DETERMINATION OF ACTIVATION PRODUCTS AND RESULTING DOSE RATES FOR THE VARIAN TRUEBEAM

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ABSTRACT

Medical linear accelerators used to treat various forms of cancers are operated at a number of different energies. A by-product of the high-energy photons produced by accelerators is activation of components within the machine itself and its surrounding bunker. The activation products pose radiological and regulatory challenges during the operation of the accelerator as well as when it is time for final decommissioning. The Varian TrueBeam is a new state-of-the-art linear accelerator now operating in the Canadian market. There is currently limited information on the production of its activation products and the resulting impacts on operation and decommissioning. In this paper, the activation products in the Varian TrueBeam accelerator are experimentally determined by performing gamma spectroscopy using a portable high-purity germanium detector (HPGe). A total of 11 isotopes are identified which includes ^{24}Na, ^{28}Al, ^{56}Mn, ^{57}Ni, ^{64}Cu, ^{66}Cu, ^{82}Br, ^{122}Sb, ^{124}Sb, ^{187}W, and ^{228}Ac. The half-lives of these isotopes range from 2.3 minutes to 60.2 days. The resulting dose rates are modelled to estimate a maximum annual dose of 3.15mSv to radiation therapists. Combining the Canadian Nuclear Safety Commission (CNSC) isotope exemption quantities found in the Nuclear Substance and Radiation Device (NSRD) regulations and the isotopic quantities determined during the gamma spectroscopy, the aggregate exemption quantity for the accelerator at any given time is determined. After 36 hours pass a decommissioning case can be presented to the CNSC for the disposal of the accelerator or shipment to a non-licensee.

INTRODUCTION

Modern medical linear accelerators used for the treatment of cancers are capable of operating at electron energies as high as 20 MeV. Above electron energies of 6 MeV, a measurable dose rate is obtained at the isocenter after beam termination. This is attributed to the activation of linear accelerator components through photonuclear reactions and neutron capture (Brusa, Cesana, Stucchi, Terrani, & Zanellati, 2008).

Photons are produced as bremsstrahlung during the collision of high-energy electrons with a heavy metal target, typically comprised of copper or tungsten. When photons exceeding the nucleon binding energy interact with a nucleus, neutrons are ejected. In the process of neutron capture, neutrons produced through (γ, n) reactions are absorbed by a nucleus and the excess energy is emitted as a photon. Over the lifetime of an accelerator many components, such as the target, flattening filter, collimators, jaws, and treatment couch, are activated through these interactions (Fischer, Tabot, & Poppe, 2008).

Although dependant on operating conditions, linear accelerators have an expected lifetime of 7 to 10 years. At the end of their life, accelerators are typically sold for scrap or returned to a remanufacturing enterprise. Since many of the accelerator components have been

exposed to a neutron fluence and activated to various extents, the requirements of the Nuclear Substance and Radiation Device (NSRD) Regulations apply. The operator is then faced with transferring the activated components to another licensee or demonstrating that it is safe for the components to enter into the municipal waste stream.

Studies have been conducted to investigate activation in previous generation accelerator models (Fischer, Tabot, & Poppe, 2008); however, the models which have been experimentally surveyed and described are approaching the end of their life and are being replaced with a new generation of machines. New accelerator models, such as the Varian TrueBeam, are capable of operating at multiple energies and in advanced modalities, including flattening filter free (FFF) mode (Varian Medical Systems, 2012). Limited information is available regarding activation products and resulting dose rates to personnel during normal operation and decommissioning activities for new generation linear accelerators.

The aim of this study was to conduct an experiment to determine the magnitude of activation, activation products, and resulting activation dose rates for the Varian TrueBeam. This work includes consideration of appropriate disposal practices in accordance with Canadian regulations and intends to aid in planning during normal operation and decommissioning.

EQUIPMENT AND METHOD

The experimental work was conducted from Friday November 8th to Sunday November 10th 2013 on a Varian TrueBeam radiotherapy accelerator located at Princess Margaret Hospital in Toronto, Ontario.

The primary experimental instrument was an ORTEC trans-SPEC-DX-100 portable high-purity germanium detector (HPGe) obtained from the Canadian Nuclear Safety Commission (CNSC). Several dose rate meters were used, including Thermo Scientific RadEye G gamma survey meters from the University of Ontario Institute of Technology (UOIT), a Victoreen 451P from CNSC, and an Automess Szintomat 6134 from Princess Margaret Hospital.

The experiment included gamma spectroscopy and dose rate measurements for short-lived and long-lived radionuclides, as well as a number of accelerator configurations. The procedure for this study closely modelled previous work (Fischer, Tabot, & Poppe, 2008), which conducted gamma spectroscopy of four common medical linear accelerators. The results are reproduced in Table 1.

Table 1: Spectroscopic measurements of previous generation linear accelerators[a] (Fischer, Tabot, & Poppe, 2008)

Isotope	$T_{1/2}$	Decay mode	Γ mSv m^2 h^{-1} GBq^{-1}	Elekta SL-18			GE Saturne 42F			Siemens Primus			Varian Clinac 2100C/D		
				A_{ap} MBq	Error %	Dose rate μSv h^{-1}	A_{ap} MBq	Error %	Dose rate μSv h^{-1}	A_{ap} MBq	Error %	Dose rate μSv h^{-1}	A_{ap} MBq	Error %	Dose rate μSv h^{-1}
^{24}Na	15.0 h	-	0.429	0.052	3.9	0.022	0.060	3.7	0.026	0.008	9.5	0.0034	0.036	4.7	0.0156
^{28}Al	2.3 m	-	0.222	1.85	6.0	0.41	4.3	4.6	0.95	2.30	5.7	0.51	9.79	19.2	2.17
^{51}Cr	27.7 d	+	0.0042	0.124	16.5	0.0005	0.40	4.0	0.0017	n.d.			n.d.		
^{54}Mn	312.3 d	+	0.11	0.073	2.4	0.008	0.13	2.8	0.015	0.024	4.5	0.0026	0.0058	12.3	0.0006
^{56}Mn	2.6 h	-	0.23	0.63	3.3	0.145	1.25	3.1	0.29	0.131	4.3	0.030	0.69	3.3	0.160
^{57}Co	271.8d	+	0.0133	0.049	6.1	0.0006	0.144	2.7	0.0019	0.0132	7.3	0.0002	0.012	9.5	0.0002
^{57}Ni	36.0 h	+	0.255	0.085	13.0	0.022	0.35	3.1	0.090	0.260	2.8	0.066	0.144	3.0	0.037
^{58}Co	70.9 d	+	0.129	0.0113	9.1	0.0015	0.037	3.9	0.0048	0.005	42.0	0.0006	0.025	4.8	0.0032
^{59}Fe	45.1 d	-	0.147	0.007	16.3	0.001	0.019	7.3	0.0028	0.005	16.0	0.0007	0.0065	23.5	0.001
^{60}Co	5.3 y	-	0.307	0.009	13.1	0.0028	0.040	3.5	0.0122	0.0079	8.3	0.0024	0.0097	8.2	0.003
^{62}Cu	9.7 m	+	0.151	1.50	5.0	0.226	0.54	5.5	0.082	0.59	6.0	0.090	3.21	3.3	0.48
^{64}Cu	12.7 h	-, +	0.029	3.78	20.5	0.110	n.d.			0.76	47.7	0.022	5.4	9.4	0.160
^{65}Zn	244.3d	+	0.073	0.006	18.7	0.0004	0.013	9.0	0.0009	0.015	6.0	0.0011	0.0127	9.1	0.0009
^{82}Br	35.5 h	-	0.343	0.059	3.7	0.0203	0.009	24.2	0.0031	0.091	4.2	0.031	0.105	3.4	0.0360
^{99}Mo	66.0 h	-	0.034	0.008	13.3	0.0003	n.d.			0.008	13.3	0.0003	n.d.		
^{122}Sb	2.7 d	-, +	0.069	0.088	5.4	0.0061	0.040	4.5	0.0028	0.0089	13.2	0.0006	0.081	4.5	0.0056
^{124}Sb	60.2 d	-	0.26	0.0318	3.8	0.008	0.0116	6.3	0.003	0.0014	16.3	0.0004	0.024	6.3	0.0061
^{184}Re	38.0 d	+	0.129	0.077	7.1	0.01	n.d.			n.d.			n.d.		
^{187}W	23.7 h	-	0.073	0.72	3.9	0.053	0.24	4.9	0.018	0.134	5.7	0.0098	1.09	3.6	0.080
^{196}Au	6.2 d	+	0.071	0.044	4.3	0.003	n.d.			0.079	5.8	0.0056	0.005	22.0	0.0004
^{203}Pb	51.9 h	+	0.045	n.d.			0.021	11.5	0.001	n.d.			n.d.		

[a]n.d. = not determined

EXPERIMENTAL PROCEDURE

Four experiments were conducted to investigate the short-lived and long-lived radionuclides of the accelerator in both flattening filter and flattening filter free mode.

Measurements were taken with and without the flattening filter in place to allow for identification of activation products directly attributed to the component. Experimental data was not gathered for the multi-leaf collimator, as it remained shielded for the duration of the experiments.

Prior to the experiment, the accelerator was operated at 15 MV with a dose rate of 600 monitor units (MU) per minute for 15 minutes before and after each treatment day in the week prior. This simulated a high-workload machine during a high-energy treatment week to saturate the accelerator with activation products. This was based on a daily workload of 20000 MU, annual workload of 5000000 MU, and 250 treatment days per year.

The HPGe detector was positioned such that the crystal was located at the accelerator's isocenter; 100 cm from the accelerator target. Dose rate meters were placed adjacent to the HPGe detector and collected both instantaneous dose readings, as well as integrated measurements. An energy calibration was performed on the HPGe detector using Ba-133 and Cs-137 check sources.

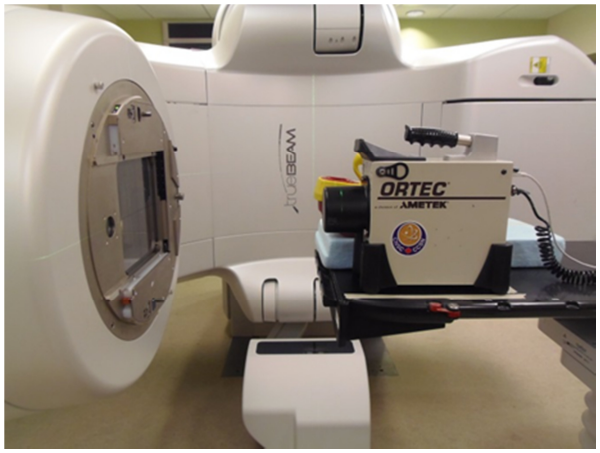

Figure 1: Experimental setup

Experiment One

During experiment one, gamma spectroscopy was conducted for four field size configurations: 40 cm x 40 cm, 15 cm x 15 cm, 10 cm x 10 cm, and 0.5 cm x 0.5 cm. These configurations represent the maximum and minimum possible field sizes used during treatment. Experiment one was completed prior to running the machine at 15 MV after the last treatment day of the week, thus gamma spectra and dose rate measurements were recorded approximately 13 hours after the last high-energy beam. This timeline modeled a potential servicing or decommissioning scenario. The resulting data investigated the effect of jaw position on observed activation products and dose rates at the isocenter.

Experiment Two

Experiment two examined the short and intermediate-lived activation products of the Varian TrueBeam. On the evening of Friday November 8th, the accelerator was run in flattening filter mode at 15 MV for 15 minutes with a dose rate of 600 MU/min and field size of 15 cm x 15 cm. Under the guidance of Princess Margaret Hospital staff, a field size of 15 cm x 15 cm was selected to most appropriately model typical clinical use of the machine. Following beam termination, the experimental equipment was quickly positioned 3 m from the accelerator target. This distance accommodated for flooding of the detector, while ensuring sufficient spectral data was obtained. Measurements were taken for periods of 1 minute, 10 minutes, and 30 minutes to capture results for short and intermediate-lived activation products.

Experiments Three and Four

Conducted on Saturday November 9th and Sunday November 10th, experiments three and four investigated the long-lived activation products of the Varian TrueBeam. As flooding of the detector was no longer a concern, experimental equipment was positioned at the isocenter. On each day, two 75 minute runs were conducted both with and without the flattening filter in place.

RESULTS AND DISCUSSION

Dose Rates

Measurements taken during experiment one investigated the effect of field size on dose rate at the isocenter. The data was obtained 13.61 hours after the last 15 MV beam run prior to the treatment day. Data for each field size was taken over 10 minute periods, during which dose rate values were recorded at the start of each interval.

The RadEye and Szintomat were used to measure instantaneous dose rates, while the

Victoreen measured an integrated dose. As the dose rate was observed to remain stable during each of the four runs, the integrated dose measured by the Victoreen was divided by the duration of the run to provide an average instantaneous dose rate for each field size.

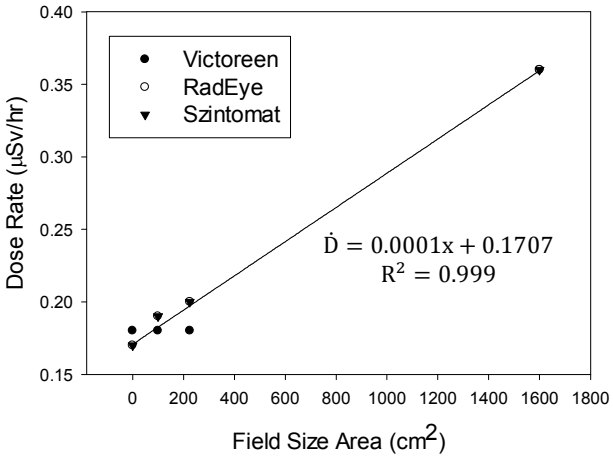

Figure 2: Dose rate vs. field size for a Varian TrueBeam 13.61 hours after last 15 MV beam

The resulting data points are tightly clustered and demonstrate a linear increase in the measured dose rate at the isocenter with increasing field size area. The calculated intercept value of 0.1707 µSv/hr can be interpreted as the dose rate attributed to the accelerator jaws in a closed position. Previous studies of Varian accelerators have shown that the jaws contribute approximately 40% of the total dose rate from activation following a high-energy beam (Varian Medical Systems, 2013). This relationship is observed in the experimental results as the maximum field size yielded a dose rate that exceeded the predicted closed jaw dose rate by a factor of 2.1.

These findings have implications to decommissioning planning and ALARA practices, as a closed jaw position is observed to reduce dose rates resulting from activation. Potential applications to facility practices and procedures may include jaw position requirements during decommissioning or servicing work on machine components such as the treatment couch and on-board imaging.

Dose to Workers

During experiments two, three, and four, dose rate measurements were taken to study the trend in dose rate over time, as well as estimate doses to radiation therapists (RTs) who may enter the treatment room shortly following beam termination. Dose rate measurements were taken at approximate 15 minute intervals during each experiment, beginning immediately after beam termination and continuing for 39 hours. The measurements were taken with a 15 cm x 15 cm field size to simulate typical clinical use.

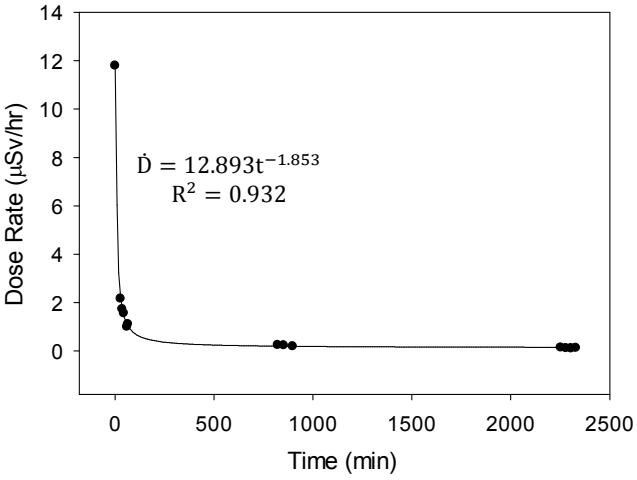

Figure 3: Dose rate vs. time after beam termination

Figure 3 shows that the measured dose rate drops off rapidly after the termination of the beam. A curve was fitted to the dataset which models the expected dose rate with respect to time after a 15 minute high-energy beam run.

$$\dot{D} = 12.893(t)^{-1.853} \quad (1)$$

To determine the approximate exposure time to a typical RT an exposure model was defined. Assuming 250 working days in a year with 15 days of vacation and 5 sick days, an RT would work 230 days. With an approximate throughput of 2 patients per hour, the RT would treat 16 patients per 8 hour shift. The model assumes 5 minutes spent in the bunker per patient with the first 2 minutes at 3 m from the target and the remaining 3 minutes at 2 m from the target. It is assumed that the accelerator window is facing towards the RT. Eq. (2) models Eq. (1) with the aforementioned parameters.

$$D_{RT} = f_{HE} \text{ x } W_d \text{x } P_{TD} \left[\frac{1}{r^2}\int_2^4 12.893(t)^{-1.853}\,dt + \frac{1}{r^2}\int_4^7 12.893(t)^{-1.853}\,dt\right] \quad (2)$$

D_{RT}	The annual estimated dose to an RT
f_{HE}	The fractional time spent treating patients at high energies (15 MV)
W_d	The number of working days in a year
P_{TD}	Patient throughput per day
r	Distance from the accelerator target (m)

Solving Eq. (2) for an isocenter distance of 1 m with the above conditions yields an estimated annual dose of 3.15 mSv.

$$D_{RT} = 3.15 \text{ mSv/yr}$$

If the fractional high-energy operating time is reduced, the corresponding doses to RTs will also be reduced proportionally. If RTs increase the time before entering the bunker and spend less time in close proximity to the accelerator head after a high-energy treatment, the annual doses received would correspondingly lower.

Gamma Spectroscopy

In order to identify the activation products in the Varian TrueBeam, gamma spectroscopy was performed. The spectroscopy results are summarized in Table 2. A total of 11 isotopes were identified using the GammaVision V6.01 software package. Many of the isotopes were identified using preinstalled standard libraries. Certain isotopes with ambiguous energies and abnormal peaks were manually resolved. In the case of ambiguous isotopes, having multiple days of post-beam termination spectral data proved to be invaluable. In these cases the differences in the count rate in subsequent days lead to the calculation of the unknown isotope's half-life. Combining the known energy of the peak and the approximate half-life, a list of potential isotopes was created. The final step leading to positive identification involved examination of each of the isotope's intensity ratios to determine if the spectrum corresponded appropriately.

Table 2 estimates the activity of the isotope based upon a reference point in the head of the accelerator. This reference point is the accelerator target located 1 m from the

Table 2: Summary of Varian TrueBeam gamma spectroscopy results

Isotope	$T_{1/2}$	Exemption Quantity (MBq)	Activity t = 0 h (MBq)	Peak Energy (keV)	Intensity	Exemption Quantities t = 0 h	Exemption Quantities t = 36 h
^{24}Na	15.0 h	0.1	0.444	1368.63	1.0	2.813	0.533
^{28}Al	2.3 m	0.01	474.599	1778.97	1.0	45793.83	-
^{56}Mn	2.6 h	0.1	3.14	846.77	0.989	19.2	0.001
^{57}Ni	36.0 h	1.0	0.168	1377.63	0.817	0.120	0.06
^{64}Cu	12.7 h	1.0	0.175	1345.84	0.473	0.171	0.024
^{66}Cu	5.1 m	0.01	8.155	1039.23	0.09	815.5	-
^{82}Br	35.5 h	1.0	0.020	698.37	0.2849	0.028	0.014
^{122}Sb	2.7 d	100	0.18	564.12	0.71	0.00074	0.001
^{124}Sb	60.2 d	1.0	0.0016	1690.98	0.4779	0.009	0.009
^{187}W	23.7 h	1.0	0.657	685.73	0.332	0.944	0.329
^{228}Ac	6.15 h	1.0	0.113	911.20	0.258	0.113	0.002
					Σ Exemption Quantities:	46632.74	0.974

isocenter. It should be noted that many of the activated components, such as the jaws of the accelerator, are located forward of the target and the 1 m distance will not accurately describe the activity of all components. However, this method of calculation provides a conservative measure for all isotopes present.

The activity of each isotope is first calculated by correcting for background radiation and determining the number of counts in the measured peak using a full-width at half maximum (FWHM) method. To determine the actual activity, the number of counts need to be corrected for intensity and the detector's absolute efficiency. The intensity refers to the average number of decays occurring at a given energy level for a specific isotope. A peak intensity of 0.5 means that a single gamma at a specific energy level will be emitted every 2 decays.

The efficiency correction is necessary as only a small fraction of the emitted gamma rays interact with the crystal. An efficiency calibration was completed using a source with a known activity placed at a distance of 1 m. The actual number of counts was divided by the total number of expected counts. The activity is given by the following equation:

$$A = \frac{C}{I\varepsilon} \tag{3}$$

A Activity (Bq)
C Number of counts corrected for background and count time (Bq)
I Intensity
ε Absolute efficiency

Since the number of counts of a given isotope decay with time, it is important to establish the activity immediately following the high-energy run. As described in the experimental setup, spectroscopy

measurements began approximately 1 minute after the high-energy beam termination. To determine the activity of the activated components at t = 0, a number of additional parameters need to be considered in Eq. (3). The isotope's half-life is used to calculate the decay constant. Additionally, the time from the high-energy beam termination to the midpoint of the spectroscopy measurement period is incorporated. The resulting equation for activity at t = 0 is:

$$A(0) = \frac{A}{e^{-\frac{\ln(2)}{T_{1/2}}t}} \quad (4)$$

A Activity (Bq)
$T_{1/2}$ Half-life (h)
t Time from beam termination to midpoint of spectroscopy measurement period (h)

To determine the number of exemption quantities (EQs) present at t = 0, the initial activity at t = 0 is divided by the individual isotope's EQ.

$$\text{EQs}\,(0) = \frac{A(0)}{EQ_{isotope}} \quad (5)$$

Canadian regulations allow for members of the public to possess quantities of radioactive material without a licence provided it is less than 1 EQ. To determine when the total aggregate EQ is less than 1, an equation is developed to express the number of EQs present at any given time for any given isotope.

$$\text{EQs}(t) = \frac{A(0)(\frac{1}{2})^{\frac{t}{T_{1/2}}}}{EQ_{isotope}} \quad (6)$$

Using the data in Table 2, the safe disposal time for the Varian TrueBeam is calculated to be the time when the following condition is met:

$$\sum_{i=1}^{11} \frac{A(0)(\frac{1}{2})^{\frac{t}{T_{1/2}}}}{EQ_{isotope}} \leq 1$$

The results show that the total number of EQs are 0.974 at t = 36 h. At this time, the activated components are below the aggregate exemption quantity and a case can be made for immediate disposal or transfer.

The Varian TrueBeam results were compared against data from previous generation linear accelerators discussed in Table 1 (Fischer, Tabot, & Poppe, 2008). By adapting Eq. (6) for the number of identified activation products and applying Canadian exemption criteria, the time until the aggregate EQ is less than 1 was determined.

Table 3: Summary of times to exemption for various accelerator models

Manufacturer/Model	Time to Exemption (h)
Varian TrueBeam	36
Varian Clinac 2100 C/D	63
Elekta SL-18	401
Siemens Primus	476

Table 3 summarizes the times to exemption for the Varian TrueBeam and a selection of previous generation accelerators. The GE Saturne 42F is excluded as it is not a currently operational model in Canada. From the results, the Varian Clinac 2100 C/D is seen to compare favourably to the TrueBeam. It is observed that both Varian

accelerator models studied reach exemption earlier than the Elekta and Siemens accelerators. This may result in a streamlined decommissioning process with respect to managing radiological hazards and meeting regulatory requirements.

CONCLUSION

The aim of this paper was to present findings on the activation products produced in the Varian TrueBeam linear accelerator. Activation products accumulated in the accelerator pose issues during operation and decommissioning. During normal operation, doses to RTs are largely a product of residual radiation resulting from the activation products. By taking dose rate measurements alongside gamma spectroscopy, annual doses to RTs were estimated to be 3.15 mSv using a patient interaction model. Gamma spectroscopy using a HPGe detector revealed 11 isotopes which are significant during decommissioning. Using Canadian exemption quantity criteria, decay calculations were performed based on the activity of each isotope. Based on these calculations, a case can be made that 36 h is an appropriate time to wait until disposal of the accelerator or shipment to non-licensees.

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