Measurement of fast neutron contamination caused by the presence of wedge and block using CR-39 detector

ABSTRACT

Objective: Undesired neutron contamination imposed to patients during treatment is among the main factors increasing the risk of secondary cancer in radiotherapy. This additional undesirable dose is due to neutron contamination production in high-energy accelerators. In this study, neutron contamination is investigated in the presence of wedge and block in 15 MV photon fields of Siemens Primus linear accelerator.

Materials and Methods: Neutron production by 30°, 45°, and 60° wedges and cerrobend block was investigated. Measurements were conducted in a 10 cm × 10 cm field at the source to – surface distance of 100 cm at 0.5, 2, 3, and 4 cm depths of a 30 cm × 30 cm × 30 cm Perspex phantom using the CR-39 passive film detectors. Chemical etching was performed using sodium hydroxide solution with 6.25 M concentration as the etchant at 85°C for 3 h.

Results: The neutron dosimetry results reveal that the presence of wedge and block increases the neutron contamination. However, the 45° wedge is most effective in producing neutron contamination. The results also show that the fast neutron contamination is lower in the steeper depths.

Conclusion: The presence of a wedge in a therapeutic high-energy photon field is a source of neutron contamination and may be of concern regarding clinical aspects. The results of this study show that superficial tissues such as skin will incur higher fast neutron contamination than the deep tissues.

KEY WORDS: Cerrobend block, CR-39 film, medical linear accelerators, neutron contamination, neutron dosimetry, wedge

INTRODUCTION

In some of the radiation therapy protocols, beam modifiers such as block, wedge filter, flattening filter, multi-leaf collimator, and asymmetric jaws are used to modify the radiation beam. Medical linear accelerators (linac) used in radiation therapy, which produces photons with energies higher than 8 MV, impose an unwanted dose to patients due to neutron production. Neutron is primarily produced due to the collision of high-energy photons with high Z materials in the head of the accelerator (target, collimators, flattening filter, and shields). Secondary cancer resulted from radiation therapy is currently a growing concern, which might be caused by exposing patients to unwanted neutrons irradiated with high-energy photon beams. Neutrons as particles with high relative biological effectiveness have a relatively high weighting factor. Therefore, neutrons have much higher biological effects than photons with identical dose. Knowing the neutron dose received by the patient during radiotherapy treatment is of utmost importance.

Several instruments can be used to measure neutrons, i.e., thermoluminescent dosimeters, bubble detectors, and solid-state dosimeters. CR-39 is one of the most common and most widely used solid-state nuclear track detectors. This type of detector works as follows: after the collision of neutrons to the detector through the production of protons, hidden tracks are formed on the surface of CR-39 due to breakdown, and damage to the film’s polymeric structure, which cannot be seen or counted even by a microscope. The etching process...
is carried out to make these tracks visible. There are several etching processes such as chemical, microwave-induced chemical, and electrochemical etching (CE). In the CE method, CR-39 detectors are immersed in an alkaline or acidic solution as the etchant for specific time duration with certain concentration and temperature. In this process, the latent tracks grow and become visible and can be countable under a microscope.[11,12]

CR-39 film dosimetry approach has many advantages such as insensitivity to ultraviolet and X-ray, maintenance of the recorded tracks, and similar composition to human tissue. Furthermore, this type of detector tends to be more sensitive to fast neutrons, which makes it as a suitable choice for fast neutron dosimetry purposes.[13,14] This detector is sensitive to alpha particles and thus can be used for measuring the background radon gas.

Biltekin et al.[15] examined neutron contamination outside and inside radiation fields of high-energy medical linear accelerators. They have measured photoneutron for Elekta and Varian accelerators at 18 MV energy. They also used bubble detector for neutron contamination evaluation. Compared to a 10 cm × 10 cm open field, the presence of dynamic and physical wedge has led to 60% and 18% increases in neutron contamination on the beam’s central axis, respectively. The neutron dose was also greater at shallow depths than the steeper depths.

Hashemi et al.[16] studied the effect of block field modifier on equivalent dose of fast neutrons from Elekta and Saturn accelerators. Polycarbonate films were used to measure the neutron dose in that study. Measurements were made on a water phantom with dimensions of 30 cm × 30 cm × 30 cm at the isocenter and also at distance of 50 cm from the isocenter. Using a lead block field modifier, field size was adjusted from 30 cm × 30 cm to 17.5 cm × 17.5 cm, and again the measurements were repeated at the isocenter and at the distance of 50 cm from the isocenter. They showed that the Elekta accelerator (with 18 MV energy) had a higher neutron equivalent dose (2.4 mSv/Gy) at the center of the field, and it was reduced to 1.8 mSv/Gy with increasing the distance to 50 cm away from the isocenter. When the lead block was placed in the field, these amounts were increased to 5.4 mSv/Gy and 2.6 mSv/Gy, respectively. Moreover, the equivalent dose of neutron for Saturn accelerator (with 25 MV energy) was 7.9 mSv/Gy at the center of the field and reduced to 1.6 mSv/Gy at 50 cm distance from the center of the field. These values were increased to 6.9 mSv/Gy and 2.3 mSv/Gy, respectively when the lead block was located on the field.

While there are various studies on the neutron contamination dosimetry for different accelerators, to the best of our knowledge, there is no any evaluation of neutron contamination due to the presence of wedge and block beam modifiers in the photon beam of Siemens Primus linac. Since the level of neutron contamination is geometry-and composition-specific, it should be measured for each type of beam modifier, and linac independently. The main purpose of this study is to measure the fast neutron equivalent dose in the presence of wedge and block in the radiation field of Siemens Primus medical linac and investigate the effect of the phantom material on neutron contamination.

MATERIALS AND METHODS

CR-39 detectors were applied for measuring the fast neutron equivalent dose to investigate the wedge and block neutron contamination effect in a 15 MV photon beam of a Siemens Primus linac. These dosimeters are sensitive to neutron and alpha particles as well. Neutron contamination was measured in the presence of 30°, 45°, and 60° angles wedges and a cerrobend block.

Calibration of CR-39 films

In the current study, CR-39 films made by TASTRAK Company (Track Analysis System Ltd., Bristol, United Kingdom) with 1.5 mm × 25 mm × 25 mm dimensions were used in the calibration and measurement procedures. The CR-39 detectors calibration was conducted in the Atomic Energy Organization of Iran (in gamma, neutron, and radon calibration laboratory). An americium-beryllium (241-Am-Be) source was used for film irradiation in the calibration step. The calibration procedure was as follows: 18 film pieces were divided into six groups. Next, in each group, three films were placed at 0.5 m distance from the source and were irradiated in the certain period with a specified neutron dose.

The fast neutron equivalent doses were 0.5, 1, 2, 3, 4, and 5 mSv in these groups. Three detectors were saved without irradiation and with the same history of the other films for the measurement of background neutron dose. Then, the background number of tracks on these films was deducted from the number of tracks on the other calibration films. Neutron tracks were counted using the conventional optical microscope after CE and a calibration curve was obtained for the CR-39 detectors. Having this information, it is possible to obtain calibration factors (fitting parameters) from the calibration curve and then determine the fast neutron equivalent dose induced from photoneutron fields.

Measurement set-up

A Siemens Primus linear accelerator (Siemens, made in Germany) with 15 MV photon energy was studied at Reza Radiation Oncology Center (Masahad, Iran), and the neutron contamination was measured for an open field and for three wedges of this linac (with 30°, 45°, and 60° angles). To evaluate the neutron contamination in the presence of a block, a piece of cerrobend block was built with dimensions of 1.5 cm × 1.5 cm × 7.0 cm (similar to a typical block used for eye shielding), and measurements were made in the presence of the shield on the central axis of the photon beam.
All measurements were done at the source–surface distance of 100 cm in a 10 cm × 10 cm photon field. The fast neutron equivalent doses were obtained in a 30 cm × 30 cm × 30 cm Perspex phantom at 0.5, 2, 3, and 4 cm depths. The measured values were based on the irradiation of 1 Gy photon dose at the depth of maximum dose. The output of the linac is 1 Gy/100 monitor units (MUs) for the open field. Wedge factors for these wedges were considered, and MU values of 166.7, 250, and 233.5 were considered for the 30°, 45°, and 60° wedges, respectively. All the wedges were placed at the “2R” direction, with the wedge’s heel part being on the right side of the linac’s gantry. The cerrobend block was placed in the center of the field so that the block shadow was matched on the CR-39 detectors; then, measurements were conducted under similar conditions of the previous steps for the wedges. The MU value was set at 107.6 in the field with a block, considering the tray factor. To reach a suitable level of reliability (repeatability), all measurements were repeated for three times.

In all the measurement procedures, three unexposed CR-39 detectors were used for background radiation measurement. These CR-39 detectors had the same history as the other detectors so that they were kept under the same conditions as the irradiated detectors were stored, and had similar CE and reading conditions as the other detectors, as well.

**Chemical etching**

As mentioned in the introduction section, CE is the process of making hidden tracks visible after irradiating CR-39 detectors. According to recommendations of the manufacturer of the detectors, the optimum condition for CE is treating CR-39 detectors in sodium hydroxide (NaOH) solution with 6.25 M concentration at 85°C for 3 h. To obtain such a stable temperature, a laboratory Bain-Marie (Memmert GmbH, Germany) was used. After etching in NaOH solution, CR-39 films were rinsed with tap water for 10 min and then washed for two times with distilled water. Then, the films were placed in a distilled water container for half an hour. Finally, the CR-39 detectors were dried with a tissue. The etching steps were quite the same in the measurement and calibration phases.

**Reading CR-39 films**

After the CE process, tracks produced by the collision of neutrons on CR-39 films would become visible. After visualization of the tracks, a Nikon model Eclipse E200-LED optical microscope from the USA was utilized. This microscope has different magnifications (×10, ×20, and ×40), and a ×10 magnification objective lens was used in the current study. To count the tracks and convert them to fast neutron equivalent doses, it is necessary to first calculate the microscopic field in which counting is done. A scaled slide was used for this purpose. Finally, microscopic fields of 0.96 mm² were applied, and the number of neutron tracks per square centimeter was obtained.

**RESULTS**

As mentioned in the previous section, CR-39 films were irradiated with prespecified doses of the neutron in the calibration step. The selected equivalent doses for the calibration were 0.5, 1, 2, 3, 4, and 5 mSv. After irradiation with a neutron source and conducting CE process, the number of tracks on the films was counted, and the density of tracks was obtained (regarding tracks/cm²). A sample image of such films that was irradiated with 0.5 mSv fast neutron equivalent dose is illustrated in Figure 1. The average number of tracks on the background films was subtracted from the number of tracks on the irradiated films. The track density on the background film related to the calibration process was 141 tracks/cm². The track density values after deduction of background radiation track values related to the calibration process are listed in Table 1. Figure 2 shows the corresponding calibration curve drawn using the values shown in Table 1. According to the linear fitted equation on this plot, the relationship between the fast neutron equivalent dose and the density of tracks was obtained as follows:

\[
H \text{ (mSv)} = 29.16 \times 10^{-4} N \text{ (tracks/cm²)} - 0.22, R^2 = 0.99 \tag{1}
\]

Where, \( H \) is the fast neutron equivalent dose regarding mSv and \( N \) is the number of tracks per cm².

The neutron contamination measurement was performed for the open field, 30°, 45°, and 60° wedge fields and for the field with a block, at 4 depths inside a Perspex phantom.
of 30 cm × 30 cm × 30 cm dimensions. To increase the reproducibility of the measurements, each measurement was repeated three times, and the mean value of the three measurements was reported. After irradiating the films in the above-mentioned conditions and performing a CE process, the number of tracks on each film was counted using a conventional optical microscope, and track density was obtained regarding tracks/cm². The number of tracks on the background films related to the measurement step was 83 tracks/cm², and this value was deducted from the tracks count on the measurement films. The track density for the different wedged fields and for the blocked field in various depths in Perspex phantom is plotted in Figure 3. Based on the calibration curve and the resulted equation, the fast neutron equivalent dose was calculated for 1 Gy photon dose at build-up depth in each set up. The fast neutron equivalent doses per 1 Gy photon dose at build-up depth (mSv/Gy) are listed in Table 2. These values are illustrated in Figure 4 in the form of a bar chart.

For a better understanding of the impact of the presence of wedge and block on the neutron contamination, the fast neutron equivalent dose of the open field was used as the baseline dose and the relative dose value (mSv/mSv) for different set ups were obtained relative to the open field. The relative fast neutron doses for different field set ups are listed in Table 3. Figure 5 shows these relative dose amounts in the form of a bar chart.

DISCUSSION

In the current study, the CR-39 film was utilized for the neutron contamination measurement in the presence of wedge and block in 15 MV photon beam of a Siemens Primus linac. As shown in Figure 1, the number of tracks per surface area of the CR-39 films (track density) is higher for the 45° wedge in all depths of the Perspex phantom. Moreover, the lowest track density values belong to the open field.

As mentioned previously, some background radiations are recorded on the films. For this reason, three films were used for eliminating the background radiation effects. All the charts were plotted after subtracting the background radiation values from the measured neutron dose values. As presented in Figure 3, the number of tracks is reduced with an increase in phantom depth probably due to the absorption of neutrons by Perspex phantom material. Perspex is composed of hydrogen, oxygen, and carbon, in which, hydrogen is a good neutron-absorbing material.

The track densities for the certain fast neutron equivalent doses are listed in Table 1. These are values after deduction of background track densities. The relationship between neutron dose and density of tracks was calculated based on the calibration curve in Figure 2, then the fast neutron equivalent dose per 1 Gy X-ray beam was obtained for the open and wedged field set-ups. As presented in Table 2 and Figure 4,
the fast neutron equivalent dose for the 45° wedge at 0.5 cm phantom depth has the highest value (1.82 mSv/Gy) while the lowest value belongs to 4 cm depth of the open field which is zero. It should be mentioned that the zero value of the fast neutron equivalent dose for 4 cm phantom depth of the open field is due to the limited sensitivity of these measurements. When a measurement method with higher sensitivity is applied, this value would not probably be zero. Followed by 45°, 60°, and 30° wedges, the cerrobend block has a higher proportion of neutron contamination.

The main reason for higher fast neutron equivalent dose in the 45° wedge is its smaller wedge factor compared to the other wedges (the wedge factors for the 30°, 45°, and 60° wedges are 0.6, 0.4, and 0.43, respectively). Since MU value is divided by a smaller value for this wedge than the other wedge factors, the maximum MU value belongs to the 45° wedge (250 MU). Therefore, the neutron contamination is more by a higher amount of MU.

It can be seen from Figure 4 that with an increase in phantom depth, the fast neutron equivalent dose is reduced in all field types, but the trend of this reduction for the blocked field is similar to the others. The reason for the lack of the same reduction trend in the cerrobend blocked field may be that only a small portion of the 10 cm × 10 cm field is blocked, therefore, the contribution of the block in producing neutron contamination is lower.

The maximum reducing trend is observed for the open field where the fast neutron equivalent dose changed from 0.31 mSv/Gy at 0.5 cm phantom depth to 0 mSv/Gy at 4 cm depth. In the second rank, the largest reducing trend of the fast neutron equivalent dose per depth belongs to the 30° wedge, for which the fast neutron equivalent dose shows a 75% decrease. The minimum fast neutron equivalent dose reduction is observed for the blocked field that shows a 31% reduction. These values suggest that, in practice, superficial tissues receive much fast neutron dose than the deeper tissues.

The relative fast neutron equivalent dose was calculated for different modes and depths. For this purpose, the dose of each data point was divided by its corresponding value for the open field. Based on the values in Table 3 and Figure 5, it can be seen that the relative dose of 45° wedge is higher due to the higher absolute fast neutron equivalent dose with the 45° wedge. Furthermore, considering the reduction of fast neutron equivalent dose with increasing the depth, a greater reduction of the relative dose is observed in the open field compared to the others. The relative dose increases with an increase in depth value so that the maximum relative dose belongs to the 45° wedge at a phantom depth of 3 cm, which is 15.82 mSv/mSv. Given the zero value of fast neutron equivalent dose at 4 cm phantom depth in the open field, no relative dose was calculated for this depth, and thus the corresponding values were not mentioned in this table and chart.

Biltekin et al. showed an increase in neutron equivalent dose in the presence of wedge in a 10 cm × 10 cm field for both Varian and Elekta accelerator. Their results are in a good agreement with those obtained in the current study for the 10 cm × 10 cm field of Siemens Primus accelerator.

Hashemi et al. studied the impact of lead block field modifier on Saturn (with 25 MV energy) and Elekta (with 18 MV energy) accelerators. In that study, the difference between the equivalent doses of 18 MV Elekta accelerator in the blocked field compared to the open field was not significant; however, it was significant for the 25 MV Saturn accelerator. On the central axis of the beam, the neutron equivalent dose for the open field with Saturn and Elekta accelerators was 7.9 mSv/Gy and 4.2 mSv/Gy, while in the blocked field it was 9.6 mSv/Gy and 5.4 mSv/Gy, respectively. There are differences between the results of the current study and those by Hashemi et al.
The reason for the differences in assessment of the neutron contamination is the fact that in the current study, a piece of cerrobend block was inserted in the center of a 10 cm × 10 cm field, while Hashemi et al. put a block around a 30 cm × 30 cm field and this field was restricted to a 17.5 cm × 17.5 cm field. Furthermore, the block of their study was made of lead while the block in this study was made of cerrobend. In addition, different accelerator models were used in these two studies and considering the different structures of accelerators from different manufacturers, the amount of neutron contaminations could be different.

Considering the neutron contamination production by a wedge, instead of the use of a wedge, alternative techniques can be used for the treatment planning in radiotherapy with high-energy photon beams. One of these techniques is flattening filter-free (FFF) technique. FFF method has several advantages compared to conventional (without removing flattening filter). The output photon flux will increase by a factor of two or more with removing flattening filter, which will lead to a reduction of treatment time. In addition, removing flattening filter reduces the scattered rays outside the field. Increased photon flux, with a constant number of electrons hitting the target, less neutron contamination per MU would be achieved. However, this advantage is negligible for low-energy X-rays used in radiosurgery and intensity-modulated radiation therapy.[17] Some other studies conducted in the field of FFF method also denote the reduction of neutron contamination with this technique.[18-20]

Alternative techniques can be used in treatments in which a wedge filter is used, for example, in breast cancer treatment. One of the alternative techniques for avoiding the use of wedge is a field-in-field technique. This technique significantly reduces the dose received by healthy organs.[21] Moreover, with the field-in-field technique, the MU is significantly lower. Due to avoiding application of wedge, the neutron contamination resulted from using wedge would be eliminated and the patient would not receive extra neutron dosage.

CONCLUSION

The presence of wedge in the path of primary high-energy photon beam increases the neutron contamination dose to some extent. Furthermore, the 45° wedge contributed more production of neutron contamination than the other wedges. The results of this study also show that superficial tissues receive much fast neutron equivalent doses than the steeper depths. It is also evident that phantom does not play an important role in the production of neutrons. It is suggested that this is considered that more fast neutron equivalent dose is produced in radiotherapy with high-energy photon beam in the presence of a wedge filter, and if it is feasible, alternative methods such as field-in-field technique be used in radiotherapy to spare organs at risk from neutron contamination.

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Conflicts of interest
There are no conflicts of interest.

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