EVALUATION OF NUCLEAR ACTIVATION OF TUNGSTEN PLATES FOR FUTURE MODELING OF A MEDICAL ACCELERATOR

RADIATION MEASUREMENTS AND INSTRUMENTATION

KEYWORDS: *activation, Monte Carlo, medical accelerator*

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Received April 17, 2008
Accepted for Publication October 16, 2008

High-energy photons from medical accelerators are used to treat tumors in cancer patients. One consequence is the production of neutrons from photonuclear interactions in the high-Z accelerator components. The release and capture of neutrons produce radioactive nuclei that can irradiate patients and medical personnel. The goal of this study is to develop a method for quantifying the activation of accelerator components using MCNPX. To benchmark this method, we took activation measurements from the irradiation of a series of zinc plates using a 55-MeV electron beam and compared them with MCNPX calculations. The measured cumulative photon-induced activity from $^{68}Zn(\gamma,p)^{67}Cu$ interactions in all of the plates was 10.8 MBq, which is in 5.4% agreement with the calculated value of 10.2 ± 1.1 MBq. Based on these results, a series of simulations were performed in order to optimize the photon- and neutron-induced activity in tungsten for subsequent experiments. The radioactivity from activated short-lived isotopes and subsequent buildup can be significant from repeated accelerator operations during a day. The approach described in this paper is useful in quantifying the origin and the amount of nuclear activation and the buildup of radioactivity.

I. INTRODUCTION

A medical linear accelerator for external beam radiation therapy is operated at energies up to 25 MeV. This high energy exceeds the photonuclear threshold energy of many materials inside the accelerator head, and these materials can release neutrons and create activated nuclei that have appreciable half-lives. The neutrons are eventually captured by the accelerator head, treatment couch, and treatment wall, creating additional activation. The subsequent decay of radioactive nuclei from both photon and neutron activation can potentially irradiate patients and medical personnel even when the accelerator is not operating. Ultimately, the photon- and neutron-induced radioactivity needs to be quantified.

Several studies have focused on estimating the photon- and neutron-induced activity by analyzing gamma spectroscopy from medical accelerators during and after the treatment.[1–9] In addition, doses to medical personnel and patients were estimated based on measurements.[10–13] Direct measurements of photon fluence and spectra in a medical accelerator room require complex measurement techniques, and can often be time-consuming and labor-intensive. Monte Carlo methods, on the other hand, have become alternative methods since they are quicker, more flexible, and less rigorous than taking measurements. To characterize the photon and neutron activation in medical accelerators using Monte Carlo methods, accurate cross-section data is needed. The Monte Carlo Neutral Particle Extended (MCNPX) code[14] has been the code of choice for these types of simulations because of its accurate and fast photon and neutron transport capabilities and its ability to handle photonuclear interactions.

Incidentally, one shortcoming of using Monte Carlo methods has been the lack of experimental data to accurately benchmark the activation processes in materials during electron beam irradiations with typical medical electron linear accelerator energies. To address this need, we have devised a methodology to quantify the photon- and neutron-induced activity using MCNPX and to compare it with experimental data. This method was first tested by comparing MCNPX simulations with a benchmark experiment performed at the Gaerttner LINAC Laboratory at Rensselaer Polytechnic Institute. Next, a series of simulations was

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performed in order to optimize the geometry of the irradiation of tungsten plates with average electron beam energy of 18.3 MeV. The optimized geometry will be used to measure the photon- and neutron-induced activity in tungsten after being irradiated by electron beams of typical medical electron linear accelerator energies.

II. METHODS AND MATERIALS

Experiments were performed at the Gaerttner LINAC Laboratory at Rensselaer Polytechnic Institute. In these experiments, 22 zinc plates were irradiated with a 55-MeV electron beam with an average current of 4 μA, and irradiation time was 40 min. The geometry of the zinc plates was square plate with the side dimension of 5.08 cm and thickness of 0.16 cm. During the activation the zinc plates were cooled by water flow through the channels, and the measurements were performed after the plates were well cooled down. Zinc was used for these experiments since the $^{68}Zn(\gamma,p)^{67}Cu$ reaction provides an easily discernable characteristic peak of 184.6 keV needed for an accurate benchmark. Even though 55 MeV is atypical of radiation therapy energies, the higher beam energy resulted in safer activation levels in the zinc plates than experiments using lower beam energies. After irradiation, the 184.6-keV gamma ray from ^{67}Cu was measured using a high-resolution high-purity germanium detector. Using a correction factor for decay and detection efficiency, the activity of the ^{67}Cu at the end of irradiation was determined. The overall accuracy of determining the activity of each plate was estimated to be $\sim$10%.

In order to compare measurement data with Monte Carlo simulations, a series of zinc plates was directly irradiated with an electron beam in MCNPX. The plates were irradiated with a beam having a Gaussian energy distribution with a mean energy of 55 MeV and a 10% full width at half maximum (FWHM). The electron beam had a uniform radial distribution with a diameter of 1.5 cm. In order to determine the activity in the plates from the $^{68}Zn(\gamma,p)^{67}Cu$ interaction the average flux binned by energy was convolved with the $^{68}Zn(\gamma,p)^{67}Cu$ cross section. This was done implicitly in MCNPX using the dose energy and dose function cards applying logarithmic interpolation between cross-section data points. The cross-section data was taken from the International Atomic Energy Agency (IAEA) recommended photonuclear cross-section database.[15] The IAEA database contained cross-section data for all naturally occurring isotopes of zinc (^{64}Zn, ^{66}Zn, ^{67}Zn, ^{68}Zn, and ^{70}Zn).

Another set of simulations was performed in order to optimize the geometry of the irradiation of 32 tungsten plates—each 0.125 cm thick and 2.5 cm in radius—with an electron beam having a Gaussian energy distribution of mean energy 18.3 MeV and 3% FWHM, which is typical of 18-MV medical accelerator beams with an average current of 4 μA, and irradiation time was 40 min. A set of eight tungsten rings with 4-cm inner radius, 9-cm outer radius, and 0.5-cm thickness was stacked orthogonal to the electron beam around the target to generate neutron activation while minimizing photon interactions in the cylinder. Water was filled between the target plates and rings to thermalize the neutrons and maximize the neutron capture in the tungsten rings. The geometry of the simulation is sketched in Fig. 1. The tungsten plates and rings were given a nominal density of 18.0 g/cm^3. Detailed physics models were used for electrons, photons, and neutrons in all simulations. The ITS electron indexing method was implemented, which picks the cross-section data consistent with the energy binning. Once again, these simulations used IAEA recommended cross-section data. The IAEA database contained cross-section data for all naturally occurring isotopes of tungsten (^{180}W, ^{182}W, ^{183}W, ^{184}W, and ^{186}W). For calculating photon activation in the target, only the $^{186}W(\gamma,n)^{185}W$ interaction was considered. Similarly, for neutron activation in the cylindrical shell, only the $^{186}W(n,\gamma)^{187}W$ interaction was considered. These two isotopes have long enough half-lives for possible future measurements.

To reduce computation time, the cutoff energies for electrons and photons were set to 5 MeV. This energy seemed appropriate since it is below the photonuclear threshold for all isotopes of tungsten and high enough to avoid unnecessary transport of secondary electrons in the problem geometry. No other variance reduction techniques were used in the simulations.

III. RESULTS AND DISCUSSION

The measured and calculated ^{67}Cu activity from the irradiation of the zinc plates is plotted in Fig. 2. The total

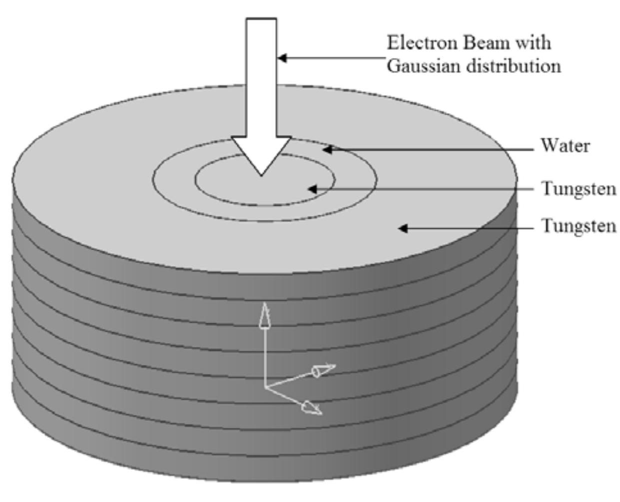

Fig. 1. The geometry sketch of tungsten plates and rings.

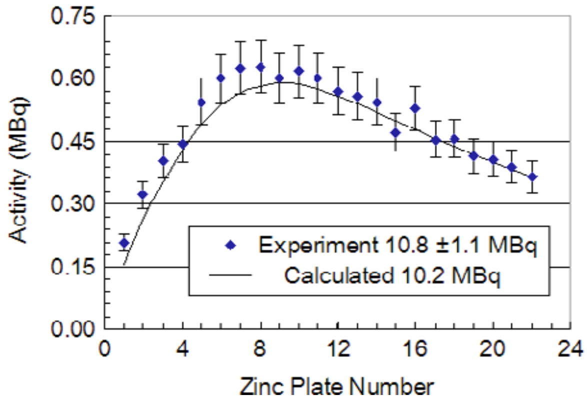

Fig. 2. Benchmark calculation of photon-induced activity of ^{67}Cu.

cumulative activities determined by measurement and calculation were 10.8 MBq and 10.2 ± 1.1 MBq, respectively, giving a 5.4% difference. Each calculated plate activity was within good agreement of the measured activity, and differences were within the estimated measurement accuracy of 10%.

The photon-induced activity determined of 31 tungsten plates irradiated with the 18.3-MeV electron beam is plotted in Fig. 3. The buildup of activity in the first two plates is due to the initial increase of photon flux from a finite range of electrons in the tungsten target. By the third plate the activity falls because of attenuation of the photon flux as a function of distance. Figure 4 plots the neutron-induced activity as a function of plate number from $^{186}W(n,\gamma)^{187}W$ interactions in the cylindrical tungsten shells surrounding the target. Since the average neutron energy produced in the target is ~1.2 MeV, the neutrons need to be moderated to improve the $^{186}W(n,\gamma)^{187}W$ yields in the shell. This was done by adding a layer of water between the target and cylinder. The mean free path of a 1.2-MeV neutron in water was calculated (~2 cm) to optimize the thickness

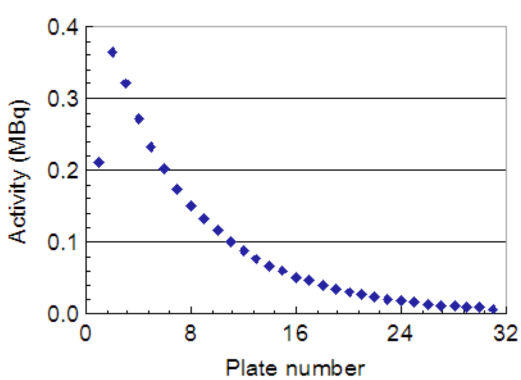

Fig. 3. Photon-induced activity of ^{185}W in the tungsten target.

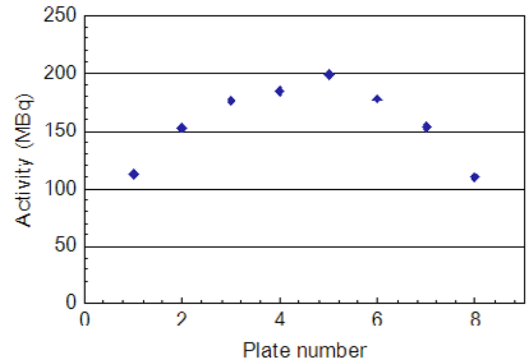

Fig. 4. Neutron-induced activity of ^{187}W in the tungsten cylinder.

of the water layer. The neutrons are emitted isotropically during activation[16] so that there is a maximum value, as shown in Fig. 3. The location of this peak can be attributed to the moderation of these neutrons through the target and water surrounding the target, as seen in Fig. 1.

IV. CONCLUSIONS

In this paper we measured the activation produced by the irradiation of a series of zinc plates using a 55-MeV electron beam. We then compared this data to MCNPX calculations. The measured cumulative photon-induced activity from $^{68}Zn(\gamma,p)^{67}Cu$ interactions in all of the plates was 10.8 MBq, which is within 5.4% agreement with the calculated value of 10.2 ± 1.1 MBq. Subsequently, a series of simulations was performed in order to optimize the geometry of an experiment to measure the photon and neutron activation in tungsten from electron irradiations with typical medical accelerator energies.

This study showed that the MCNPX code can be used to simulate nuclear activation. Using detailed models of medical accelerators and accelerator rooms, the photon and neutron activation in any location in the treatment room can be calculated. These tools can be used to quantify the origin and the amount of nuclear activation and the buildup of radioactivity produced during medical accelerator operation. Subsequently, these tools can be used to determine the dose to the patient or medical personnel from this activation.

REFERENCES

1. H. W. FISCHER, B. TABOT, and B. POPPE, "Comparison of Activation Products and Induced Dose Rates in Different High-Energy Medical Linear Accelerators," *Health Phys.*, **94**, 272 (2008).

2. H. W. FISCHER, B. TABOT, and B. POPPE, "Activation Processes in a Medical Linear Accelerator and Spatial Distribution of Activation Products," *Phys. Med. Biol.*, **51**, N461 (2006).

3. H. W. FISCHER and K. PEICK, "Activation Products in a Medical Linear Accelerator," *Radiother. Oncol.*, **51**, Suppl. 1, S59 (1999).

4. Y. WANG, M. D. C. EVANS, and E. B. PODGORSAK, "Characteristics of Induced Activity from Medical Linear Accelerators," *Med. Phys.*, **32**, 2899 (2005).

5. D. S. FOLLOWILL, M. S. STOVALL, S. F. KRY, and G. S. IBBOTT, "Neutron Source Strength Measured for Varian, Siemens, Elekta and General Electric Linear Accelerators," *J. Appl. Clin. Med. Phys.*, **4**, 189 (2003).

6. L. AHLGREN and L. E. OLSSON, "Induced Activity in a High-Energy Linear Accelerator," *Phys. Med. Biol.*, **33**, 351 (1988).

7. K. J. WEEKS, "Method for Determining Photonuclear Production of Radioisotopes Using High-Energy Electron Beams," *Med. Phys.*, **26**, 49 (1999).

8. M. ROIG, V. PANETTIERI, M. GINJAUME, and A. SANCHEZ-REYES, "Photonuclear Isotope Characterization of a Siemens KDS 18 MV Linac Head," *Phys. Med. Biol.*, **49**, N243 (2004).

9. A. KONEFAL, K. POLACZEK-GRELIK, and W. ZIPPER, "Undesirable Nuclear Reactions and Induced Radioactivity as a Result of the Use of the High-Energy Therapeutic Beams Generated by Medical Linacs," *Radiat. Prot. Dosim.*, **128**, 133 (2008).

10. J. A. RAWLINSON, M. K. ISLAM, and D. M. GALBRAITH, "Dose to Radiation Therapists from Activation at High-Energy Accelerators Used for Conventional and Intensity-Modulated Radiation Therapy," *Med. Phys.*, **29**, 598 (2002).

11. R. BARQUERO, R MENDEZ, H. R. VEGA-CARRILLO, M. P. INIGUEZ, and T. M. EDWARDS, "Neutron Spectra and Dosimetric Features Around an 18 MV Linac Accelerator," *Health Phys.*, **88**, 48 (2005).

12. B. PERRIN, A. WALKER, and R. MACKAY, "A Model to Calculate the Induced Dose Rate Around an 18 MV ELEKTA Linear Accelerator," *Phys. Med. Biol.*, **48**, N75 (2003).

13. A. ALMEN, L. AHLGREN, and S. MATTSSON, "Absorbed Dose to Technicians due to Induced Activity in Linear Accelerators for Radiation Therapy," *Phys. Med. Biol.*, **36**, 815 (1991).

14. J. S. HENDRICKS et al., "MCNPX, Version 2.5," LA-UR-04-0569, Los Alamos National Laboratory (2004).

15. "Handbook of Photonuclear Data for Applications: Cross Sections and Spectra," IAEA-TECDOC-1178, International Atomic Energy Agency (2000).

16. J. C. LIU, W. R. NELSON, K. R. KASE, and X. S. MAO, "Calculation of the Giant-Dipole-Resonance Photoneutrons Using a Coupled EGS4-MORSE Code," *Radiat. Prot. Dosim.*, **70**, 49 (1997).