Effects of tertiary MLC configuration on secondary neutron spectra from 18 MV x-ray beams for the Varian 21EX linear accelerator

Rebecca M. Howell^{a)} and Stephen F. Kry

Department of Radiation Physics, The University of Texas M. D. Anderson Cancer Center, 1515 Holcombe Boulevard, Houston, Texas 77030

Eric Burgett

Department of Nuclear and Radiological Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332

David Followill

Department of Radiation Physics, The University of Texas M. D. Anderson Cancer Center, 1515 Holcombe Boulevard, Houston, Texas 77030

Nolan E. Hertel

Department of Nuclear and Radiological Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332

(Received 24 March 2008; revised 19 April 2009; accepted for publication 31 May 2009; published 12 August 2009)

The effect of the jaw configuration and the presence and configuration of the tertiary multileaf collimator (MLC) on the secondary neutron spectra for an 18 MV Varian 21EX linear accelerator (linac) is investigated in detail. The authors report the measured spectra for four collimator (jaw-and-MLC) configurations. These configurations represent the extreme settings of the jaws and MLC and should therefore describe the range of possible fluence and spectra that may be encountered during use of this linac. In addition to measurements, a Monte Carlo model was used to simulate the four collimator configurations and calculate the energy spectra and fluence at the same location as it was measured. The Monte Carlo model was also used to calculate the sources of neutron production in the linac head for each collimator configuration. They found that photoneutron production in the linac treatment head is dominated by the order in which the primary photon beam intercepts the high-Z material. The primary collimator, which has the highest position in the linac head (in a fixed location), is the largest source of secondary neutrons. Thereafter, the collimator configuration plays a role in where the neutrons originate. For instance, if the jaws are closed, they intercept the beam and contribute substantially to the secondary neutron production. Conversely, if the jaws are open, the MLC plays a larger role in neutron production (assuming, of course, that it intercepts the beam). They found that different collimator configurations make up to a factor of 2 difference in the ambient dose equivalent. © 2009 American Association of Physicists in Medicine. [DOI: [10.1118/1.3159301](https://doi.org/10.1118/1.3159301)]

Key words: secondary neutrons, MLC, spectrum, Varian, tertiary collimation

I. INTRODUCTION

Photons with energies $> \sim 7$ MeV can generate neutrons through interactions with structures within the linear accelerator (linac), treatment room, and patient.¹ Most secondary neutrons are generated in the high-Z components of the linac head, e.g., the target, primary collimator, secondary collimator, and multileaf collimator (MLC). The target and primary collimator have a fixed location in the linac head, whereas the secondary collimator and the MLC are movable so they can be positioned inside or outside the x-ray field to block portions of it. The secondary collimator consists of two sets of movable jaws commonly referred to as the “lower” (X) and “upper” (Y) jaws. The location of the MLC within the linac head depends on the manufacturer. For instance, the MLC may replace the upper jaws (as in the Elekta linac) or the lower jaws (as in the Siemens linac), or it may be added as a tertiary level of collimation without changes in the upper and lower jaws (as in the Varian linac).²

In a recent study,³ we compared the secondary neutron spectra generated by the three most widely used commercially available medical linacs employing MLC; the Elekta Precise, Siemens ONCOR, and Varian Clinac 21EX.³ The measurements were made with the collimator configurations set up such that the MLC and jaw positions of the linacs were as similar as possible (with the jaws and MLC closed). However, because the Varian MLC is added without replacing a set of jaws, there are more possible collimator configurations for the Varian linac than the other two linacs. Thus, in our present study, we investigated the effects of the Varian MLC’s tertiary configuration on secondary neutron spectra.

II. MATERIALS AND METHODS

II.A. Measurements

All measurements were conducted on a Varian Clinac 21EX linac (Varian Medical Systems, Palo Alto, CA),

TABLE I. Collimator configurations (i.e., position of jaws and MLC) for the neutron spectrum measurements in this study.

	Configurations			
	1	2	3	4
Jaws	Closed	Open	Closed	Open
MLC	Closed	Closed	Removed	Removed

equipped with a 120-leaf Millennium MLC and operated at 18 MV. The neutron energy spectra were measured in air for four collimator configurations (summarized in Table I). In all configurations, the term “jaws” refers to both upper and lower jaws. In configuration 1, the jaws were completely closed (field size= $0.4\times0.4\text{ cm}^2$) and the MLC were closed. Data for configuration 1 were measured as part of a previous study.³ In configuration 2, the jaws were completely open (field size= $40\times40\text{ cm}^2$) and the MLC was closed. In configurations 3 and 4, the MLC was physically removed from the linac and measurements were carried out with the jaws closed (configuration 3) and the jaws open (configuration 4). These configurations represent the extreme settings of the jaws and MLC and should therefore describe the range of possible fluence and spectra that may be encountered while operating a Varian 21EX. For each configuration, the measurement location was in the patient plane (100 cm from the target) and 40 cm from the isocenter (away from the gantry).

The neutron energy spectra were determined using the ¹⁹⁷Au-based Bonner sphere technique described by Howell and co-authors.^{3,4} The measured neutron spectra were used to calculate three parameters of interest: The average energy, the total neutron fluence, and the ambient dose equivalent ($H^*(10)$). The $H^*(10)$ was calculated by applying the International Commission on Radiation Protection and Measurements (ICRP) quality-conversion coefficients to the solution spectrum. Ambient dose equivalents are reported using both ICRP-21 and ICRP-74 conversion coefficients.⁵⁻⁷

II.B. Monte Carlo calculations

In addition to conducting foil activation measurements of the neutron spectra, we performed Monte Carlo calculations using a previously developed Monte Carlo model [in MCNPX (v.2.5) code⁸] of a Varian 2100 linac operated at 18 MV, as described by Kry, *et al.*⁹ Briefly, this model included the beamline components, as well as the structural and shielding components of the linac head, gantry, treatment couch, and treatment vault. Thus, it simulated both neutron production and scattering throughout the gantry and treatment vault. A schematic of the Monte Carlo model showing neutron tally location at a source-to-axis distance of 100 cm and at a point 40 cm away from the gantry isocenter (in the inferior direction along the treatment couch) is provided in Fig. 1.

We used this Monte Carlo model to simulate the four collimator configurations. For each configuration, the energy spectrum and fluence were calculated at the same location at

FIG. 1. Schematic Monte Carlo model of the Varian 2100 linac showing neutron tally location at a source-to-axis distance of 100 cm and at a point 40 cm away from the gantry isocenter (in the inferior direction along the treatment couch). Measurements were made in the corresponding location.

FIG. 2. Unfolded neutron spectra measured in configurations 1 and 3.

which they were measured to corroborate the measured spectrum and fluence. The fluence and energy spectrum were calculated within a 2-cm-diameter sphere using a track-length estimate of the flux (F4 tally).⁸ Neutron production per source particle was converted to neutrons per monitor unit (MU) based on the number of source particles per MU conversion factor previously determined by Kry *et al.*⁹ for this model. The Monte Carlo model was also used to deter-

mine the sources of neutron production in the linac head for each collimator configuration by calculating the net neutron production within each linac component.

III. RESULTS

III.A. Measurements

The unfolded neutron spectra are shown in Figs. 2–4. Er-

FIG. 3. Neutron spectra measured in configurations 2 and 4.

FIG. 4. Neutron spectra measured in configurations 1 and 2.

ror bars are shown for all unfolded spectra and were determined using the IQU_FC33 program by propagating the uncertainties in the measurement data and in the starting spectrum. All figures are plotted on the same scale for easy comparison. A quantitative summary of the neutron properties for the four collimator configurations is presented in Table II, which shows the measured neutron fluence per MU, the average energy of the measured spectrum, and the ambient dose equivalent ($H^*(10)$) for each configuration.

Figure 2 shows the measured neutron spectra for configurations 1 and 3 (MLC closed and removed, both measured with upper and lower jaws closed). Approximately 6% less neutrons were detected when the MLC were closed (configuration 1) than when it was removed (configuration 3); additionally, there was a slight shift in the energy spectrum to higher energy when the MLC were removed (0.24 MeV for configuration 1 and 0.29 MeV for configuration 3). These data indicate that when the jaws are closed, the presence of the MLC does not substantially affect the neutron fluence, but it does slightly reduce the average neutron energy through inelastic scatter.

Figure 3 shows the measured neutron spectra for configurations 2 and 4 (with the MLC closed and removed, both measured with upper and lower jaws open). Approximately 40% more neutrons were detected when the MLC was closed (configuration 2) than when it was removed (configuration 4). Thus, when the jaws are open, the MLC becomes a notable source of neutrons because it intercepts the primary photon beam. The fluence measured in the patient plane is particularly heightened when neutrons are produced in the MLC because the MLC is closer to the patient plane than other neutron sources such as the jaws.

Figure 4 shows the measured neutron spectra for configurations 1 and 2 (jaws open and closed, both measured with the MLC closed). The most dramatic difference in the measured spectrum was observed between these configurations. For instance, the neutron fluence was substantially higher when the jaws were open ($1.91 \times 10^5 \text{ n cm}^{-2} \text{ MU}^{-1}$ for configuration 2) than when they were closed ($1.18 \times 10^5 \text{ n cm}^{-2} \text{ MU}^{-1}$ for configuration 1). These data again indicate that the MLC becomes a substantial source of neutron production when it is the only collimator being used and

TABLE II. Parameters calculated from the measured spectra for the four collimator configurations. Total uncertainties are shown to the right as percentages.

Jaw and MLC configuration (1–4)	Φ per MU ($10^3 \text{ n cm}^{-2} \text{ MU}^{-1}$)	Average energy (MeV)	ICRP-21 $H^*(10)$ per MU (Sv/MU)	ICRP-74 $H^*(10)$ per MU (Sv/MU)
Jaws closed MLC closed (1)	118 (1.8%)	0.24	1.3×10^{-5} (6%)	1.80×10^{-5} (6%)
Jaws open MLC closed (2)	191 (2.1%)	0.39	3.0×10^{-5} (4%)	4.10×10^{-5} (5%)
Jaws closed MLC removed (3)	126 (1.6%)	0.29	1.7×10^{-5} (6%)	2.30×10^{-5} (6%)
Jaws open MLC removed (4)	136 (2.2%)	0.40	2.3×10^{-5} (4%)	3.10×10^{-5} (5%)

FIG. 5. Measured spectrum and Monte Carlo calculated spectrum for configuration 1.

it therefore intercepts the primary photon beam. There was also an increase in the average energy (from 0.24 to 0.39 MeV) when the jaws were open (configuration 2) as compared to when they were closed (configuration 1) (Table II). In configuration 1, when the photon beam intercepted the jaws, more neutrons were produced high in the linac head. These neutrons, which originated in the jaws, were then degraded in energy through inelastic scatter (which is the dominant neutron interaction for fast neutrons incident on tungsten)¹ in the MLC. In contrast, in configuration 2, more

neutrons originated in the MLC and were thereby unlikely to undergo scatter interactions before being detected.

III.B. Monte Carlo calculations

The Monte Carlo calculated and measured neutron spectra for configurations 1 and 3 are shown in Figs. 5 and 6, respectively. A quantitative comparison of the measured and calculated data for the four collimator configurations is presented in Table III, which shows the measured neutron flu-

FIG. 6. Measured spectrum and Monte Carlo calculated spectrum for configuration 3.

TABLE III. Quantitative comparison of the measured and calculated data for the four collimator configurations is presented in Table III, which shows the measured neutron fluence per MU, the average energy of the measured spectrum, and the ambient dose equivalent ($H^*(10)$) for each configuration.

Jaw and MLC 9 configuration (1–4)	Φ per MU ($\text{n cm}^{-2} \text{ MU}^{-1}$)		Ratio Meas./Calc.	Average energy (MeV)		Difference Meas. – Calc. (MeV)
	Measured	Calculated		Measured	Calculated	
Jaws closed MLC closed (1)	1.18×10^5	1.02×10^5	1.16	0.24	0.21	0.03
Jaws open MLC closed (2)	1.91×10^5	1.35×10^5	1.41	0.39	0.34	0.05
Jaws closed MLC removed (3)	1.26×10^5	1.19×10^5	1.06	0.29	0.24	0.05
Jaws open MLC removed (4)	1.36×10^5	9.36×10^4	1.45	0.40	0.28	0.12

ence per MU, the average energy of the measured spectrum, and the ambient dose equivalent ($H^*(10)$) for each configuration.

The average agreement in fluence for the measured and calculated data for all configurations was 27%. The calculated and measured data agreed very well for collimator configurations 1 and 3: 6% and 16%, respectively. Agreement for was somewhat worse for configurations 2 and 4: 41% and 45%, respectively. However, this type of difference is still reasonable given the inherent difficulties in neutron detection¹⁰ and is consistent with differences reported by Kase *et al.*¹¹ There was also reasonable agreement in the average energy between the measured and the calculated data for all configurations: 0.06 ± 0.03 MeV. Additionally, the average energies for the measured and calculated data followed the same trends, with the highest average energy being reported for configuration 4, followed by configurations 2 and 3, and finally the lowest energy was reported for configuration 1.

In addition to the calculated spectra, the Monte Carlo model was used to calculate the sources of neutron production in the linac head. Table IV shows the absolute neutron production in each linac component with neutron production as a percentage of all components shown in parentheses next to the absolute production values. Because most neutron production occurs in the linac's beamline components, we included only these components in Table IV. The overall contribution from the jaws, especially the upper jaws, was considerably higher than that from the MLC. For all configurations, the primary collimator was found to be the dominant source of neutron production. The upper jaw contributed

substantially to the neutron production when it intercepted the primary photon beam (closed field). Conversely, when the jaws were open, the upper jaws contributed only minimally to the neutron production. The lower jaws were only minimally relevant in the configurations considered here because they never intercepted the primary photon beam. Like the upper jaw, the MLC contributed substantially to the total neutron production when it intercepted the primary photon beam (configuration 2). However, when the jaws were closed above it (configuration 1), the MLC reduced the energy of the neutrons produced higher in the linac head. The results from the Monte Carlo simulations support the trends observed in the measurements, one of which is the substantial amount of neutron production in the MLC when the MLC intercepts the primary photon beam.

IV. DISCUSSION

In the present study, we found that collimator configuration affects the photoneutron production in the linac head. Our data are consistent with those reported recently by Zanini *et al.*¹² In their study, Zanini *et al.* performed Monte Carlo simulations to investigate the photoneutron dose for the Varian Clinac 2300C/D for an 18 MV beam using various collimator configurations. Two of their configurations are similar to ours: (1) The upper and lower jaws were partially closed (field size = $10 \times 10 \text{ cm}^2$) and the MLC was fully open (field size = $40 \times 40 \text{ cm}^2$) and (2) the upper and lower jaws were fully open (field size = $40 \times 40 \text{ cm}^2$) and the MLC was partially closed (field size = $10 \times 10 \text{ cm}^2$). For the former case, Zanini *et al.* reported that 31.0% of the photo-

TABLE IV. Absolute neutron production (10^6 neutrons per source particle) for beamline components in each collimator configuration. Values in parentheses provide neutron production as a percentage of the net neutron production.

	Jaws closed MLC closed	Jaws open MLC closed	Jaws closed MLC removed	Jaws open MLC removed
Target	92.5 (14.8%)	92.7 (15.0%)	92.5 (14.8%)	92.6 (17.9%)
Primary collimator	325.6 (52.2%)	326.1 (52.8%)	325.7 (52.2%)	326.3 (63.0%)
Flattening filter	79.1 (12.7%)	79.3 (12.8%)	79.1 (12.7%)	79.1 (15.3%)
Upper jaw	125.0 (20.0%)	6.6 (1.1%)	125.2 (20.1%)	8.5 (1.6%)
Lower jaw	−5.1 (−0.8%)	6.4 (1.0%)	−4.4 (−0.7%)	9.0 (1.7%)
MLC	−1.9 (−0.3%)	104.6 (16.9%)	0.0 (0.0%)	0.0 (0.0%)

TABLE V. Our current measured photoneutron data and the measured and Monte Carlo calculated data of Kase *et al.* for a Varian linac operated at 18 MV beam energy (Refs. 3 and 11).

	Kase <i>et al.</i> ^a		Configuration 3 ^b	
	Calc.	Meas.	Calc.	Meas.
Neutron fluence	1.40×10^5	8.00×10^4	1.19×10^5	1.26×10^5
Average energy	0.36	0.42	0.24	0.29

^aFrom Kase *et al.*: 18 MV Varian (not equipped with MLC) with jaws in the closed position (Ref. 11).

^bConfiguration 3 from the current study: 18 MV Varian with the jaws closed and MLC removed.

neutron production occurred in the jaws, while only 0.3% occurred in the MLC. Conversely, for the latter case, the investigators reported that photoneutron production decreased in the jaws (to 16.7%) and increased in the MLC (to 14.6%).¹² These findings are similar to ours, both in terms of the trends observed in the data and in the actual levels of neutron (percent) production. With the MLC open or removed, the photon beam has minimal interaction with the MLC, so a higher proportion of the photoneutrons is produced in the jaws. Conversely, when the MLC is closed, it intercepts the primary photon field so it contributes more substantially to the photoneutron production.

Our data are also consistent with the data reported by Kase *et al.*⁹ In their study, Kase *et al.* reported Monte Carlo calculated and measured spectra data for a Varian Clinac (not equipped with a MLC) for an 18 MV beam.¹¹ Table V shows our data measured for configuration 3 side by side with the data reported by Kase *et al.* for a closed jaw configuration (at source-to-detector distances of 100 and 40 cm from the gan-

try isocenter). Our measured and calculated fluence data are within 20% of the measured fluence reported by Kase *et al.*, which is reasonable agreement for neutron measurements.

In this study, we examined the effects of tertiary collimation and collimation configuration on the secondary neutron spectrum for an 18 MV Varian Clinac. This work evolved from a previous evaluation of three commercially available linacs (all equipped with a MLC) that are the most widely used in a clinical setting. All measurements were done using a single technique with the collimator in a single position (all closed).³ We observed there that the tertiary configuration of the Varian MLC added a layer of dissimilarity in the total amount of collimation present in the linac head. Thus, it seemed logical to compare our previously measured spectra for the 18 MV beam energy from the other manufacturers to the spectra measured in the Varian linac after the MLC had been removed. Figure 7 shows the secondary neutron spectra for 18 MV photon beams for the Siemens and Elekta linacs (with the MLC and jaws closed) and the Varian linac (in configurations 1 and 3). When the MLC was removed from the Varian linac, there was approximately the same amount of collimation in all three linac models. Correspondingly, Fig. 7 illustrates that when the tertiary MLC on the Varian linac was removed, the average neutron energy increased slightly and was consistent with the energy of the neutrons produced by for the Siemens and Elekta linacs. The presence of the tertiary Varian MLC clearly lowers the average neutron energy below that of the other linacs. However, this small change in energy is much less important to the dose equivalent than the large differences observed in the total neutron fluence between different accelerators or configurations.

FIG. 7. Measured photoneutron spectra for 18 MV photon beams for the Varian Clinac 21EX, Elekta Precise, and Siemens ONCOR linacs. Secondary neutron spectra for 18 MV photon beams for Siemens and Elekta spectra with the MLC and jaws closed and those for the Varian linac under two different conditions: Jaws closed and MLC closed (configuration 1) and jaws closed and MLC removed (configuration 3).

V. CONCLUSION

Photoneutron production in the linac head is determined by the magnitude of the primary photon beam that intercepts the high-Z material. The primary collimator, which is located the highest in the linac head (in a fixed location), is always the largest source of secondary neutron production because it always intercepts large amounts of the primary photon beam. Thereafter, the configuration of collimators downstream then determines the source of secondary neutron production. If the jaws are closed, they intercept the photon beam and contribute substantially to the secondary neutrons. Conversely, if the jaws are open, the MLC may play a substantial role in neutron production (assuming it intercepts the photon beam).

By adding/removing the MLC and changing the collimator configurations, we observed notable variations in the neutron fluence and ambient dose equivalent (a difference of up to a factor of 2). This difference is the maximum range one may encounter by changing collimator configurations, and the difference in neutron production is likely to be much less for clinical variations in collimator configurations.

ACKNOWLEDGMENTS

This work was supported by a grant from the Georgia Tech–Emory Fund for Innovative Cancer Technologies (GTE-FICT). Salary support for R. M. Howell was provided in part by Grant No. K01CA125204 from the National Cancer Institute.

^{a)}Author to whom correspondence should be addressed. Electronic mail: rhowell@mdanderson.org; Telephone: (713) 563-2493; Fax: (713) 563-2482.

¹National Council on Radiation Protection and Measurements, "Neutron contamination from medical electron accelerators," Report No. 79

(NCRP, Bethesda, MD, 1984).

²AAPM Task Group 50, "Basic applications of multileaf collimators," Report No. 72 (American Association of Physicists in Medicine (AAPM), Madison, WI, 2001).

³R. M. Howell, S. K. Fry, E. Burgett, N.E. Hertel, and D. S. Followill, "Secondary neutron spectra from modern Varian, Siemens, and Elekta linacs with multileaf collimators," *Med. Phys.* **36**, 4027 (2009).

⁴R. M. Howell, N. E. Hertel, Z. Wang, J. Hutchinson, and G. D. Fullerton, "Calculation of effective dose from measurements of secondary neutron spectra and scattered photon dose from dynamic MLC IMRT for 6 MV, 15 MV, and 18 MV beam energies," *Med. Phys.* **33**, 360–368 (2006).

⁵International Commission on Radiation Protection and Measurements, *ICRP Publication 21: Data for Protection Against Ionizing Radiation from External Sources—Supplement to ICRP Publication 15* (Pergamon, Oxford, 1973); *Ann. ICRP* **21**, 1–101 (1973).

⁶International Commission on Radiation Protection and Measurements, "ICRP Publication 74: Conversion coefficients for use in radiological protection against external radiation," *Ann. ICRP* **26**(3–4), 1–205 (1996).

⁷International Commission on Radiation Units and Measurements, "Conversion coefficients for use in radiological protection against external radiation," *ICRU Report No. 57* (1998).

⁸J. S. Hendricks, G. W. McKinney, L. S. Waters, T. L. Roberts, H. W. Egdorf, J. P. Finch, H. R. Trellue, E. J. Pitcher, D. R. Mayo, M. T. Swinhoe, S. J. Tobin, J. W. Durkee, F. X. Gallmeier, J. Lebenheft, and W. B. Hamilton, "MCNPX, Version 2.5.0," Los Alamos National Laboratory Report No. LA-UR-05-2675 (Los Alamos National Laboratory, Los Alamos, NM, 2003).

⁹S. F. Kry, U. Titt, D. Followill, F. Pönisch, O. N. Vassiliev, R. A. White, M. Stovall, and M. Salehpour, "A Monte Carlo model for out-of-field dose calculation from high-energy photon therapy," *Med. Phys.* **34**, 187–190 (2007).

¹⁰D. J. Thomas and A. V. Alvera, "Bonner sphere spectrometers—a critical review," *Nucl. Instrum. Methods Phys. Res. A* **476**, 12–20 (2002).

¹¹K. R. Kase, X. S. Mao, W. R. Nelson, J. C. Liu, J. H. Kleck, and M. Elsalim, "Neutron fluence and energy spectra around the Varian Clinac 2100C/2300C medical accelerator," *Health Phys.* **74**, 38–47 (1998).

¹²A. Zanini, E. Durisi, F. Fasolo, C. Ongaro, L. Visca, U. Nastasi, K. W. Burn, G. Scielzo, J. O. Adler, J. R. M. Annand, and G. Rosner, "Monte Carlo simulation of the photoneutron field in linac radiotherapy treatments with different collimation systems," *Phys. Med. Biol.* **49**, 571–582 (2004).