13-16], as well as rate of diffusion, absorption, and attenuation of sound [12]. Regarding this, optical computed tomography (CT), X-ray CT, and ultrasound have been studied as alternative methods [17].

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The ease of access to X-ray CT devices in radiotherapy centers [18, 19] and the convenience of this method in terms of cost and imaging duration have increased the tendency to use CT for the production of gel dosimeter images [13, 20]. Trapp *et al.* (2001) indicated that a change in attenuation coefficient (μ) with absorbed dose can account for the observed change in CT number (ΔN_{CT}) in the CT images of irradiated polyacrylamide gel (PAG) [14].

In theory, mass density is the intrinsic gel parameter that according to *Equation 1* is related to the linear attenuation coefficient [14], and consequently to the CT number:

$$\mu \approx N_e \sigma_e \rho \qquad (1)$$

Where N_e is the number of electrons per mass unit and σ_e is the cross-sectional area per electron.

In addition, Trapp *et al.* (2002) directly measured the changes in PAG linear attenuation coefficient (μ) and PAG density by changing the absorbed dose [14]. It should be noted that no mass is added to polymer gels through irradiation. Therefore, the observed change in density is due to either a redistribution of the mass within the gel, or a change in gel volume [18]. According to the literature, the change in linear attenuation coefficient is mainly attributed to a variation in electron density originating from the expulsion of water in the polymer clusters [21, 22].

tudies on polymer gel dosimetry with CT have reported that despite the linear enhancement of polymer gel response (i.e., polymerization) to the uptake of up to 20 Gy, this method has a low sensitivity as indicted by the slope of dose-response curve. Consequently, the X-ray gel dosimetry method has not be considered as a practical and efficient alternative method for polymer gel dosimetry so far [15, 23-25]. This is due to the fact that the density changes caused by absorption are very small (%1 Gy) [26] and produce images with low signal-to-noise ratio (SNR) and contrast [13, 27], thereby making the dosimetry results unacceptable for clinical applications.

The proposed methods of increasing SNR in the CT image of polymer gels consist of multi-level scans and averaging of multiple images of the same slice of polymer gels [13]. Obviously, the gel receives a small additional radiation dose at each scan. The inaccuracy of the gel response to the CT dose can be reduced by several methods, including the optimization of the gel formulations, optimization of the CT parameters, and reduction of the non-radiant CT image or background image in order to eliminate the effects of an additional CT dose.

Studies have shown that the increase in the energy of beam photons and the hardening of the radiation spectrum reduce the noise of the polymer gel images [28]. The authors of the current article assumed that the optimization of the photon spectra of a conventional CT imager can affect the quality of the resultant gel images.

ATo the best of our knowledge, no comprehensive study has investigated the effect of photon beam spectra on the quality of polymer gel images. With this background in mind, the present study was conducted to investigate the effects of photon beam spectra on the image of irradiated polymer gel using Monte Carlo (MC) simulation. There are many studies on the application of MC method in radiation dosimetry in the literature.

The MC simulation of a CT scan unit has been used to analyze different dosimetric methods to evaluate the imaging parameters and optimize the use of X-ray CT [29-34]. In an MC study conducted by Hayati *et al.* to simulate gel imaging by CT, a conventional CT scanner was modeled with single detector row, and the gel image was reconstructed from MC calculations. In the mentioned study, the dose-response curve of gel polymer was obtained using the resultant images of the gel [35]. In other words, a conventional CT scanner was simulated to investigate the imaging process of the irradiated polymer gels.

BConsidering the mentioned study, the aim of the current research was to investigate the photon beam spectra of a CT scanner in order to enhance the contrast and reduce the noise in the MC-based images of polymer gels. To this end, we considered different tube voltages of a conventional CT and used suitable physical filters.

Materials and Methods

In line with the purpose of the study, simulations were accomplished using the MCNPX (2.6.0) MC code. The geometric information of the Somatom Spirit CT scanner (Siemens, Germany) was collected through direct measurement and technical manual of the device. The simulated parts included X-ray tube, collimators, single-array detectors, and a cylindrical phantom containing PAG polymer at the isocenter (Figure 1). To score the number of the photons (n/cm^3) entering the detector cells, F4 tally was employed.

AIn addition, the variance reduction method named “forced collision” (FCL:P) was applied for photons. Image reconstruction was performed by importing one projection data to a MATLAB m-file to achieve the sinogram matrix. The symmetric phantom facilitated the creation of a sinogram matrix by repeating the projection data for other projections. In the current research, we used the MC input file of a previous study performed by Hayati et al. [35].

The simulated CT scan was verified by comparing the calculated CT number for the water phantom with the actual values of the CT number for water. The gel images were obtained from vials containing different gel densities. The information related to the density and absorbed dose of PAG was derived from a study carried out by Trapp *et al.* (21).

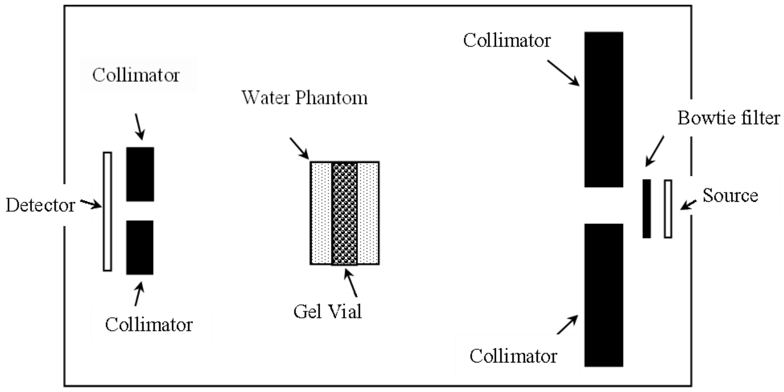

Figure 1. Top view of the geometry modeled by MCNPX Monte Carlo code for a conventional X-ray computed tomography scanner

The images of the gels were reconstructed and depicted by means of MATLAB software (MathWorks, USA). The changes in the density of the PAG gel due to irradiation with different doses, ranging 0-20 Gy, were also recorded [21].

To evaluate the effect of different photon spectra of the CT scanner, the gel images were reconstructed with photon maximum energies of 60, 80, 100, 120, and 140 kVp in three different situations, including without physical filtering, with a copper filter, and with a copper+tin filter. Furthermore, in order to investigate the impact of photon spectra in a wider range, several monochromatic beams were used as photon sources in the MC model. In this regard, the monochromatic beams were considered with the energies of 20, 30, 40, 80, 120, and 140 KeV.

The physical filters included a copper filter with a thickness of 0.5 mm and a combination of copper and tin filters with the thicknesses of 0.5 and 0.25 mm, respectively. The polychromatic photon spectra for different filters were taken from the SpekCalc software (version 1). This software is able to calculate the X-ray tube spectrum based on the MC method. Moreover, it has the ability to change the target material, angle of the anode, as well as type and thickness of physical filters.

In MC simulation, PAG dosimeter was simulated with different densities indicating different absorbed doses. The output file of the MCNPX code provided the photon flux per detector, which was entered into an m-file of MATLAB software. The transformation of the MC data into the CT image consisted of two parts, namely the creation of a sinogram matrix and image reconstruction of the sinogram matrix using filtered back-projection algorithm.

The method of subtracting the background image from the images was also used to increase the SNR. The background image was an image of the phantom containing water. The CT numbers of water and air in the background image were obtained using 15,000 pixel region of interest inside and outside the phantom area.

n the current study, two distinct types of dosimeter sensitivities were employed to explain the obtained results. In the evaluation of the dose-response curve of a polymer gel, point sensitivity was considered as the sensitivity derived from a line between the CT number at the dose of 0 Gy and CT number at the desired dose in each dose level. The average sensitivity of a gel was calculated by averaging the mean of the point sensitivities. Finally, the change percent in dose response (ΔN) was obtained using *Equation* ٢, as follows:

$$\% \, \Delta N_{CT} = 100 \times \frac{\Delta N_{filter} - \Delta N_{no\ filter}}{\Delta N_{no\ filter}} \tag{2}$$

Results

In order to verify our Monte Carlo model, an MC-simulated image was obtained from the homogenous water phantom containing an air hole at the center. Similar to the real scanner, the noise content of the background region was less than 5%. The variation in the CT number of water was less than 1% in five different regions of the phantom. Furthermore, the obtained CT numbers of the air and water were very close to the experimental values.

Figure 2 illustrates the images produced from the MC calculated projections. Figure 3 depicts the photon beam spectra of the X-ray tube of the CT scanner, which were created by SpekCalc software. These spectra were employed as photon sources in the MC model of a conventional CT scanner and defined in the source definition card of the MCNP input file.

Evidently, the area under the curves reduced significantly for all spectra with the application of the physical filters. Overall, physical filters increased the average energy of the spectrum by eliminating the low-energy part of the spectra. The effect of physical filters, including copper (Cu) and copper+tin (Cu+Sn), was higher for lower maximum energy beams. For example, the reduction of photon fluence was higher for 60 KeV beam (Figure 2.e), compared to those for other energies.

Figure 4 shows the dose-response curves of poly-energetic spectra with different maximum energies in three modes, including without physical filter, with copper filter, and with copper+tin filters.

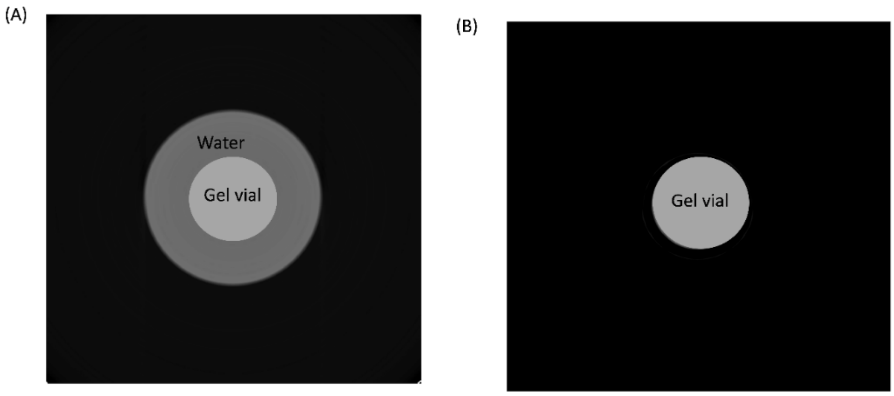

Figure 2. Reconstructed cross-sectional images taken at 120 kVp with a copper filter, a) water phantom with vial gel, b) the same image after background subtraction

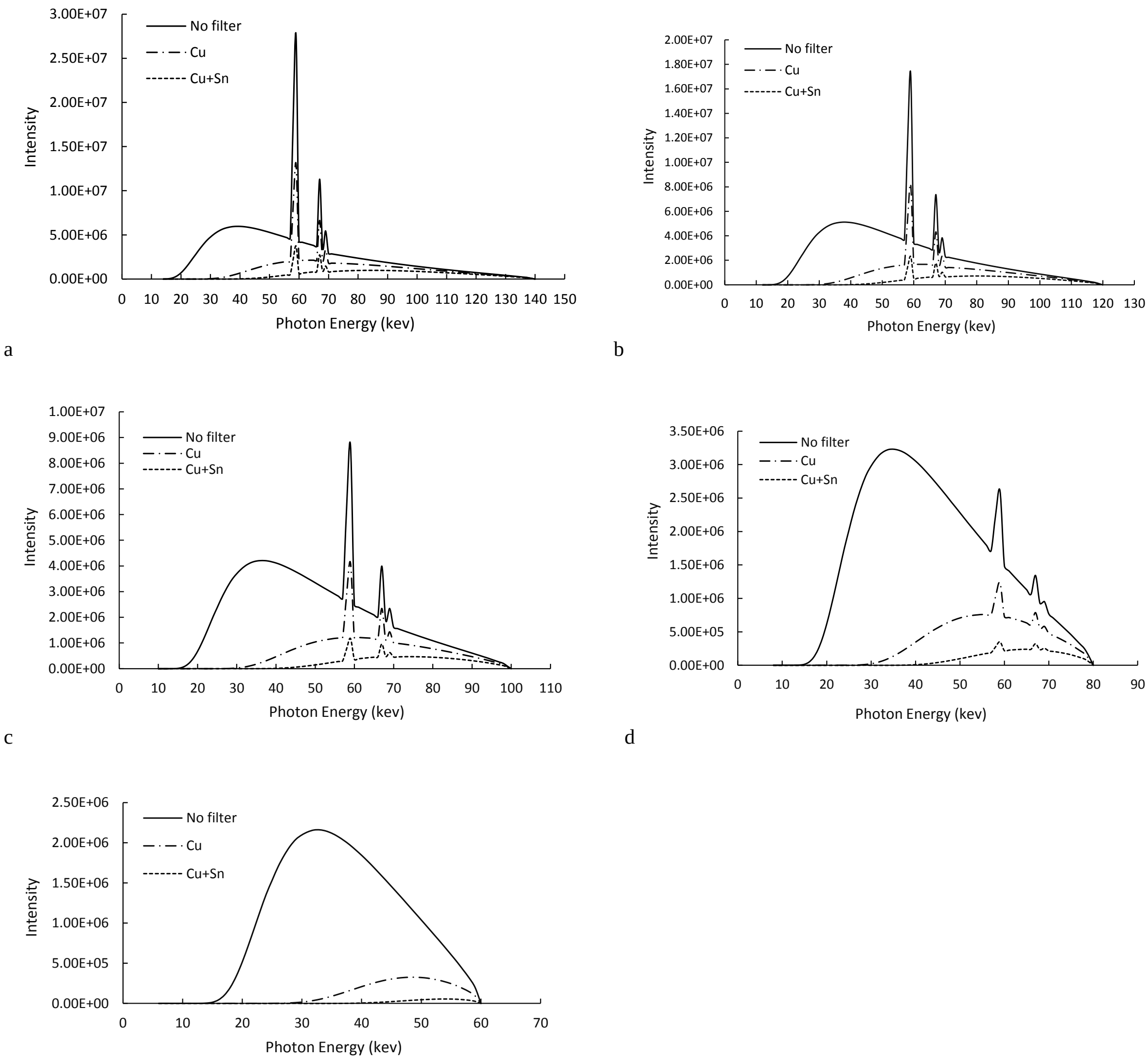

Figure 3. Effect of a copper filter with a thickness of 0.5 mm and a copper+tin filter with the thicknesses of 0.5 and 0.25 mm, respectively, on poly-energetic X-ray spectrum. (The maximum energies of photons were (a) 140 keV, (b) 120 keV, (c) 100 keV (d), 80 keV, and (e) 60 keV.)

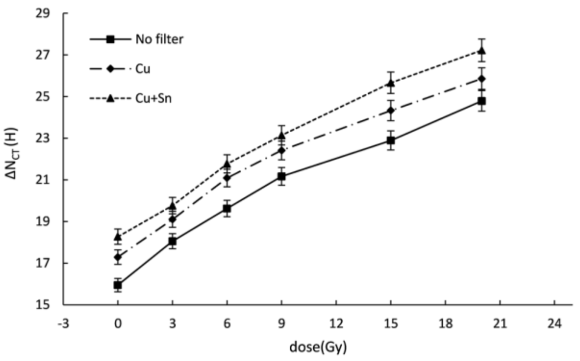

Figure 4. Dose-response curves of poly-energetic spectra at 60 keV in three modes, including without a physical filter, with a copper filter, and with a copper+tin filter.

It was observed that CT number variation in each dose was higher for Cu+Sn filter for the maximum photon energy of 60 keV. This pattern was observed for all studied polychromatic photon beams used in the current study.

Figure 5 displays the dose-response curves for mono-energetic beams. The energy range of mono-energetic beam began from 20 keV, which is not available in the conventional CT units. However, this energy was also studied to provide more information about the dependency of sensitivity to photon beam energy. The 20 keV beam had the lowest CT number changes while for energies higher than 30 keV, these variations got closer to each other. Similar to polyenergetic beam, there was a linear relationship between dose and CT number variations in mono-energetic beam.

To have more quantitative data and compare sensitivity, the mean sensitivities of gel were calculated for different beams, including poly- and mono-energetic beams, over the used absorbed doses of 0-20 Gy. Table 1 presents the mean sensitivity for all energies and beam qualities. To evaluate the effect of beam quality, the mean energies of the studied photon spectra were summed up (Table 1).

Figure 6 demonstrates the mean sensitivity of polymer gel in terms of the mean energy of polychromatic beams. The mean sensitivity changes were estimated based on average energy and for the three studied modes, including without any physical filter, with a copper filter, and with a copper+tin filter. The highest sensitivity for all energies, except for 60 kVp, was observed for the copper filter. In this regard, the highest sensitivity at an energy of 140 kVp was achieved for the copper filter (0.625 H/Gy). As the results indicated, in the CT gel dosimetry, the highest increase in average sensitivity was obtained as 23% for the 140 kVp spectrum with copper filter and copper+tin filter. However, at the tube voltages of 80 and 60 kVp, these changes were not considerable.

Table 1. Mean sensitivity of polychromatic spectra and monochromatic beams

Energy	0.25mm Sn+0.5mm Cu	0.5mm Cu	Sensitivity	Mean energy
140-p	—	—	0.552	59.5
140-p	—	√	0.625	75.2
140-p	√	√	0.620	86.6
120-p	—	—	0.532	54.9
120-p	—	√	0.610	69.9
120-p	√	√	0.603	79.5
100-p	—	—	0.528	49.8
100-p	—	√	0.566	63.9
100-p	√	√	0.553	71.8
80-p	—	—	0.536	43.6
80-p	—	√	0.555	56.6
80-p	√	√	0.515	62.9
60-p	—	—	0.554	36.7
60-p	—	√	0.541	47.0
60-p	√	√	0.517	51.3
140-m	—	—	0.520	—
120-m	—	—	0.510	—
80-m	—	—	0.509	—
40-m	—	—	0.511	—
30-m	—	—	0.503	—
20-m	—	—	0.209	—

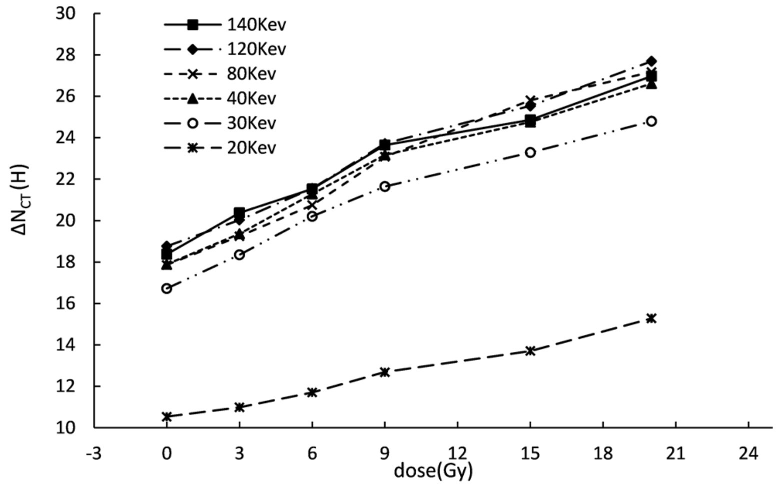

Figure 5. Dose-response curves for six monochromatic beams

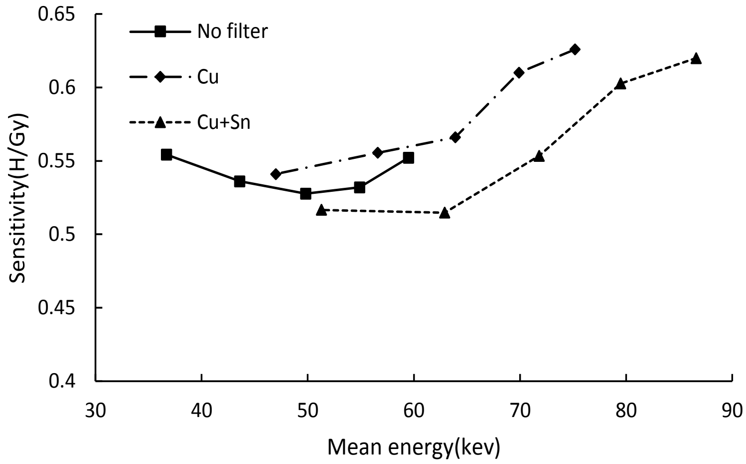

Figure 6. Mean sensitivities without a physical filter, with a copper filter, and with a copper+tin filter

Discussion

X-ray photon spectra can be considered as a factor affecting the sensitivity of polymer gel dosimetry using x-ray CT [20-23]. This was shown previously by changing the photon spectra using different kVp selection. However, no study reported the application of physical filter made of different materials to improve the sensitivity of polymer gel dosimeters. The purpose of the current research was to investigate the effect of radiation spectrum on the CT imaging of polymer gel by application of physical filters. Due to the fact that the CT polymer gel dosimetry was primarily proposed based on the changes in electron density of irradiated gels, the increase in sensitivity was expected by improving x-ray spectra used for imaging.

BThe considerable interaction of photons with polymer gel were Compton collisions. Therefore, to see the effect of photon energy on the acquired CT images of polymer gels and avoid the limitation of experimental studies, different X-ray spectra were simulated using MC method, and the whole imaging process for gel dosimetry was modeled by MCNPX code.

ur results showed that the response-dose curve can be conformed to a linear function in a dose range of 0-20 Gy for all physical filters used in this study. The linearity of polymer gel response was consistent with the results of Hilts et al [20] and Hindmarsh [24]. InBased on figures 4 and 5, showing the dose-response curve for poly- and mono-energetic beams, it is evident that the linear function fit well for all dose-response curves. The comparison of the dose sensitivity lines revealed that the application of the physical filter on the spectrum was effective in the dose response or sensitivity of the gel. However, it should be noted here that there is no similar study in the literature about the effect of beam filtering with physical filters on polymer gel sensitivity. Thus we were not able to do comparison with others.

y the enhancement of photon energy, the linear attenuation coefficient of water decreases due to the reduction of photoelectric collisions. However, this lead to the enhancement of the contrast-to-noise-ratio, which results in a higher sensitivity in the obtained gel images. The significant energy ranges for the photoelectric collision in water and Compton collision are < 20 keV and 20 keV-10 MeV, respectively [36]. In the previous studies, the kVp enhancement was recommended only to reduce the noise content of the resultant gel images.

TConsequently, the results of the spectra with a copper filter and copper+tin filter showed an upward trend of sensitivity with energy elevation. This can be attributed to the fact that high-energy photons have a higher chance to penetrate the phantom; therefore, more photons are detected and used for image formation. This issue will create a higher contrast-to-noise-ratio, and consequently a larger difference between the obtained CT numbers of water and irradiated gels.

AThe installment of the physical filter led to the removal of a part of the spectrum responsible for the photoelectric collision. On the other hand, in the energy range of 100 keV-10 MeV, Compton collision was the dominant collision in water and tissue [36]. Therefore, due to the fact that the CT polymer gel dosimetry was proposed to be based on the changes in electron density, the increase in sensitivity was expected to occur based on Compton collisions. Comparison The comparison of the dose-response curves of monochromatic beams demonstrated that the increase in energy was effective in the dose response of gel in CT images. In this regard, the sensitivity with 20 keV beam was lower than those with other energies.

As indicated in Figure 5, the mean sensitivity for mono-energetic beams suddenly enhanced with an increase in energy from 20 to 30 keV. At an energy of 20 keV, the absorption rates of radiation were 70% and 30% in water due to photoelectric interaction and Compton scattering, respectively. On the other hand, these values were recorded as 31% and 61%, for an energy of 30 keV, respectively. Regarding this, it seems that the cause of low-dose response and low sensitivity at 20 keV was the change in the relative number of dominant collisions.

Conclusion

As the findings revealed, the variation of the linear attenuation coefficient in irradiated gel was due to the enhancement of mass density. The elevation of electron density led to the increase in the CT number. The irradiated polymer gel was modeled inside the gantry of a modeled CT scanner. The dose-response curve was calculated for several photon beam spectra to find the optimum sensitivity for polymer gels.

The results showed that the changes in the tube spectrum in the CT scanner affected the sensitivity of the gel and could increase it. For the physical filters used in this research, the response-dose curves were conformed to the linear function in a range of 0-20 Gy. Therefore, tube spectra can be considered as an effective factor in improving the sensitivity of the gel, and can increase the sensitivity by changing the tube spectrum. The physical filters used in this study were among the common filters adopted in radiology. Therefore, it is essential to find newer filters in order to compare and obtain the most suitable spectrum for CT polymer gel dosimetry.

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