research article

The influence of shielding reinforcement in a vault with limited dimensions on the neutron dose equivalent in vicinity of medical electron linear accelerator

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Background. High energy electron linear accelerators (LINACs) producing photon beams with energies higher than 10 MeV are widely used in radiation therapy. In these beams, fast neutrons are generated, which results in undesired contamination of the therapeutic beam. In this study, measurements and Monte Carlo (MC) simulations were used to obtain neutron spectra and dose equivalents in vicinity of linear accelerator.

Materials and methods. LINAC Siemens Oncor Expression in Osijek University Hospital is placed in vault that was previously used for ^{60}Co machine. Then, the shielding of the vault was enhanced using lead and steel plates. Measurements of neutron dose equivalent around LINAC and the vault were done using CR-39 solid state nuclear track detectors. To compensate energy dependence of detectors, neutron energy spectra was calculated in measuring positions using MC simulations.

Results. The vault is a source of photoneutrons, but a vast majority of neutrons originates from accelerator head. Neutron spectra obtained from MC simulations show significant changes between the measuring positions. Annual neutron dose equivalent per year was estimated to be less than 324 μSv in the measuring points outside of the vault.

Conclusions. Since detectors used in this paper are very dependent on neutron energy, it is extremely important to know the neutron spectra in measuring points. Though, patient dosimetry should include neutrons, estimated annual neutron doses outside the vault were far below exposure limit of ionizing radiation for workers.

Key words: vault reconstruction; ^{60}Co decommission; Monte Carlo simulations; CR-39; neutron dose equivalent

Introduction

High energy electron linear accelerators (LINACs) producing photon beams with energies higher than 10 MeV are widely used in radiation therapy (RT). In these beams, fast neutrons are generated, which results in undesired contamination of the therapeutic beam.[1-6] Neutron contamination in high-energy RT implies an increase of secondary radiation-induced cancer risk.[7] It is also well known that an essential requirement for successful radiation therapy is that the discrepancies between dose distributions calculated at the treatment planning stage and those delivered to the patient are minimized.[8] All modern RT modalities aim to be highly conformal, which is achieved by using

many small fields and requires longer beam-on times. The additional dose from photoneutrons is proportional to the beam-on time[9], causing higher photoneutron doses then expected in modern RT techniques, so it is important to determine the full radiation field correctly in order to evaluate the exposure of patients and medical personnel.

The head of the LINAC is the primary source of photoneutrons in vicinity of linear accelerators since it consists mainly of high-Z materials such as tungsten and steel.[1,10] Also, the vault in which the machine is placed can be the source of photoneutrons.[11] In Croatia, three linear accelerators were placed in vaults that were previously used for ^{60}Co machines.[5] Because of the difference in photon energies between the devices, shielding of the vault had to be enhanced. Also, ^{60}Co and LINAC machines and their auxiliary systems differ in size. ^{60}Co vaults are smaller than the vaults designed for high energy photon LINACs and during the reconstruction of ^{60}Co vaults for LINACs, the main limitation was the space. The vault walls had to be enhanced for photon shielding, but there was no space for adding more concrete to the walls. Therefore, lead and steel panels were added into the walls instead.

LINAC Siemens Oncor Expression 18 MV placed in Osijek University Hospital is one of the LINAC's placed in the reconstructed vaults. Measurements of the neutron flux and dose equivalent that were done in Osijek University Hospital are already published.[2] Measurements were done during all stages of installation, namely before and after lead shielding was added to the walls. It was done using

solid state nuclear track detector (SSNTD) LR115.[5] Back then, the neutron spectra at the positions of measurements were unknown and the results had a large uncertainty due to the energy dependence of detectors. In this paper the measurements were repeated with SSNTD CR-39, but energy dependence was taken into consideration using Monte Carlo (MC) simulations. Neutron dose equivalents for patients and staff were assessed and compared to the results presented before.[2]

Additionally, we investigated the origin of the photoneutrons to show if the steel panels added to the vault walls could be significant sources of photoneutrons. The MC simulations were done for different orientations of the gantry and different points around the accelerator and vault in order to show whether these panels increase total radiation dose to patients and staff.

Materials and methods

The model of dual photon beam (6MV and 18 MV) medical LINAC Siemens ONCOR Expression at Osijek University Hospital was built using MCNP611® beta code.[12] Due to negligible cross sections for neutron productions in a low energy photon beam (6 MV), only the high energy photon beam (18 MV) was modeled. Data used for accelerator's geometry building and materials of which accelerator's head consists were provided by manufacturer. Model of the accelerator head was built as it was described in our previous publications.[1,10,13] For the purpose of this study the accelerator vault was also constructed using MCNP Code (Figure 1). The model of the vault was built using macrobodies, such as boxes and cylinders. The materials for the model were taken from Compendium of Material Composition Data for radiation transport modeling.[14] The majority of vault walls is made of concrete and bricks. As seen in the Figure 1, lead panels were placed in the vault wall (D) and the wall that defines the maze (C). The door at the maze entrance is made of lead and filled with paraffin. All the data used in construction of the vault were obtained from the technical service of Osijek University Hospital.

Each simulation had at least $5 \cdot 10^8$ initial events (electrons incident on target). The criteria for acceptance of the simulations were that R value (relative error) falls below 0.1 and that all 10 statistical checks are met.[12] The energy cut-off for both electrons and photons was 1 keV, and for neutrons it remained 0 MeV. The continuous energy neutron cross sections
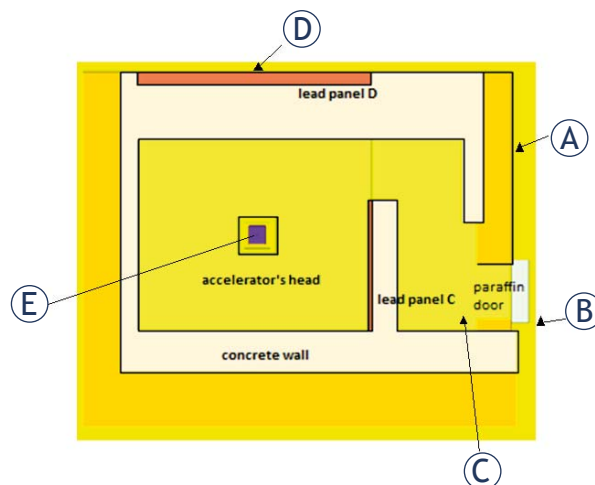

FIGURE 1. Top view (down) of the vault where Siemens Oncor Expression accelerator at Osijek University Hospital is placed with marked positions of measurements. **(A)**, **(B)** and **(D)** are positions outside the vault, **(C)** and E are inside the vault. Position E is in isocenter.

library ENDF/B-VII (Evaluated Nuclear data file B-VII) was used for neutron transport.[15]

In Figure 1, measuring positions (A, B, C and D) used previously are presented.[5] In this research, the measurements were done using SSNTD CR-39 in the same measuring positions as before, with additional measuring position E in isocenter. Therefore, F4 tallies for detecting neutrons in positions A, B, C, D and E were modeled. Tallies in positions A, B, C and D were modeled as boxes with dimensions 20x20x20 cm³ while the tally at the isocenter was modeled as a box with dimensions 1x1x1 cm³. The efficiency of the calculations is very low because only a few percent of all the electrons impinging on target produce photons in the beam, and only a few of those photons with high energies produce photoneutrons. To improve efficiency of MC simulations, *i.e.* particle sampling in the detector region, DXTRAN spheres were setup around all neutron detectors. Neutron spectra were collected in energy bins ranging from $1 \cdot 10^{-9}$ to 18 MeV in logarithmic scale that corresponds to energy bins for the NCRP flux to dose conversion factors.[16] Each detector had all the model cells flagged, in order to determine the place of origin of neutrons. 18 MV photon beam with field size 10x10 cm² was modeled. Simulations were run with accelerator head pointing down (gantry angle 0°) and in the direction of point D (gantry angle 270°).

As seen in the Figure 1, the measurements were performed in five positions: at the operator's console (A), on both sides of the vault door approximately 150 cm above the floor (B –outside the vault, C – inside the vault), on the outside wall of the accelerator vault at the central axis of the beam (D) (5) and isocenter (E). Position E is important for radiation protection of a patient while positions A, B, C and D are important for the staff working in the area around the vault. In our previous measurements with SSNTD LR 115 and boron converter, the dose was calculated without known neutron spectra for the aforementioned positions.[5] In this research, spectra for measuring positions are obtained and taken into account when calculating neutron dose.

The neutron detector consisted of CR-39 solid state nuclear track detector with dimensions 2x3 cm² and boron foil BN-1 (ALGADE Laboratoire DOSIRAD, France) that is a ¹⁰B converter for reaction (n,α). Detectors that contain a ¹⁰B converter are very sensitive to low energy neutrons and less sensitive to fast neutrons.

After the irradiation, CR-39 detectors were separated from boron foils and etched in 30% KOH aqueous solution at 70°C for 6 hours. After etching, detectors were rinsed in distilled water and dried. The detectors were scanned with built-in microscope camera (Zeiss Axiovert 200) using 10x16 magnification. 100 images were taken on average for each film. The number of images depended on the number of tracks registered on the film. In order to get a less than 10% error, the measured area had to be large enough, so that the number of counted tracks is over 100 (N>100).[17]

Tracks were counted using ImageJ/Fiji 1.46 software. First, the tracks were counted manually, *i.e.* track by track. Manual track counting was used as a reference. Tracks were counted so that each track in the image was marked. Marked tracks were added to a tally sheet. Manual counting is time consuming and impractical, especially if there are many images to process. Therefore, counting was automated. Images were converted to grayscale and a grayscale threshold was applied along with other criteria (track size, shape). Tracks in processed images were counted automatically by the software. Track density is a quantity obtained by division of counted tracks and total area of film used for counting.

As in previous measurements CR-39 detectors were placed in positions A, B, C, D and E approximately 150 cm above the floor as in.[5] Measurements for gantry angles 0° and 270° with collimator opening 10cm x 10cm were done for all 5 measuring points.

Since track densities in measuring positions A, B and D are comparable to background measurements, we investigated the total neutron fluence in these positions and how many neutrons reaching these positions are going to produce alpha particles that will eventually form track in SSNTD CR-39. Total neutron fluencies, number of alpha particles and the spectra for positions A, B, C, D and E, for gantry angles 0° and 270°, are obtained from MCNP simulations. The spectra for 0° and 270° are convoluted with cross section of neutron on boron for reaction ¹⁰B (n, α) ⁷Li. Cross section data is taken from ENDF/B-VII (Evaluated Nuclear Data File B-VII).[15] Therefore, the probability of alpha particles production per 1 atom of boron is obtained. The number of tracks on CR-39 is proportional to the number of alpha particles originating from boron foil. The quantity used in experimental part is track density in units track/mm² (mm² is approximately the size of the field of view that was used for detector scanning on microscope). In order to compare experimental data with simulation, the number of alpha particles per mm² of boron has to be calculated and normalized to 2500 MU. Using the data obtained from the manufacturer, the num-
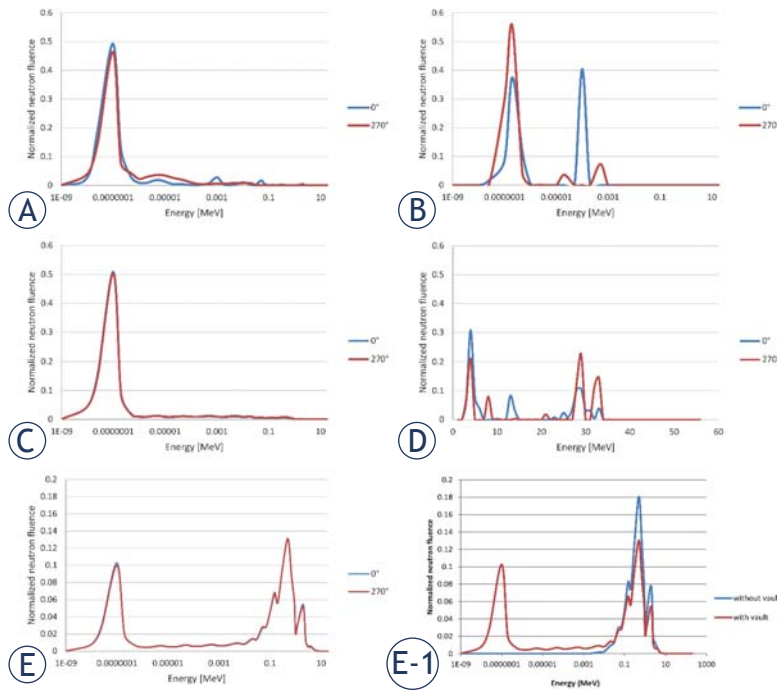
FIGURE 2. Neutron spectra in measuring positions **(A)**, **(B)**, **(C)**, **(D)** and **(E)** for photon field size 10 x 10 cm² and gantry angles 0˚ and 270˚. **(E - 1)** is normalized neutron spectrum in measuring position E for simulations with and without vault.

ber of alpha particles produced in (n,α) reaction on 1 mm² of boron foil was calculated.

Statistical analysis

Relative error of MC simulations is below 10% which is in agreement with statistical checks performed by code itself.[12] All measurements using SSNTD were repeated at least 6 times and relative error did not exceed 8.7%. Relative error in experimental measurements was estimated the maximum deviation from mean.

Results

Calculated normalized neutron fluence spectra for 10x10 cm² field and gantry angles 0º and 270º in

TABLE 1. Total MC calculated neutron fluence in measuring positions A, B, C, D and E for gantry angles 0° and 270°. Neutron fluence is in number of neutrons per cm² per electron impinging on target. Results are normalized to source particle

	Measuring position				
Gantry angle	A	B	C	D	E
0˚	$5.6 \cdot 10^{-13}$	$5.3 \cdot 10^{-14}$	$3.6 \cdot 10^{-10}$	$8.4 \cdot 10^{-24}$	$1.5 \cdot 10^{-8}$
270˚	$6.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-14}$	$4.2 \cdot 10^{-10}$	$1.6 \cdot 10^{-22}$	$1.5 \cdot 10^{-8}$

measuring points A,B,C, D and E are presented in Figure 2 as well as neutron spectrum in isocenter (measuring position E) calculated in simulations with and without vault (Figure 2, E–1).

Total MC calculated neutron fluence per electron impinging on target in measuring positions A, B, C, D and E for gantry angles 0° and 270° is presented in Table 1.

Normalized neutron fluence obtained from MC calculations according to the place of origin is presented in Figure 3. Data is given for all measuring positions and gantry angles 0˚ and 270˚.

Track density caused by background irradiation was 0.47 tracks per mm² with its standard deviation 0.09 tracks per mm². Track density caused by background radiation is subtracted from measured track density. In measuring positions A, B and D measured track density is slightly larger than background. Mean value of detector sensitivities for all measuring position is 0.0002.

Neutron dose equivalents for all measuring positions for gantry angles 0° and 270° together with already published data[2] are presented in Table 2.

Discussion

Neutron spectra obtained from MC simulations show significant changes between the measuring positions (Figure 2). There are also changes in spectra (Figure 2) when gantry angle changes from 0° to 270°. Since detectors used in this paper are very dependent on neutron energy, it is extremely important to know the neutron energy in measuring points. Simulations with and without LINAC vault have shown that surrounding structures also influence the neutron fluence and energy spectrum (Figure 2, E-1). Therefore, it is important to simulate not only the accelerator, but all surrounding structures as well.

Furthermore, neutron spectrum with vault has a significant neutron component in lower energy part of spectrum, around 0.1 eV. Simulations that include the vault have 38% larger neutron fluence than simulations without vault. The reason for that is because the vault serves as a box that does not allow neutrons to escape so they are bouncing back and forth in the vault. Therefore, more neutrons are detected on the tally in isocenter (E). When simulation doesn't include the vault, neutrons are dispersed and it is easy for them to escape. Furthermore, the vault itself is a source of photoneutrons with small energies, but only 1% of all neutrons detected in isocenter originate from

the vault walls (Figure 3, position E). Therefore, the small energy peak mainly comes from the wall attenuation of neutrons originating from accelerator head. It means that a part of the neutron fluence will move from high to low energy part of the spectrum which can be observed in Figure 2, E-1.

According to Table 1, the change of the gantry angle did not have significant influence on total neutron fluence in measuring positions A, B, C and E, but in position D total neutron fluence is 20 times larger for gantry angle 270° than for angle 0°. This was an expected result since the photon beam is directly pointed to the position D when gantry is rotated to 270°. Position D is on the outer side of the wall which contains a lead panel used for high energy photon shielding purposes. At the same time, the lead panel has become a source of photoneutrons (Figure 3).

According to MC simulations in measuring positions C and E there is a great number of alpha particles that can produce track in detector and consequently in these positions, track densities are significantly larger than track density caused by background radiation. However, in positions A, B and D (especially D) number of alpha particles is 1 or several orders of magnitude smaller. Mean value of detector sensitivities for all measuring position is 0.0002, *i.e.* every 5000th neutron reaching detector will make track in the detector.

According to Table 2 our previous measurements[5] overestimated neutron dose equivalent, especially for measuring position D. The underlying reason for overestimation was the unknown neutron spectra in measuring positions. Measuring position E (isocenter) was added to this research, since the neutron dose to patients was one of the interests of this study. Neutron dose equivalent in isocenter is 3.3 mSv per Gy photon dose in isocenter. If we take a radiotherapy treatment of prostate for example, with prescribed dose of 74 Gy and all rectangular fields 10x10 cm^2 4 field box technique, 250 MU daily, then the equivalent neutron dose is 0.3 Sv. The neutron dose is comparable to
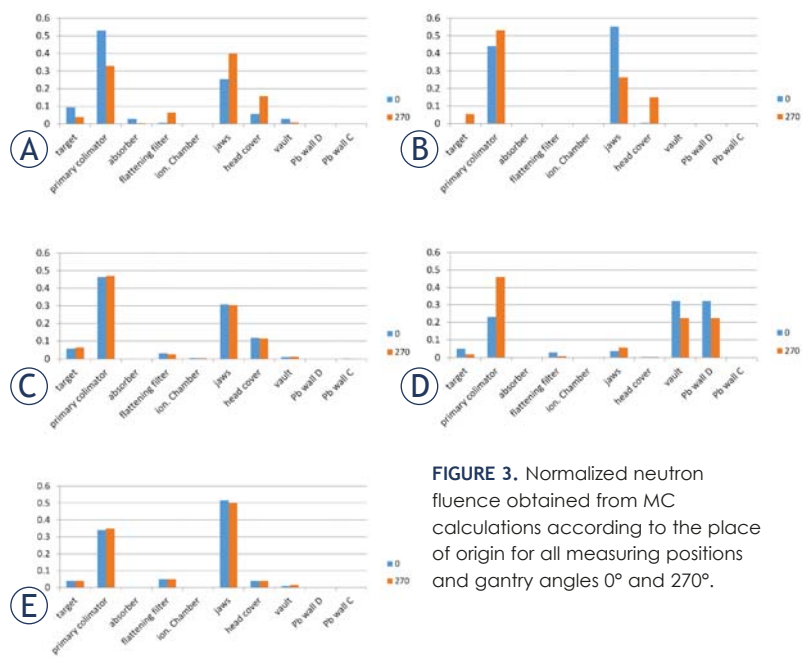

FIGURE 3. Normalized neutron fluence obtained from MC calculations according to the place of origin for all measuring positions and gantry angles 0° and 270°.

the published results.[18] Measurements with neutron dosimeters that consist of SSNTD CR-39 and boron foil BN-1 showed that neutron dose rate in isocenter is large enough that these detectors can be used in in vivo patient dosimetry. Neutron dose to the patient can be calculated from track density and calibration coefficients listed in Table 3.

Outside the vault, in positions A, B and D, it is difficult to measure the neutron dose because the track density on detectors is of the same order of magnitude as track density caused by the background radiation. Therefore, application of neutron dosimeters described in this study in personal dosimetry is questionable. According to the MC simulations, mean neutron dose per year in is 324 µSv, 83 µSv and $2.7 \cdot 10^{-5}$ µSv in positions A, B and D respectively. Calculated neutron doses are far below exposure limit of ionizing radiation for workers which is 20 mSv per year.[19] Therefore, neutron personal dosimetry is not necessary. In our previ-

TABLE 2. Neutron dose equivalents in µSv per Gy photon dose in isocenter for all measuring positions and gantry angles 0° and 270°

		Gantry 0°					Gantry 270°				
		A (µSv/Gy)	B (µSv/Gy)	C (µSv/Gy)	D (µSv/Gy)	E (µSv/Gy)	A (µSv/Gy)	B (µSv/Gy)	C (µSv/Gy)	D (µSv/Gy)	E (µSv/Gy)
Poje et al.[5]	LR 115	0.04	0.08	10	0.04		0.1	0.17	20	0.13	
	Active detector	0.052	0.1	14.3	0.052						
Our results	CR-39	0.008 (0.0006)	0.0006 (0.00004)	8.2 (0.6)	$1.3 \cdot 10^{-12}$ ($7 \cdot 10^{-14}$)	3297 (264)	0.01 (0.008)	0.004 (0.0002)	10.3 (0.5)	$4.21 \cdot 10^{-11}$ ($2 \cdot 10^{-12}$)	3333 (202)

Data from Table 2 are obtained by using calibration coefficients for neutron detector CR-39. In Table 3 calibration coefficients for measuring positions C and E are presented.

TABLE 3. Calibration coefficients for neutron detector CR-39 for measuring positions C and E for gantry angles 0° and 270°

Position	G 0°	G 270°
	µSv/(track/mm²)	µSv/(track/mm²)
C	6,52	11,20
E	151,61	194,97

ously published data[5], estimated dose for workers was 2 mSv per year which is higher than the doses estimated in this study.

Conclusions

Problem of placing high energy linear accelerators in small vaults that are not originally built for linear accelerators is still very present in Southern European countries. Since the space is limited, photon shielding problems are often solved by inserting lead or iron plates in vault walls. High Z elements are new sources of photoneutrons which complicate assessment of neutron spectra and dose in vicinity of linear accelerators. In this study, MC simulations of linear accelerator Siemens Oncor Expression in Osijek University Hospital were done and neutron spectra and dose equivalents in vicinity of linear accelerator were obtained. It is important to include the vault in MC model when assessing neutron dose to patients, otherwise the dose can be overestimated. Simulations showed that lead panels inserted as photon shielding in vault walls are the source of photoneutrons and they contribute to patient and staff dose. However, neutron dose to staff working in vicinity of accelerator vaults is small and there is no need for personal neutron dosimetry. In experimental part of this study, SSNTD CR-39 was used to measure neutron doses in positions inside and outside the vault. Neutron dose rate outside the vault was of the same order of magnitude as the background radiation and their use in personal dosimetry is questionable. In isocenter, neutron detectors are calibrated against spectra obtained from MC simulations and can be used in *in vivo* dosimetry to estimate neutron dose to patients.

Acknowledgments

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