Secondary neutron spectra from modern Varian, Siemens, and Elekta linacs with multileaf collimators

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Neutrons are a by-product of high-energy x-ray radiation therapy (threshold for $[\gamma, n]$ reactions in high-Z material ~ 7 MeV). Neutron production varies depending on photon beam energy as well as on the manufacturer of the accelerator. Neutron production from modern linear accelerators (linacs) has not been extensively compared, particularly in terms of the differences in the strategies that various manufacturers have used to implement multileaf collimators (MLCs) into their linac designs. However, such information is necessary to determine neutron dose equivalents for different linacs and to calculate vault shielding requirements. The purpose of the current study, therefore, was to measure the neutron spectra from the most up-to-date linacs from three manufacturers: Varian 21EX operating at 15, 18, and 20 MV, Siemens ONCOR operating at 15 and 18 MV, and Elekta Precise operating at 15 and 18 MV. Neutron production was measured by means of gold foil activation in Bonner spheres. Based on the measurements, the authors determined neutron spectra and calculated the average energy, total neutron fluence, ambient dose equivalent, and neutron source strength. The shapes of the neutron spectra did not change significantly between accelerators or even as a function of treatment energy. However, the neutron fluence, and therefore the ambient dose equivalent, did vary, increasing with increasing treatment energy. For a given nominal treatment energy, these values were always highest for the Varian linac. The current study thus offers medical physicists extensive information about the neutron production of MLC-equipped linacs currently in operation and provides them information vital for accurate comparison and prediction of neutron dose equivalents and calculation of vault shielding requirements. © 2009 American Association of Physicists in Medicine. [DOI: [10.1118/1.3159300](https://doi.org/10.1118/1.3159300)]

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I. INTRODUCTION

Radiation therapy can be delivered using several commercially available medical linear accelerators (linacs). Despite the nominal similarity of these instruments, different manufacturers employ different approaches in the design of the radiation therapy equipment.¹ One such difference is the accelerating potential of the incident electrons impinging a high-atomic number (Z) target to produce a bremsstrahlung photon beam, e.g., a nominal 18 MV x-ray beam may have a maximum photon energy of 18.75 or 15.25 MeV depending on the linac design the manufacturer has adopted.² In addition to variations in the photon spectra, the composition and design of head shielding components also vary between manufacturers.^{3,4}

Another difference that has recently developed between medical linacs is in beam collimation. Medical accelerators use collimators to block out portions of the radiation beam. All accelerators have a primary collimator, made of a high- Z

absorber that has a fixed location within the accelerator head and cannot be moved. Below the primary collimator is a secondary level of collimation that consists of two sets of movable jaws of high- Z material that can be moved independently to generate different rectangular field sizes (maximum field size is 40×40 cm²); these are commonly referred to as the X and Y (or upper and lower) jaws. Older accelerators only have these two levels of field-shaping devices built into the linac treatment head. However, advances in technology have led to design modifications in the collimating systems of modern accelerators. In particular, recent advances include multileaf collimators (MLCs), which consist of two banks of independently moving tungsten alloy leaves that can be used to generate almost any field shape.⁵ While MLCs are standard in modern medical linacs, different manufacturers have made different modifications to incorporate MLC into their collimation designs; for instance, the three leading manufacturers have adopted the following strategies: Elekta North America (Norcross, GA) has replaced the upper collimating

TABLE I. Irradiation parameters.

Linac model	Energy (MV)	Upper jaw	Lower jaw	MLC	MU per irradiation	Dose rate
Varian 21EX	15	Closed	Closed	Closed	6000	600
	18	Closed	Closed	Closed	5000	600
	20	Closed	Closed	Closed	5000	600
Elekta	15	N/A	Closed	Closed	9500	600
Precise	18	N/A	Closed	Closed	5000	500
Siemens	15	Closed	N/A	Closed	9500	500
ONCOR	18	Closed	N/A	Closed	10000	500

jaws with MLC while retaining the lower jaws; Siemens Medical Solutions USA (Malvern, PA) has replaced the lower jaws with MLC, while retaining the upper jaws; and Varian Medical Systems (Palo Alto, CA) has added a tertiary level of collimation (a MLC) while making no modifications to the upper or lower jaws.⁵

Photons with energies greater than approximately 7 MeV can generate neutrons through interactions with components within the accelerator and structures in the treatment room and patient.³ Most secondary neutrons are generated in the high-Z components of the linac head, e.g., the target, primary collimators, secondary collimators, and MLC.^{3,4} These neutrons then penetrate the linac head shielding, scatter throughout the treatment vault, and may ultimately deposit dose in the patient.

Many studies have been performed to characterize the secondary neutrons from high-energy linacs, but most have investigated only one type of linac and the analytic techniques have varied widely.^{6–12} A comprehensive study by Followill *et al.*⁶ reported total neutron source strengths around many different medical linac models. However, many of the data were for older linacs (most of which were not equipped with MLC) and the authors did not report neutron spectra, which have a direct impact on the dose equivalent to the patient.

The aim of this work therefore was to compare the secondary neutron spectra, fluence, and dose equivalent produced by modern linacs equipped with MLCs from Elekta, Siemens, and Varian. The measurements were conducted with the collimator configurations set up such that the MLC and jaw positions would be as similar as possible between machines, i.e., the jaws and MLC closed. Finally as a natural extension of this work, we used the spectral data to calculate shielding parameters relevant for high-energy treatment vaults for each linac model.

We found relatively small differences in the secondary neutron energy spectra between the three manufacturers' linacs, with the Varian neutron spectra having slightly lower energies than spectra from the other two models. Total neutron fluence and ambient dose equivalents were found to be highest for Varian and lowest for Siemens and Elekta linacs.

II. MATERIALS AND METHODS

II.A. Linacs and facilities

We made measurements using the following linacs: Elekta Precise, Siemens ONCOR, and Varian Clinac 21EX because these are the “state of the art” linacs from each manufacturer. Measurements were made for 15 MV and 18 MV x-ray beam energies for the Elekta and Siemens linacs and for 15, 18, and 20 MV x-ray beam energies for the Varian linac (Siemens and Elekta do not offer 20 MV beams). We determined the hospitals at which to make measurements by reviewing the M. D. Anderson Cancer Center Radiological Physics Center database, which has information regarding equipment and beam energies at facilities throughout the United States and Canada. Measurements were made at eight different locations in the United States and Canada: Atlanta VA Hospital (Decatur, Georgia), the University of Texas at M. D. Anderson Cancer Center (Houston, Texas), Radiotherapy Clinics of Georgia (Atlanta, Georgia), the Moffitt Clinic at Tampa General (Tampa, Florida), University of Iowa Hospitals and Clinics (Iowa City, Iowa), Shands Jacksonville Medical Center (Jacksonville Florida), Moses Cone Regional Cancer Center (Greensboro, North Carolina), and the Tom Baker Cancer Center (Calgary, Alberta).

II.B. Irradiation parameters

The irradiation parameters for each measurement are shown in Table I. The measurements were conducted with the collimator configurations set up such that the MLC and jaw positions would be as similar as possible between machines. Thus, measurements on the Elekta Precise were performed with the MLC and lower jaws closed; measurements on the Siemens ONCOR were performed with the upper jaws and MLC closed; and measurements on the Varian 21EX were performed with the upper jaws, lower jaws, and MLC closed.

The maximum dose rate setting [monitor units (mu)/min] was used for all irradiations. The total number of monitor units (MU) set for each measurement was between 5000 and 10 000 to ensure that an adequate number of neutrons would be produced to achieve good counting statistics. Spectral flu-

FIG. 1. Schematic diagram of the measurement location: All measurements were performed in the patient plane 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).

ence results were normalized per MU to allow comparisons between linac make and models. All linacs were calibrated by physicists working at each facility according to the current AAPM protocol, TG-51, to deliver 1 cGy/MU at the depth of the maximum dose for a 10×10 cm² field.¹³

II.C. Measurement location

All measurements were performed in the patient plane 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). A simple diagram of the measurement location is provided in Fig. 1. This location was chosen based on previous work by Kry *et al.*, which demonstrated that at this measurement location, neutrons are a major contributor of dose relative to the photon component of dose outside the treatment field, but still inside the patient.¹⁴

II.D. Neutron measurements

Measurements were performed using gold foil activation in Bonner spheres, as detailed by Howell *et al.*¹⁵ Bonner spheres were utilized in the current work because this detection system responds over a very large energy range and has a nearly isotropic response.^{16–18} The system consists of a series of six high-density polyethylene moderating spheres ranging from 2 to 12 in. in diameter surrounding a thermal neutron detector placed at the center of the spheres. In the current study, ¹⁹⁷Au foils were used because activation foils are a passive detector and therefore are appropriate for use inside the treatment vault where an active detector would be affected by pulse pileup and electromagnetic noise. ¹⁹⁷Au primarily has a large thermal neutron cross section that follows a $1/v$ response below 0.7 eV. It also possesses a large resonance capture cross-section peak at about 4.89 eV and

many smaller resolved resonances between 10 eV and 10 keV. This detailed cross-section response was calculated for each Bonner sphere and is described by the response matrix (described in Sec. II.D.2).

After irradiation, we measured the 411 keV γ -ray photopeak for each foil using a high-purity germanium detector. Each foil was counted until a statistical uncertainty of less than 4.5% was achieved. The activity at the end of irradiation was calculated for each foil. Each complete set of measured data included seven measured activities (one for each Bonner sphere and one for the bare detector). These data, however, cannot directly provide a continuous neutron spectrum because the number of detectors is finite and because the foil data represent integral quantities, whereas the spectrum is a differential quantity. Thus, the spectra are determined from the measured data via mathematical deconvolution, i.e., unfolding.

II.E. Neutron spectra unfolding

For a Bonner sphere spectrometer (BSS), the detector response function, $\sigma_j(E)$, and the radiation spectrum is, $\phi(E)$, are given by a degenerate Fredholm integral equation of the first kind,¹⁷

$$R_j = \int \sigma_j(E) \phi(E) dE, \quad j = 1, 2, \dots, M. \quad (1)$$

Methods for solving Eq. (1) cannot be applied when the response function is unknown (as in the case of a BSS). However, $\sigma_j(E)$, can be approximated by a response matrix having discrete values and Eq. (1) becomes¹⁷

$$R_j = \sum_{i=1}^N \sigma_{ij} \phi_i, \quad j = 1, 2, \dots, M, \quad (2)$$

where R_j is the detector count rate of the j th detector in counts per unit time, σ_{ij} is the detector response of the j th detector to neutrons in the i th energy interval, N is the total number of energy groups, and M is the number of detectors. Since N is larger than M , there is no unique solution to this equation. An appropriate neutron spectrum is determined from the measured data via mathematical deconvolution (unfolding), which is the process of selecting a particular solution spectrum from an infinite number of spectra that fit the data.^{17,18} An appropriate solution is defined as a spectrum which fits the detector data within reasonable error limits and has physically acceptable characteristics (non-negative, etc.).¹⁷ There are many different unfolding algorithms including SPUNIT, BON, MAXED, and SAND-II.¹⁷ All of these algorithms require three parameters to calculate a solution spectrum: Measured data, a response matrix for the BSS, and a starting spectrum.^{17,18}

In the current work, the solution spectra were determined using the MXD_FC33 unfolding algorithm which is part of the few channel unfolding programs in the UMG package (version 3.3).¹⁹ The MAXED algorithm requires an *a priori* spectrum, e.g., an initial estimate of the spectrum for unfolding. The *a priori* spectrum is also referred to as a starting spec-

trum. This spectrum should be physically realistic based on some knowledge on the spectrum being measured. The MAXED algorithm also requires a set of response functions. The best solution is achieved when response functions are specific to the detection system used for the measurements.

MXD_FC33 algorithm is based on the FORTRAN code MAXED (*maximum entropy deconvolution*) specifically written for the deconvolution of multisphere neutron spectrometer data. There are several advantages to using this unfolding code over other techniques: (1) It permits inclusion of *a priori* information in a well-defined and mathematically consistent way, (2) the user can input response functions for their specific detector, and (3) the solution spectrum is a non-negative function that can be written in a closed form, permitting sensitivity analysis and uncertainty propagation of the MAXED solution spectrum. A full description of the MAXED code, MXD_FC33 is provided by Reginatto and Goldhagen.²⁰

In the present study, neutron unfolding was carried out in the following way: (1) An *a priori* spectrum was determined using a Bayesian statistics method (described below), (2) this *a priori* spectrum was then input into MAXED as the starting spectrum, (3) the MAXED code then used the response functions and the starting spectrum to select the solution spectrum which best fits the measured data while maximizing the relative entropy between the starting spectrum and the solution spectrum.

II.E.1. Neutron spectra unfolding: *A priori* spectrum

The *a priori* spectra were determined using Bayesian statistics methodology. A Bayesian fit of the measured data was determined using a Bayesian optimization program (written for WINBUGS) to achieve a physically realistic spectrum with a high-energy Maxwellian evaporation peak, an intermediate energy component (with $1/v$ dependence), and a thermal peak; each component was allowed freedom in amplitude, slope, and energy location. Additionally, the evaporation peak and the thermal peak were allowed freedom in centroid location, full width at half maximum values, and skew. The intermediate energy region was allowed to be linearly continuous, vary its high-energy and low-energy end points, its amplitude, and its slope. The Bayesian optimization program then created a list of best fit parameters. Finally, these parameters are input into a FORTRAN code which produces the *a priori* spectrum for use in MAXED unfolding.

II.E.2. Neutron spectra unfolding: Response matrix

The sensitivity of each Bonner sphere with a thermal neutron detector to different incident neutron energies is referred to as a response matrix. MXD_FC33^{19–21} allows the input of user created (detector specific) response matrices. In this work we used a response matrix specifically calculated for the ¹⁹⁷Au-based Bonner sphere system. The response matrix was calculated by Wang *et al.*²² using MCNP5. The calculations are briefly described here and we refer the reader to the original article for a further description.²² An (n, γ) reaction

tally was used to calculate the ¹⁹⁸Au production rate in the detector for different incident neutron energies. Responses were generated for 58 neutron energy groups ranging from 10^{-10} to 15 MeV from a single MCNP run using the SCX tally option (the tally score is binned according to the energy group of the source neutron that resulted in the score). Models were run using 1×10^9 particles, and source energy biasing (SB card) was performed to reduce statistical uncertainties. The responses were calculated in units of $\text{Bq g}^{-1}/\text{n cm}^{-2}$ and are reproduced in Fig. 2. The computed responses were verified by measurements performed with a ²⁵²Cf neutron source of a known emission rate.²²

II.F. Calculated neutron parameters

The measured neutron spectra were used to calculate four parameters of interest; the average energy, total neutron fluence, the ambient dose equivalent ($H^*(10)$), and the neutron source strength (Q). Additionally, the direct, scattered, and thermal components of the fluence were determined.

The ambient dose equivalent was calculated for each solution spectrum using the IQU_FC33 program in the UMG package which applies the International Commission on Radiation Protection and Measurements (ICRP) quality-conversion coefficients to the solution spectrum.^{25,26} Ambient dose equivalents are reported using both ICRP-21 and ICRP-74 conversion coefficients to allow comparison with current and earlier published data.^{25–27}

The neutron source strength was calculated based on the measured fluence (Φ) according to the following equation:²⁴

$$\Phi_{\text{tot}} = \frac{\beta Q_n}{4\pi d^2} + \frac{5.4\beta Q_n}{2\pi S_r} + \frac{1.3Q_n}{2\pi S_r}, \quad (3)$$

solved for Q

$$Q_n = \frac{\Phi_{\text{tot}}}{\frac{\beta}{4\pi d^2} + \frac{5.4\beta}{2\pi S_r} + \frac{1.3}{2\pi S_r}}, \quad (4)$$

where S_r is the total surface area of the treatment room (in m^2), d is the distance from the neutron source to the measurement location (in meters), and β is the transmission factor for neutrons that penetrate the head shielding (1.0 for lead and 0.85 for tungsten).²⁴ In the current work, we used a β value of 0.93 for all Q calculations since all linacs in the study use both lead and tungsten shielding. A representative room surface area of 210 m^2 was selected to for use in the Q calculations. This value was taken as the average vault size from the work of Followill *et al.*,⁶ and their demonstration that Q values are largely insensitive to the room surface area (thus allowing for the use of a standard vault size).

The total fluence is the sum of the direct (Φ_{dir}), scattered (Φ_{sc}), and thermal (Φ_{th}) neutron fluence components.²⁴ The direct, scattered, and thermal components were calculated for each of the measured spectra using the total fluence for each solution spectrum and Eqs. (5)–(7).

$$\Phi_{\text{dir}} = \frac{\beta Q_n}{4\pi d^2}, \quad (5)$$

FIG. 2. Response matrix (calculated using MCNP5) for the ^{197}Au -based Bonner sphere system. Responses are shown as a function of energy in units of $\text{Bq g}^{-1}/\text{n cm}^{-2}$ for the 2, 3, 5, 8, 10, and 12 in. Bonner spheres.

$$\Phi_{\text{sc}} = \frac{5.4\beta Q_n}{2\pi S_r}, \quad (6)$$

$$\Phi_{\text{th}} = \frac{1.3Q_n}{2\pi S_r}. \quad (7)$$

II.G. Uncertainty analysis

The UMG package has a program which is specifically designed for uncertainty analysis of the unfolded spectrum, IQU_FC33. This program uses the fluence output file to propagate the uncertainty in the measurement data and the default spectrum. Reginatto *et al.* provided a full description of error propagation in the IQU_FC33 program in Ref. 21.

The consistency of the unfolded spectrum can be checked with respect to the measured data by comparing the measured counts $M_{\text{meas}}(d)$ of sphere d with the calculated counts for sphere d , $dM_{\text{calc}}(d)$ which result from folding the response function of sphere d with the unfolded spectrum. This consistency check is carried out by the MXD_FC33 algorithm during the unfolding process.^{19–21}

III. RESULTS

An example of a starting spectrum (generated using the method described above in Sec. II E 1) is shown in Fig. 3 which compares the starting spectrum and the final solution spectrum for the Varian 15 MV linac. In this figure, structures in the starting spectrum which were consistent with the measured data were preserved (by the unfolding) in the final solution spectrum, while data in the starting spectrum which were non consistent with the measured data were modified in the final solution spectrum.

An example of the consistency calculations that are carried out for all MAXED final spectra is provided in Fig. 4 for the Varian 15 MV linac; the ratio of $M_{\text{meas}}(d)$ and $M_{\text{calc}}(d)$ is plotted for each Bonner sphere; error bars are calculated by the MXD_FC33 program and provide an estimate of the statistical uncertainties in the measured data and uncertainty from the starting spectrum added in quadrature.¹⁹ Examination of Fig. 4 suggests that the final spectrum (shown in Fig. 3) is consistent with the measured data and the response of the detectors, e.g., the ratio of $M_{\text{meas}}(d)$ and $M_{\text{calc}}(d)$ for all spheres is within $\pm 10\%$ of a 1.0 ratio.

The measured neutron spectra (for all linacs and energies included in this investigation) per MU are illustrated in Figs. 5–9. Error bars are shown for all unfolded spectra and were determined using the IQU_FC33 program by propagating the uncertainties in the measurement data and from the starting spectrum. Figure 5 shows spectra from 15 MV x-ray beams produced by all three manufacturers. Although subtle differences can be discerned in the spectra, they are similar overall, with fast neutron peaks centered at around a 0.23 MeV and similar average energies (mean average energy = $0.23 \text{ MeV} \pm 0.04$), as shown in Table II. Each spectrum also shows a low-energy tail that arose from neutrons scattered throughout the treatment vault. The obvious distinction between the three spectra is the total neutron fluence per MU (Table II). The 15 MV Elekta Precise beam resulted in the lowest secondary neutron fluence: 2.2 times lower than that for the Siemens ONCOR and 5.2 times lower than that for the Varian 21EX. Because the energy spectra are similar, the differences in fluence between the three spectra correspond directly to differences in the ambient dose equivalent (Table II).

Figure 6 shows spectra from the three linac models pro-

FIG. 3. Comparison of the starting spectrum and the final solution spectrum for the 15 MV Varian linac.

ducing 18 MV x-ray beams. Again, the energy spectra are qualitatively similar, while large differences are evident in the total neutron fluence per MU. As with the 15 MV beams, the peak neutron energy from the 18 MV beams was approximately 0.23 MeV and the spectra had similar average energies (mean average energy = $0.24 \text{ MeV} \pm 0.03$, see Table II). The secondary neutron fluence (and thus ambient dose equivalent) was highest for the 18 MV Varian 21EX beam,

which was 2.9 times greater than that of the Elekta linac and 3.4 times greater than that of the Siemens linac.

Figure 7 shows the 15, 18, and 20 MV spectra for the Varian 21EX linac. Figures 8 and 9 show the neutron spectra from the 15 and 18 MV Elekta Precise and Siemens ONCOR, respectively. The spectra are qualitatively similar, with the obvious distinction that fluence per MU increased with energy for each linac. For the Varian linac, there was a 1.7-

FIG. 4. An example of the consistency results that are carried out for all MAXED solution spectra for the Varian 15 MV linac; ratios of the measured counts $M_{\text{meas}}(d)$ and the calculated counts $M_{\text{calc}}(d)$ for Bonner sphere, d .

FIG. 5. Measured photoneutron spectra for Varian 21EX, Elekta Precise, and Siemens ONCOR linacs with a 15 MV nominal photon beam energy and jaws and MLC closed.

fold increase in fluence as the energy increased from 15 to 18 MV and a 1.4-fold increase as energy went from 18 to 20 MV (Table II). For the Elekta linac, the 18 MV beam had 3.0 times more neutrons than the 15 MV beam (Table II). However, for the Siemens ONCOR, the total fluence increased by only 18% as the energy went from 15 to 18 MV (Table II).

The calculated Q values for each linac make and energy are provided in Table III. These values can be used to estimate the required vault door materials required for shielding against neutrons. The reader is referred to NCRP-151 for a full description of the application of Q values.²⁴ The contributions of different components of the neutron fluence to the total number of neutrons can also be derived from Eqs.

FIG. 6. Measured photoneutron spectra for Varian 21EX, Elekta Precise, and Siemens ONCOR linacs with an 18 MV nominal photon beam energy and jaws and MLC closed.

FIG. 7. Measured photoneutron spectra for Varian 21EX linacs with nominal photon beam energies of 15, 18, and 20 MV and the upper and lower jaws and MLC closed.

(5)–(7) using the measured fluence values and the derived Q values. Our measurements indicated that 68% of the neutrons were direct for all accelerators, while 26% were scattered, and 6% were thermal. Because direct neutrons are not only the most numerous but also have the highest energy, kerma factors and quality factors,^{23,27,28} these neutrons are the dominant component of the dose equivalent for all accelera-

tors. Thermal neutrons are associated with small kerma factors and therefore contribute a minimal amount to the dose equivalent.^{23,27,28}

IV. DISCUSSION

In the present study, we found qualitative similarity (no major energy shifts were observed) in the secondary neutron

FIG. 8. Measured photoneutron spectra for Elekta Precise linacs with nominal photon beam energies of 15 and 18 MV and the upper jaws and MLC closed.

FIG. 9. Measured photoneutron spectra for Siemens ONCOR linacs with nominal photon beam energies of 15 and 18 MV and the lower jaws and MLC closed.

spectra generated by the three most popular modern linacs equipped with a MLC. In Figs. 5 and 6 the Varian spectra appear to have slightly higher energies compared to the Siemens and Elekta spectra. This small difference in energy may perhaps be attributed to the additional high-Z material in the Varian linac head due to the tertiary configuration of the Varian MLC which adds an additional level of collimation to the linac head compared to the Siemens and Elekta models. The Varian MLC (when in the closed position) may have a slight softening effect on the neutrons originating higher in the linac head via inelastic scatter. However, this energy difference is small and has much less impact on the dose equivalent than the differences in the total fluence. For a given manufacturer of linac, different nominal photon ener-

gies had almost no effect on the average neutron energy and variation within manufacturers was within 0.1 MeV.

Large differences were observed in the total fluence for the different linacs studied in this investigation, which varied according to the manufacturer and photon energy. For both 15 and 18 MV beam energies, the Varian 21EX linacs had the highest neutron fluences. For the 15 MV beam energy, the Elekta Precise linacs had the lowest fluence, while for the 18 MV beam energy, the Siemens ONCOR had the lowest fluence.

The total number of secondary neutrons is highly dependent on the photon spectra from which they originate. Beams with more photons with energies above the (γ, n) threshold will result in more (γ, n) reactions and ultimately a higher

TABLE II. Parameters calculated from photoneutron spectra for the Varian 21EX, Elekta Precise, and Siemens ONCOR linacs for all photon beam energies investigated in this study. Total uncertainties are shown on the right as percentages.

Linac	Nominal x-ray energy (MV)	Φ per MU ($10^3 \text{ n cm}^{-2} \text{ MU}^{-1}$)	Average energy (MeV)	$H^*(10)$ per MU (Sv/MU) ICRP-21	$H^*(10)$ per MU (Sv/MU) ICRP-74
Varian 21EX	15	69.7 (1.9%)	0.23	7.4×10^{-6} (6%)	1.1×10^{-6} (6%)
	18	118.0 (1.8%)	0.24	1.3×10^{-5} (6%)	1.9×10^{-5} (6%)
	20	169.0 (2.7%)	0.24	1.9×10^{-5} (6%)	2.6×10^{-5} (6%)
Elekta Precise	15	13.5 (1.4%)	0.27	1.7×10^{-6} (5%)	2.5×10^{-6} (5%)
	18	40.2 (1.1%)	0.26	5.5×10^{-6} (5%)	8.4×10^{-6} (5%)
Siemens ONCOR	15	29.5 (1.4%)	0.20	3.1×10^{-6} (5%)	4.8×10^{-6} (5%)
	18	34.8 (1.3%)	0.21	3.8×10^{-6} (6%)	5.2×10^{-6} (7%)

TABLE III. Neutron source strength (Q) calculated for the linacs and photon beam energies investigated in this study.

Linac model	Energy (MeV)	Q (n/Gy)
Varian 21EX	15	1.02×10^{12}
	18	1.72×10^{12}
	20	2.46×10^{12}
Elekta ONCOR	15	2.46×10^{11}
	18	5.86×10^{11}
Siemens Primus	15	4.30×10^{11}
	18	5.07×10^{11}

total secondary neutron fluence than beams with fewer photons above that threshold.³ The general convention for beam energy specification in photon beam therapy is that the beam energy is specified based on the maximum accelerating potential of the electrons incident on the Bremsstrahlung target, with the average energy of the photon beam being approximately 1/3 of the maximum accelerating potential. However, this is merely a generalization and the true energy specification is defined by the depth of maximum dose ($D_{\max}$) and the percent depth dose at 10 cm (PDD₁₀) in water. For a given MV specification, the maximum accelerating potential may differ slightly between manufacturers of different linacs, but $D_{\max}$ and PDD₁₀ are consistent across manufacturers.

Sheikh-Bagheri and Rogers² previously reported photon spectra for Varian 15 MV, Varian 18 MV, and Siemens 18 MV beams. They reported maximum photon energies of 18.75 MeV for the 18 MV Varian beam, 15.00 MeV for the 15 MV Varian beam, and 15.25 MeV for the Siemens 18 MV beam. The maximum energy of photons in the Siemens 18 MV and Varian 15 MV spectra are considerably lower than that of photons in the 18 MV Varian beam, e.g., the 18 MV Varian photon spectrum has more high-energy photons (above the $[\gamma, n]$ threshold) than the 15 MV Varian or 18 MV Siemens spectra. This difference is the primary reason for the nearly twofold increase in secondary neutron fluence for the 18 MV Varian beam compared to the Siemens 18 MV and Varian 15 MV beams.

Less information has been published on the photon spectra for the remaining models and energies. Pena *et al.* used a Monte Carlo technique to model the 15 MV Siemens Primus photon spectrum.²⁹ They reported a nominal incident electron energy of 11.5 MeV with a Gaussian distribution (full width at half maximum of 14%).²⁹ In a subsequent publication, Pena *et al.* reported photoneutron spectra for the 15 MV Siemens Primus.⁸ Qualitatively, our spectra are in reasonable agreement with theirs, where our peak energy is slightly lower, and our fluence at the peak is about 20% lower. It is noteworthy that our data were measured at 40 cm inferior to isocenter, while the data of Pena *et al.* were simulated at the isocenter, which could account for the observed differences. A quantitative comparison is difficult because Pena *et al.* did not report total fluence or average energy.

Our neutron fluence and average energies for the Varian 21EX are consistent with those reported by Kase *et al.*,⁹ who reported calculated neutron data from Monte Carlo simulations and measured spectra data from Bonner sphere studies for Varian Clinacs operating at 10, 15, 18, and 20 MV, with data obtained at seven locations in the treatment room.⁹ In their study, both the upper and lower jaws were in the closed position. However, the linacs were not equipped with an MLC. The calculated and measured data of Kase *et al.* obtained 40 cm inferior to the beam isocenter are provided in Table IV for comparison with the current findings.⁹ Both fluence and average energy are in reasonable agreement be-

TABLE IV. Measured photoneutron data from the current study and previously reported measured and Monte Carlo calculated data for Varian linacs with 15, 18, and 20 MV photon beam energies.

Energy	Neutron fluence (n cm ⁻² MU ⁻¹)			Average energy (MeV)		
	Kase <i>et al.</i> ^a		Current study	Kase <i>et al.</i> ^a		Current study
	Calc.	Meas.		Calc.	Meas.	
15	7.6×10^4	5.3×10^4	6.67×10^4	0.3	0.19	0.23
18	1.4×10^5	0.8×10^5	1.18×10^5	0.36	0.42	0.24
20	1.5×10^5	1.1×10^5	1.69×10^5	0.36	0.29	0.24

^aReference 8.

tween the two studies. Our measured fluence values are between 31% and 53%, greater than the measured values reported by Kase *et al.*, but this deviation is within the range of deviation between the measured and the calculated values reported by Kase *et al.* which spanned from 36% to 75%. The average energy calculated in the current work is slightly lower than that reported by Kase *et al.*, but again is within the deviation of their measured and calculated data.

Chibani and Ma calculated neutron dose for an 18 MV Siemens Primus, and for 15 MV and 18 MV Varian linacs from Monte Carlo simulations.¹² They did not report the neutron spectra, but they reported the neutron dose per photon Gy for 10×10 cm² fields for each of the beams. Their absolute neutron dose values are lower than those reported here, but they used a different methodology to calculate neutron dose as well as different field sizes compared to our current work. Despite these differences, there is agreement in the data trends. Chibani and Ma reported that the Varian 15 MV beam results in 1.5 times less neutron dose than the Varian 18 MV beam; we report similar decrease of 1.7. Chibani and Ma also reported that the Siemens 18 MV beam results in 4.0 times less neutron dose than the Varian 18 MV beam; we found a similar decrease of 3.7.

Direct comparison with spectra reported in literature for the 18 MV Elekta Precise and the 15 MV Siemens ONCOR is more difficult because our measurement setup was different from that used by other authors, and quantitative comparisons are difficult if average energies or total fluence are not reported. Qualitatively, our neutron spectrum for the Elekta Precise was consistent with the spectrum reported by Zanini *et al.* for a similar 18 MV Elekta.¹⁰

We note that in this study, the tertiary configuration of the Varian MLC adds a level of collimation to the linac head compared to the Siemens and Elekta models. We have studied in depth the effects of different collimation configurations in the Varian 21EX (including changes in the jaws and MLC) on the secondary neutron spectra produced; these findings are the subject of a subsequent manuscript.

V. CONCLUSION

In our current work we compared the secondary neutron spectra produced by modern MLC-equipped linacs from three manufacturers. We determined the spectra using a single measurement technique and consistent collimation configurations. We found that there were relatively small differences in the secondary neutron energy spectra produced by the Elekta, Siemens, and Varian linacs, but the total fluence was highly variable between manufacturers. The Varian neutron spectra had slightly lower energies than the spectra from linacs manufactured by Elekta and Siemens. However, the total neutron fluence and ambient dose equivalents were found to be highest for Varian and lower for Siemens and Elekta linacs. The findings of the current study are important for understanding and evaluating the secondary neutron production from various modern linacs. This information will be

of value to medical physicists who may need to predict neutron exposures from high-energy radiotherapy and those designing shielding for treatment vaults.

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