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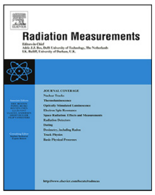

Analysis of the relationship between neutron dose and Cerenkov photons under neutron irradiation through Monte Carlo method

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HIGHLIGHTS

- Relationship between Cerenkov photons and neutron dose in water was investigated.
- Neutron dose has good correlation with Cerenkov photons between 0.01 eV and 100 eV.
- Ratio of neutron dose to Cerenkov photons is energy-independent at specified case.
- Cerenkov radiation also has the potential application in neutron dose measurement.

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ABSTRACT

To theoretically explore the feasibility of neutron dose characterized by Cerenkov photons, the relationship between Cerenkov photons and neutron dose in a water phantom was quantified using the Monte Carlo toolkit Geant4. Results showed that the ratio of the neutron dose deposited by secondary electrons above Cerenkov threshold energy to the total neutron dose is approximately a constant for monoenergetic neutrons from 0.01 eV to 100 eV. With the initial neutron beam energy from 0.01 eV to 100 eV, the number of Cerenkov photons has a good correlation with the total neutron dose along the central axis of the water phantom. The changes of neutron energy spectrum and mechanism analysis also explored at different depths. And the ratio of total neutron dose to the intensity of Cerenkov photons is independent of neutron energy for neutrons from 0.01 eV to 100 eV. These findings indicate that Cerenkov radiation also has potential in the application of neutron dose measurement in some specific fields.

1. Introduction

Cerenkov radiation is a kind of electromagnetic radiation emitted when a charged particle travels at a speed greater than the phase velocity of light in the medium. Since its discovery, Cerenkov radiation has been widely used in different applications, such as nuclear physics and astrophysics (Jelley, 1955; Gorham et al., 2000; Pedaletti et al., 2013). The existence and velocity of high-speed particles can be identified by Cerenkov detector (Shiozawa et al., 1998; Haxton, 1987). Cerenkov radiation has also been extended to the application in biological imaging studies. As a new optical imaging modality, Cerenkov luminescence imaging has been researched for the potential of the diagnosis of cancer, the assessment of treatment efficacy, and the guidance of cancer surgery, etc (Ma et al., 2014; Tang et al., 2015; Robertson et al., 2009).

More recently, Cerenkov radiation has been applied in the dose measurement from therapeutic electron and photon beam irradiations, and the feasibility of its usage has been demonstrated through theoretical analysis and experimental verification (Glaser et al., 2013; Helo et al., 2014; Shu et al., 2016; Jang et al., 2012; Yoo et al., 2013; Jarvis et al., 2014). The clinical translation process of this technique is still under investigating.

In fact, Cerenkov photons can also be generated under neutron

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irradiation during the transportation of the secondary charged particles. Researchers have developed the water Cerenkov neutron detector for monitoring and tracking spent fuel storage, radioactive waste containers and special nuclear materials, etc (Dazeley et al., 2009, 2012; Cheon and Kim, 2015). The application of Cerenkov neutron detector has the advantages of both affordable and deployable in these areas. One of the recent developments is the determination of the thermal neutron flux in the facilities of thermal neutron source using the Cerenkov fiber-optic radiation sensor (Jang et al., 2013).

It is also very meaningful to obtain the neutron dose. The quality assurance and control of neutron beam requires the obtainment of the distribution of neutron dose, which is the critical process to ensure the therapeutic effect in boron neutron capture therapy. Besides, neutron dose measurement may contribute to radiation safety and protection of radiation workers or the public. In this study, we will explore the physics of Cerenkov radiation emission from neutron beams in water phantom, and theoretically investigate the relationship between Cerenkov radiation and neutron dose for the realization of neutron dose measurement using Cerenkov radiation, which has been seldom investigated.

2. Materials and methods

2.1. Physics principle of Cerenkov radiation from neutron interactions

The Cerenkov radiation from neutron irradiation is not directly generated from neutrons, but from the secondary charged particles. When the energy of a secondary charged particle is higher than Cerenkov threshold energy in the specified medium, optical photons will be emitted. The Cerenkov threshold energy can be calculated according to the refraction index of the medium.

$$T_{\text{threshod}} = E_0\left(\frac{1}{\sqrt{1-\frac{1}{n^2}}}-1\right) \tag{1}$$

Where T_{threshod} is the threshold energy above which the charged particle can emit Cerenkov photons, E_0 is the rest energy of the charged particle, n is the index of refraction of the medium (Jelley, 1955). For instance, the Cerenkov threshold energy is 0.263 MeV for electron and 485 MeV for proton when the refraction index of water is 1.33.

When the target is water, the secondary charged particles under neutron irradiation are mainly recoil nuclei and secondary electron. Recoil nuclei can be generated from neutron elastic scattering and inelastic scattering. However, considering the energy range of neutrons is lower than 20 MeV in this study, and consequently the maximum kinetic energy of the recoil nuclei ($Z \geq 1$) is far lower than the Cerenkov threshold energy ($>=485$ MeV). The secondary electrons of recoil nuclei also do not have sufficient energy to emit Cerenkov photons according to the calculated results. The secondary electrons also can be generated by the interaction of secondary gamma rays from the neutron capture reaction. For neutron capture with hydrogen and oxygen atoms, the typical energies of the emitted gamma rays are 2.224 MeV, 0.871 MeV, 1.088 MeV, 2.184 MeV and 3.272 MeV. Therefore, the maximum energy of the consequent secondary electrons of the captured gamma ray would be higher than the threshold energy (0.263 MeV) of the generation of Cerenkov radiation. One can expect that the main cause of the Cerenkov radiation for neutron irradiation in water is the secondary electrons from the gamma ray of neutron capture reaction. Based on the cross sections of neutron capture reaction, the primary production mechanism of Cerenkov photons is the interaction effect between the medium and secondary electrons from the gamma rays generated by neutron capture with hydrogen atoms, which contributes at least 99% of total Cerenkov photon numbers according to the calculated results.

2.2. Monte Carlo simulation

Geant4 Monte Carlo package (Agostinelli et al., 2003; Allison et al., 2006) was employed to investigate the relationship between Cerenkov photons and dose deposited during neutron irradiation. The prepackaged QGSP_BIC_HP physic list with additional optical physics process was adopted in all simulations. The QGSP_BIC_HP package includes standard electromagnetic and hadronic physics processes and has been suggested for the simulation of neutron interaction for neutrons below 20 MeV (Geng et al., 2016). A cut-off value of 0.01 mm was chosen in Geant4.

In this study, a 10×10 cm^2 neutron field was employed to perpendicularly irradiate a $50 \times 50 \times 50$ cm^3 water phantom, as shown in Fig. 1. A stack of $2 \times 2 \times 0.2$ cm^3 voxels along the central axis were built to score the quantities of interest. The parameters studied in this paper include the number of Cerenkov photons, neutron dose deposited by the secondary electrons with energy higher than Cerenkov threshold (D_c) and total neutron dose (D_t). A series of neutron beam energies from 0.001 eV to 10 MeV were investigated. All simulations were performed with 10^9 primary particles.

3. Results and discussion

3.1. Dose deposition characteristic of monoenergetic neutron

In order to analyze the relation of the dose deposition characteristic and the Cerenkov radiation for monoenergetic neutron, we first calculated the ratio of the neutron dose deposited by secondary electrons with energy greater than the Cerenkov threshold energy (D_c) and the total neutron dose (D_t) for different monoenergetic neutron energies. These quantities of interest were obtained in the first scoring voxel along the central axis in order to avoiding the change of the neutron energy with the increased depth. Therefore, the dose deposition in this scoring volume was considered to be caused by the initial beam energy. The results are shown in Fig. 2.

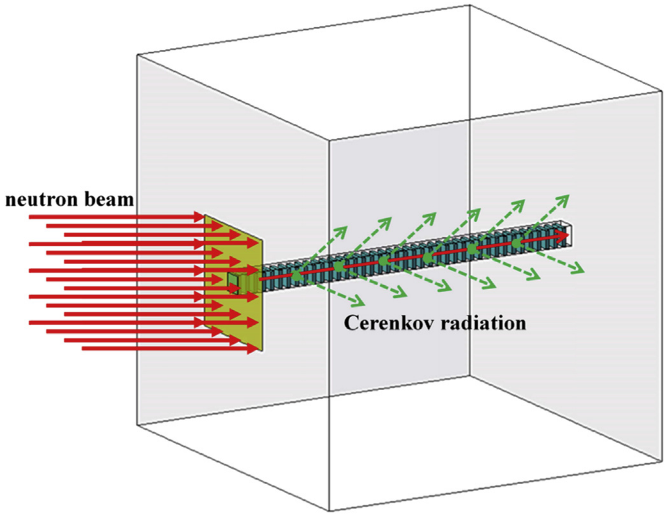

Fig. 1. Schematic of the geometry and beam setup in Monte Carlo simulations.

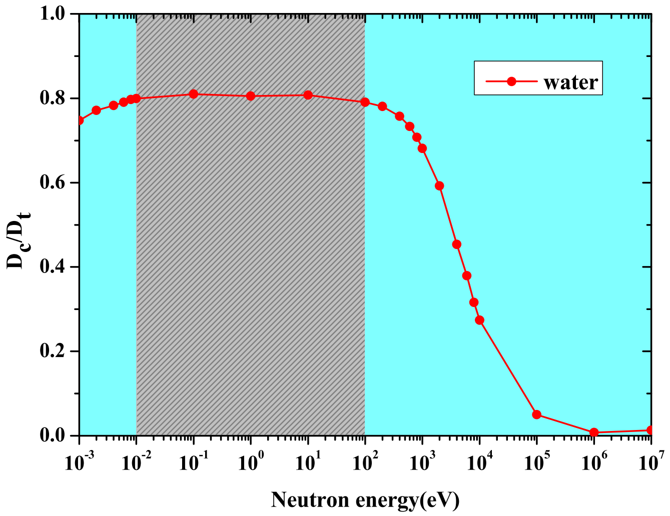

Fig. 2. The ratio of dose from electrons above the Cerenkov threshold energy (D_c) to total neutron dose (D_t) for different initial neutron energies.

Fig. 2 shows that the ratio of D_c to D_t is found to be approximately a constant 0.8 for the energy from 0.01 eV to 100 eV. The main contribution of neutron dose comes from the neutron capture reaction in this range. For energies outside of this interval, the ratio is smaller and obviously energy dependent. This is due to the increasing portion of dose from recoil nuclei caused by neutron elastic scattering, and therefore, the portion of dose from electrons above the Cerenkov threshold energy is relatively decreased.

Previous studies have demonstrated that the intensity of Cerenkov photons is approximately proportional to the dose deposition from secondary electrons with energy higher than the Cerenkov threshold energy (Glaser et al., 2013; Helo et al., 2014; Shu et al., 2016). Taken together, the total neutron dose also can be correlated with the number of Cerenkov photons for the monoenergetic neutrons from 0.01 eV to 100 eV.

3.2. Depth distribution of neutron dose and Cerenkov photons

To further study the reliability of the relation between neutron dose and Cerenkov radiation inside a water phantom, the total neutron dose (D_t) and the number of Cerenkov photons per unit mass of the medium (N_c) were scored in the voxels along the central axis. We calculated these distributions for a series of initial neutron energies. The distributions of the total neutron dose and the number of Cerenkov photons for several representative energies between 0.01 eV and 100 eV are compared in Fig. 3, and outside this energy interval in Fig. 4. All the data were normalized by the maximum value in each curve.

Fig. 3 shows good correlations between the total neutron dose and the number of Cerenkov photons when the energy is in the plateau region in Fig. 2. The response relationship between neutron dose and Cerenkov photons can be explained as follows. The contributions of dose from secondary electrons generated by gamma rays to the neutron dose is about 98% and almost constant at different depths in this range according to the calculated results. And the dose from secondary electrons generated by gamma rays can be characterized by Cerenkov photons (Glaser et al., 2013). Thus, the number of Cerenkov photons can be related to neutron dose.

While the energy is outside of the plateau region in Fig. 2, the results in Fig. 4 clearly show that Cerenkov photons curves have certain differences from the neutron dose distributions. For the energies of 0.001 eV and 1 keV, the results indicated a certain degree of response relationship between neutron dose and Cerenkov photons although the differences at shallow depths are bigger than that at deeper locations. This can be explained by the ratios for the energies of 0.001 eV and 1 keV in Fig. 2, which are not far away from the plateau region. For the energy of 10 keV and 1 MeV, the portion of dose caused by neutron elastic scattering is higher and not constant at different depths. It will not emit Cerenkov photons during dose deposit of this part, thus cannot correlate dose with Cerenkov photons.

3.3. Neutron energy spectrum along depth for different initial neutron beam

The energy spectrum of the neutron gradually changed with the increase of penetration distance, which also made the ratios change of different neutron interaction processes contribute to the neutron dose. To analyze the impact of neutron energy spectrum on the relationship between neutron dose and Cerenkov photons, we obtained the neutron energy spectrum at different depths for different initial neutron energies. The results are shown in Fig. 5. All the data were normalized by the maximum value in each figure.

As can be seen from the figure, neutrons of energies from 0.01 eV to 100 eV are the main part of total neutrons at different depths for neutron beam energies from 0.01 eV to 100 eV. This is the reason that neutron dose can be well characterized by Cerenkov photons in this specified energy interval. For the energy of 0.001 eV, the energy of majority neutrons will also become larger than 0.01 eV through the thermal neutron up-scattering in a short distance, which may provide the opportunity to realize the dose measurement of neutrons with energy lower than 0.01 eV. Meanwhile, the existence of the response relationship between Cerenkov radiation and neutron dose at deeper locations for the energy of 0.001 eV also can be explained by Fig. 5. For the energy of 1 keV, it can be noticed that the energy of some neutrons is larger than 100 eV at depth of 1 cm, and neutrons are also concentrated on the energies from 0.01 eV to 100 eV at deeper depth. The varying degrees of deviation between Cerenkov photons and neutron dose at different depths in Fig. 4 can be explained through the neutron energy spectrum. Therefore, the energy spectrum of the neutron determines the response relationship between Cerenkov photons and neutron dose.

3.4. Relationships among dose from electrons with energy higher than Cerenkov threshold energy, total neutron dose, and Cerenkov photons

The generation mechanism of Cerenkov radiation under neutron irradiation is the secondary electrons generated by gamma rays. For neutrons from 0.01 eV to 100 eV, the gamma dose is the main contributor of neutron dose, which provides the possibility of neutron dose characterized by Cerenkov photons. Cerenkov radiation can be emitted only when the energy of secondary electrons generated by gamma rays is higher than the Cerenkov threshold energy. Thus, it is very necessary to explore the contribution of those secondary electrons dose to neutron dose.

The ratio of the neutron dose from electrons with energy higher than the Cerenkov threshold energy 0.263 MeV (D_c) to the total neutron dose (D_t) at different depths was calculated. For energies within the plateau in Fig. 2 such as 0.01 eV, 1 eV and 100 eV, the ratio shown in Fig. 6 is independent of the initial beam energy. The ratios are 0.8 at shallow depths, which are consistent with the values of initial neutron energies as shown in Fig. 2. For the energies of 0.001 eV and 1 keV, the ratio first increases and then decreases along with depth.

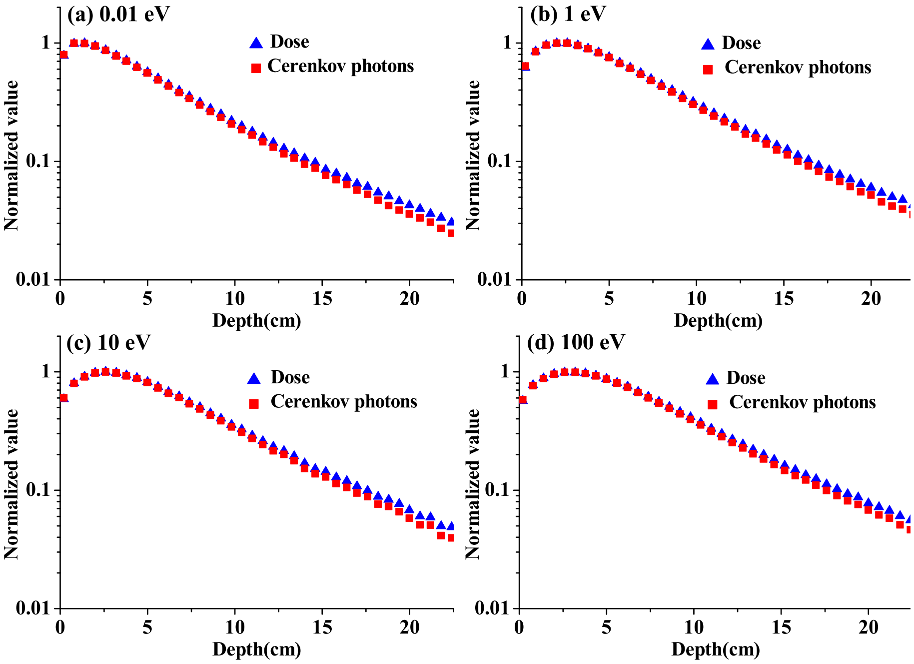

Fig. 3. Comparison between total neutron dose and the number of Cerenkov photons. The results for beam energies 0.01 eV, 1 eV, 10 eV and 100 eV are depicted in panel (a) to (d).

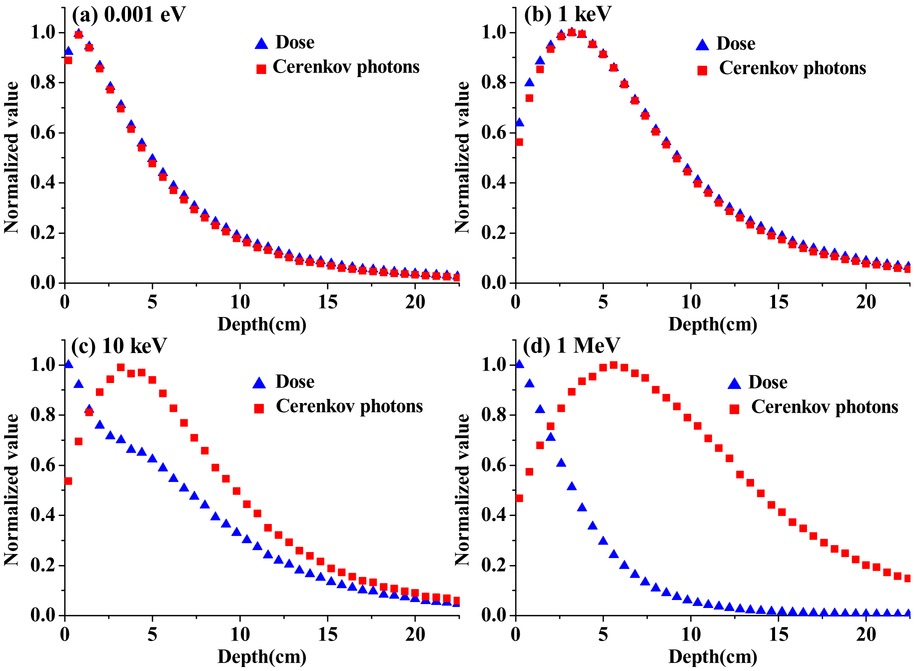

Fig. 4. Comparison between total neutron dose and the number of Cerenkov photons. The results for beam energies 0.001 eV, 1 keV, 10 keV and 1 MeV are depicted in panel (a) to (d).

According to the results, neutron dose from electrons with energy higher than 0.263 MeV has a proportional relationship with the total neutron dose in any spatial locations for neutrons from 0.01 eV to 100 eV. It is also necessary to correlate the neutron dose from electrons with energy higher than 0.263 MeV (D_c) with the number of Cerenkov photons per unit mass of the medium (N_c). The ratio of D_c to N_c for different initial neutron energies are shown in Fig. 7. As observed, this ratio is independent of the initial beam energy at each depth. Although it is not a constant, the coefficient between D_c and N_c also can be determined by the depth. Thus, Cerenkov radiation can be directly used to correlate with the neutron dose at different depths.

3.5. Quantitative relationship between total neutron dose and Cerenkov photons

The findings in this study show that Cerenkov radiation has a good correlation with total neutron dose for neutron beam energies from 0.01 eV to 100 eV in a water phantom. However, further determination of the quantitative relationship between total

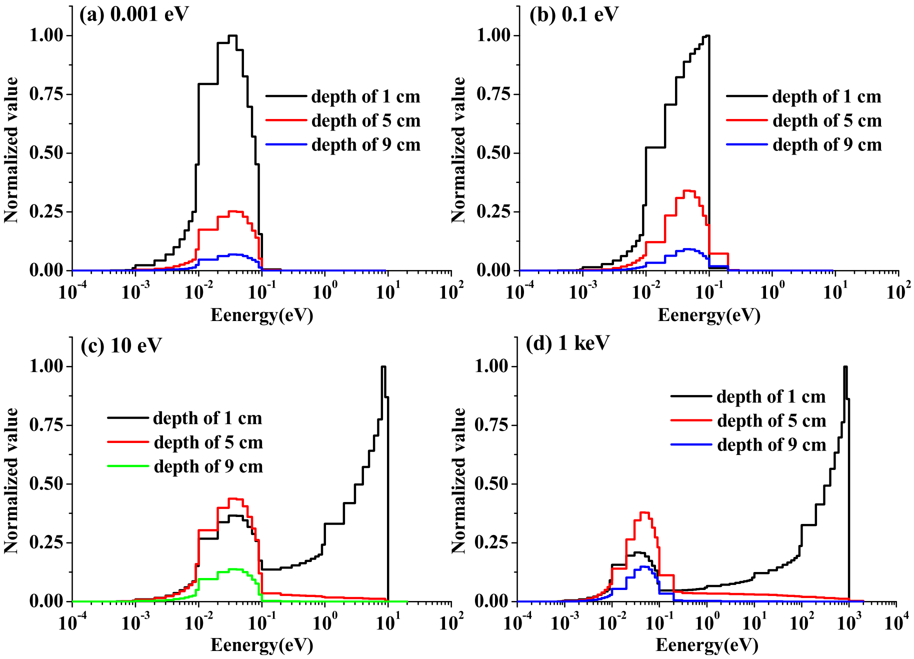

Fig. 5. The energy spectrum of the neutron at different depths for different initial neutron energies.

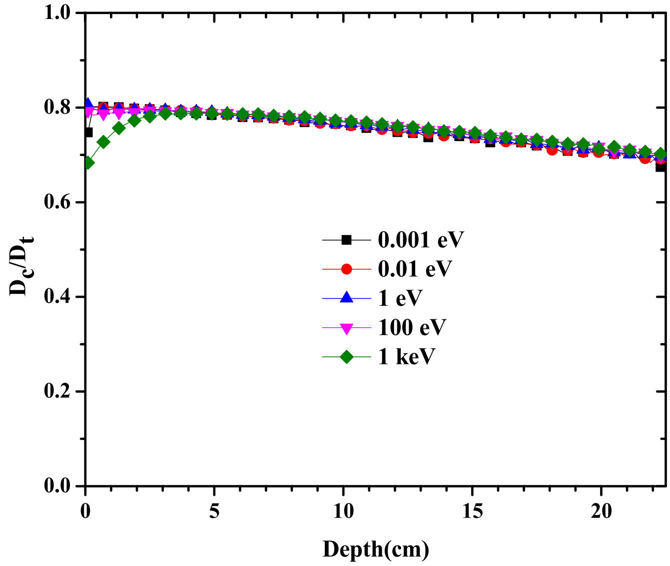

Fig. 6. Ratio of dose from electrons with energy higher than 0.263 MeV (D_c) to the total neutron dose (D_t).

neutron dose (D_t) and the number of Cerenkov photons (N_c) is especially critical to realize the further application in practice. The quantitative relationships at different depths for different initial neutron beam energies are shown in Fig. 8.

The proportionality coefficient increases linearly with the increase of the depth. This was also caused by the increased portion of low-energy neutron. The linear correlation equation between the proportionality coefficient (y) and depth (d) is fit to be $y = 1.71 \times 10^{-17}d + 1.6 \times 10^{-15}$ with an $R^2 = 0.96$ for the data from the three neutron energies. Hence, the number of Cerenkov photons can be transformed into neutron dose through the proportionality coefficient determined by the depth in theory.

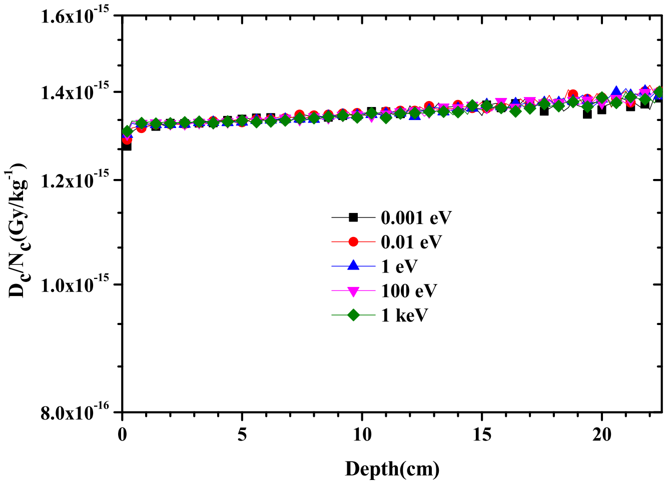

Fig. 7. The ratio of the neutron dose from electrons with energy higher than the Cerenkov threshold energy (D_c) to the number of Cerenkov photons per unit mass of the medium (N_c).

4. Conclusions and discussions

In this study, we analyzed the generation of Cerenkov photons under neutron irradiation and investigated the relationship between Cerenkov radiation and neutron dose in a water phantom. Our Monte Carlo simulation results show that the ratio of the neutron dose deposited by electrons above the Cerenkov threshold energy to the total neutron dose is approximately a constant for the monoenergetic neutron energies ranging from 0.01 eV to 100 eV. For neutron beams with initial energies between 0.01 eV and 100 eV, the total neutron dose can be well correlated with the number of Cerenkov photons at different depths in water phantom. We also analyzed the deviation between Cerenkov photons and neutron dose through the changes of neutron energy spectrum along depth. Meanwhile, the relations among total neutron dose,

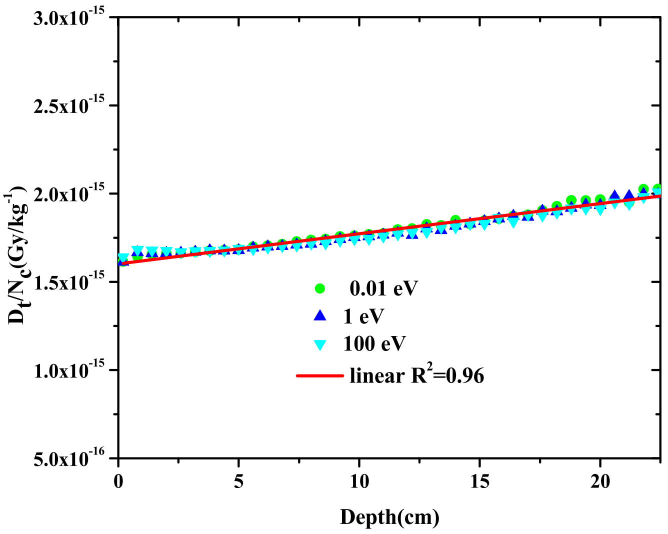

Fig. 8. Proportionality coefficients between total neutron dose (in the unit of Gy) and the number of Cerenkov photons per unit mass (in the unit of kg^{-1}) at different depths for different initial neutron beam energies.

the neutron dose deposited by electrons with energy higher than the Cerenkov threshold and the number of Cerenkov photons were also explored. In addition, the proportionality coefficient between total neutron dose and the number of Cerenkov photons per unit mass was found to be dependent on the depth in the water phantom. The number of Cerenkov photons at different depths may be obtained through optical tomography by using optical detector array, and then neutron dose can be obtained at different depths. The exploration of this work may contribute to design a new type of water Cerenkov neutron detector which will be able to measure neutron dose in the future.

Although our preliminary data showed that the response relationship between the number of Cerenkov photons and total neutron dose only exists for neutron energies from 0.01 eV to 100 eV. However, for monitoring and tracking spent fuel storage, radioactive waste containers and special nuclear materials, the low energy neutrons are the main measuring object after pass through the shielding layer. The quality assurance of thermal neutron beam in boron neutron capture therapy also needs to measure the characteristics of thermal neutron. Meanwhile, neutrons with energy lower than 0.01 eV do not have much impact on dose measurement due to the existence of thermal neutron up-scattering effect. Therefore, neutron dose measurement using Cerenkov radiation has application foreground in these areas.

Nevertheless, to realize the application of neutron dose measurement using Cerenkov radiation in practice, all the factors in complex measurement conditions need to be further addressed accordingly to achieve an accurate measurement. Firstly, the measurement in mixed radiation fields is the difficult problem that researchers must face. Based on the usage of Cerenkov radiation in gamma and electron dose measurement, total dose measurement of gamma, electron and neutron by using one detector is worth looking forward to. Secondly, the effect of background signal must be considered during the detection of Cerenkov photons. The background signals may include background light, Cerenkov photons generated by cosmic muons or gamma rays from the environment in the detector, etc. For background light, it can be addressed through background correction or adding optical shielding layers. For background radiation, due to its low fluence in general, the impact on detection of neutron may be little, but the detail impact still needs further study. Furthermore, it is also important to further study the structure design of detector, detection method of Cerenkov photons, and so on. Overall, to experimentally test the proposed method in this work is still challenging and will be further discussed in the future work.

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