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ARTICLE

Identification of Induced-Radioactivity in Medical LINAC Using a NaI(Tl)-Crystal Detector

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The exposure of tissues to large amount of radiation is a major concern of clinicians who use radiotherapy to treat patients for solid tumors. We assessed the amount of radioactivity induced by therapeutic x-ray beams used in radiotherapy. To measure the energy spectra of γ-rays emitted from the activated materials using a NaI(Tl)-crystal detector, the detector was placed inside the heads of the medical linear particle accelerators (LINACs) of two Clinac 21EXs machines and one Clinac 21EX platinum (Varian Medical System, USA). The energy spectra were measured for one hour of data acquisition (DAQ) time, and then another spectrum was measured under the same conditions for 58~59 hours. The ratios of full photopeak areas in the two γ-ray spectra were compared with standardized values calculated using the lifetimes of induced-isotope candidates, which were selected for their characteristic γ-ray energies and the atomic components of LINAC heads. In order to minimize errors originated from backgrounds and neighboring peaks, the photopeak areas were obtained by fitting the peak components with Gaussian functions and background components with a polynomial function. Using the energy-resolution relationships of NaI(Tl)-crystal detectors, the widths of the Gaussian functions were determined. The calculated ratios of photopeak areas for the two different DAQ times were 40.6 (^{203}Pb), 27.7 (^{187}W), 34.6 (^{82}Br), 28.3 (^{54}Mn) and 34.7 (^{57}Ni). The measured area ratios of these photopeaks tagged in γ-ray spectra were 40.3, 27.3~29.6, 31.5~36.9, 28.5 and 35.1~39.0 respectively. These values are consistent with each others.

KEYWORDS: radiotherapy, induced radioactivity, LINAC

I. Introduction

Radiation treatment for deeply located solid tumors commonly employs high-energy x-ray beams greater than 10 MV to reduce the radiation dose to normal tissues located in the therapeutic beam path. However, x-rays that emit energy greater than 8.5 MeV may activate high-Z materials in LINAC, which then produce characteristic γ-rays in the decay process. Photonuclear interactions and nuclear interactions with secondary neutrons produce remnant nuclides that may be radioactive and long-lived. Subsequently, these nuclides undergo β+, β- and γ decay, and characteristic γ-rays are emitted [3, 4].

Previous studies of induced radiation typically described hazards to LINAC operators [1-6]. However, few of these studies have evaluated Varian LINACs because of the complexity of the Varian radiotherapy equipments and the low amounts of radiation produced via their activation.

According to the results of previous studies, the highest levels of radioactivity are found in the gantry heads of LINACs, since these are exposed by the highest levels of photon fluence. Therefore, we measured the γ–ray spectra in Varian LINAC heads to assess the amounts of the induced activities.

II. Materials and Methods

We measured γ-ray spectra produced via the decay process of radioactive nuclides for Clinac Model 21EXs and Clinac Model 21EX Platinum, both of which operated at 15 MV in high-energy x-ray mode. Figure 1 illustrates the general geometry of Varian LINAC head components including the target, primary collimator, flattening filter, jaw,

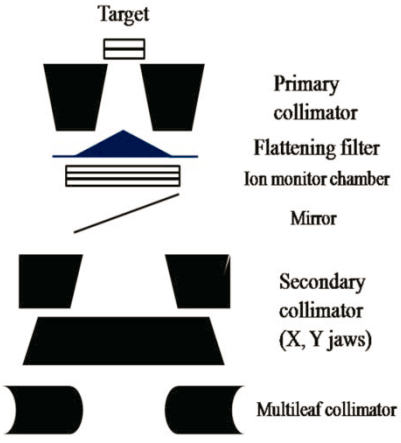

Fig. 1 Schematic diagram of general Varian LINAC head structure

and multi-leaf collimator (MLC) [7, 8]. All collimators were retracted during measurements to install the detector as deep within the LINAC head as possible.

The data acquisition (DAQ) system consisted of a Thallium-doped Sodium Iodide (NaI)-crystal detector (802, Canberra, USA) coupled with a photomultiplier tube (PMT),

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a pre-amplifier (276, Ortec, USA), an amplifier (590A, Ortec, USA) and a multi-channel analyzer (Trump-Pci, Ortec, USA). The characteristic γ-rays were detected as scintillation light produced by NaI-crystals. Although the resolution of NaI-crystal detectors is poorer than that of high purity germanium detectors, NaI-crystal detectors were used in this experiment due to their excellent light yield and ease of use.

A PMT converts light signals into electronic signals. The pre-amplifier precedes an amplifier downstream of the PMT to minimize the effect of electronic noises in other electronic circuits and cables. Before being acquired by the multi-channel analyzer board, the signals were converted into integrated shapes and amplified through a amplifier. The acquired signals were calibrated to a standard energy scale using a ^{137}Cs source.

All experiments were carried out on weekends to avoid interruptions from radiation treatments for patients. All collimators including jaws and multi-leaf collimators were opened and the NaI-crystal detector placed inside near the mirror. We measured γ-ray spectra for one hour of DAQ time, and then we measured another spectra under the same geometric conditions for 58~59 hours to obtain data for long-lived isotopes. The acquired spectra were analyzed using a purpose-made software program, Gammavision-32 (Ortec., USA) [9].

III. Results and Discussion

A. Photopeak area ratio study

The target, primary collimators and jaws of LINACs are made mostly of tungsten (W). The flattening filters consist of steel alloy. Copper (Cu), nickel (Ni) and lead (Pb) are the main atomic components of shielding materials in the accelerators. These atoms can be activated by exposure to high energy photons. As a result, many isotopes can be produced during the beam exposure time. Some candidates of isotopes with long life times and large branching fractions are listed in Table 1.

Table 1. Probable candidates of induced isotopes in LINAC heads

Isotope	Half-life	Gamma energy (keV)	Production
^{187}W	23.7 h	480, 686	^{186}W(n, γ)^{187}W
^{62}Cu	9.74 m	511(Annihilation)	^{63}Cu(γ, n)^{62}Cu
^{57}Ni	35.6 h	1378, 1920	^{58}Ni(r, γ)^{57}Ni
^{28}Al	2.24 m	1778	^{27}Al(n, γ)^{28}Al
^{56}Mn	2.58 h	847	^{55}Mn(n, γ)^{56}Mn
^{54}Mn	312 d	835	^{55}Mn(γ, n)^{54}Mn
^{203}Pb	51.9 h	279	^{204}Pb(r, γ)^{203}Pb
^{82}Br	35.3 h	619, 777	^{81}Br(n, γ)^{82}Br

The acquired spectra shown in Fig. 2, are similar in shape. The γ-ray spectra were measured using three Varian LINACs heads: (a) spectra obtained for one hour and (b) spectra obtained for 58~59 hours after taking measurement (a). Seven peaks were resolved in each spectrum. The fitting method was used to identify the induced isotopes, and to evaluate photopeak signals, which contain information about the full energies of characteristic γ-rays, the detector resolution and the relative radioactivity. All selected peaks were fitted with the second polynomial function for the background part and Gaussian function for the peak parts using ROOT (version 5, CERN, Switzerland).

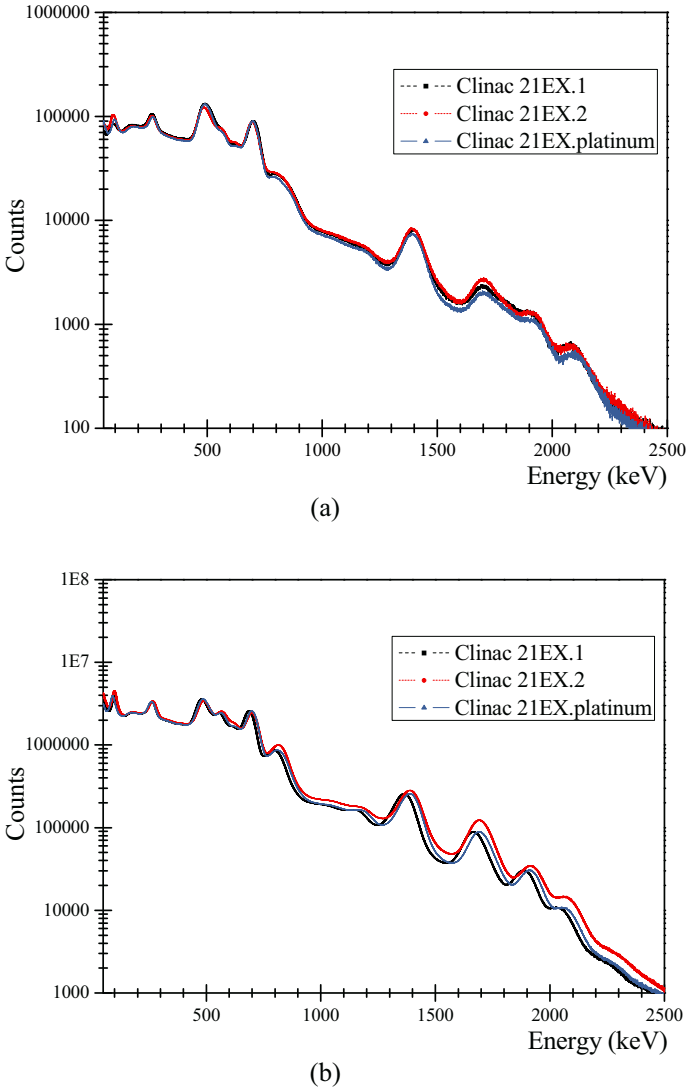

Figure 2 γ-ray spectra acquired at the heads of three LINACs : (a) one hour DAQ time, (b) 58 (Clinac 21EX.2) and 59 hours of DAQ time

Since the energy deposition efficiency in NaI-crystal detectors is dependent on the energy of incoming photons, the ratio of peak areas should be calculated according to the energy of incoming photons. The ratios of photopeak areas of γ-rays from the same isotopes can be calculated without any consideration of detection efficiency, as they are only dependent on DAQ time and the lifetime of the isotope. We acquired the γ-ray spectra for two different time scales. The spectrum measured for one hour and the spectrum measured over 59 hours DAQ time after the one hour measurement, are different shape due to the differing lifetimes of isotopes. Since the area ratio of the two photopeaks tagged with the same energy in both spectra is related to the lifetime of the

Table 2. Measured peak ratios for each LINACs

Peak	Peak Energy (keV)	Clinac21EX.1	
		59/1 ratio	Error
1	261	35.8	0.1
2	482	25.3	0.1
3	562	33.6	0.1
4	693	31.1	0.1
5	806	43.9	0.3
6	1382	35.5	0.1
7	1900	23.1	0.5
Peak	Peak Energy (keV)	Clinac21EX.2	
		59/1 ratio	Error
1	261	39.4	0.1
2	482	27.3	0.1
3	562	25.7	0.1
4	693	25.6	0.1
5	806	20.2	0.2
6	1382	36.1	0.1
7	1900	43.9	1.7
Peak	Peak Energy (keV)	Clinac21EX.p	
		59/1 ratio	Error
1	261	43.4	0.1
2	482	23.3	0.1
3	562	28.5	0.1
4	693	27.3	0.1
5	806	11.6	0.1
6	1382	36.1	0.1
7	1900	49.3	1.4
Peak	Peak Energy (keV)	Average	
		Ratio	Error
1	261	39.5	3.8
2	482	25.3	2.0
3	562	29.3	4.0
4	693	28.0	2.8
5	806	25.2	16.7
6	1382	35.9	0.4
7	1900	38.8	13.8

Isotope which corresponds to the γ-ray energy, the ratios calculated using DAQ time and lifetime may be compared with the measured ratios as shown in Table 2.

The decay rate of radioactive nuclides can be formulated as a simple exponential decay function. The ratio of photopeak areas can be simply expressed as

$$\frac{\int_{1}^{60} I(t)\,dt}{\int_{0}^{1} I(t)\,dt} = \frac{e^{-\lambda} - e^{-60\cdot\lambda}}{1 - e^{-\lambda}} \qquad (1)$$

where λ is the decay constant and $I(t)$ is the activity of the isotope at time t.

The activated nuclides were tagged by the characteristic energies of decaying γ-rays as well as the ratio of the fitted areas for full peaks. The γ-ray energies and the lifetimes of isotopes were used to identify activated nuclides in LINAC heads as shown in Table 3, where just the averaged ratios and the errors involving the ratio variations in machines are listed, since the ratios of photopeaks are independent on the machine structure and the integrated x-ray fluence.

The 261 keV peak, 482 · 693 keV peak, 562 keV peak, 806 keV peak and 1382 · 1900 keV peak were evaluated as γ-rays produced by ^{203}Pb, ^{187}W, ^{82}Br, ^{54}Mn and ^{57}Ni respectively. Due to time delays between measurements and x-ray exposures, short-lived isotopes such as ^{28}Al (2.24 min), ^{62}Cu (9.74 min) and so on were not detected.

The lifetime ratio and the photopeak area ratio in the 806 keV peak differ greatly. The width of the peak is 30 keV. It is possible that the peak is a composite of several peaks. In addition, the irregular background shape may explain the discrepancy. More study needs about the peak contamination of other induced-isotopes due to detector resolution limitation.

Table 3. Radioactive nuclides identified by γ-ray peak energies and lifetime ratios for LINAC heads

E (keV)	Candidates				photopeak area ratio (Average)
	Isotope	E (keV)	Half -life	Lifetime ratio	
261	^{203}Pb	297	51.9 h	40.6	39.5 ± 3.8
482	^{187}W	480	23.7 h	27.7	25.3 ± 2.0
562	^{82}Br	554	35.3 h	34.6	29.3 ± 4.0
693	^{187}W	686	23.7 h	27.7	28.0 ± 2.8
806	^{54}Mn	835	312 d	58.8	25.2 ± 16.7
1382	^{57}Ni	1378	35.6 h	34.7	35.9 ± 0.4
1900	^{57}Ni	1920	35.6 h	34.7	38.8 ± 13.8

B. Photopeak peak width study

In general, the energy resolution of scintillation detectors σ/E, as a function of the incoming radiation energy E, can be expressed by

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \qquad (2)$$

where the circled + represents quadratic addition, a is stochastic term determined by the fluctuation of the deposited energy; b is a "noise" term determined by the noise of the photo-receiver; and c is a constant term determined by the non uniform light output of the scintillation material [10]. The fitting parameters b and c are much smaller than a, so that they are negligible.

Since the widths of each peak are dependent on their peak energies, information about energy resolution is also helpful for the peak identification. Figure 3 shows fitting results for the peak widths corresponding to their peak energies. The fitting curve was constructed using the energy resolution relationship in Eq. 2. Some peak values disagree with the fitting curve. These differences may be due to contamination from other radioactive nuclides or background instability.

The 806 keV peak was identified as a contaminated peak considering its full peak area ratio and width. The new width values of all peaks were calculated assuming that the width error of 806 keV peak is infinite. This assumption fixed widths in peak fitting, allowing new peaks to be resolved and more reliable ratios to be achieved. Table 4 lists re-identified induced-isotopes in comparison with re-calculated

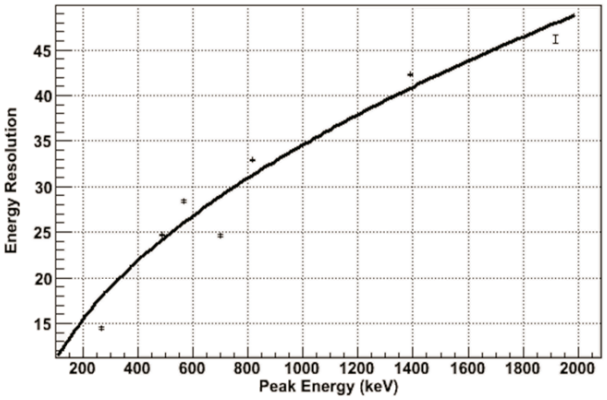

Fig. 3 Fitting parameters of peak width values (points) and fitting energy resolution curve (solid line)

photopeak area ratio with lifetime ratio. As the 806 keV peak was expressed as two peaks, the photopeak area ratios in Table 4 were more consistent with lifetime ratios than those in Table 3.

Through resolution analysis, the systematic error of the photopeak area ratio could be examined.

Table 4. Radioactive nuclide re-identified by photopeak widths

E (keV)	Candidates				Full peak area ratio
	Isotope	E (keV)	Half-life	Lifetime ratio	
262	^{203}Pb	297	51.9 h	40.6	40.3 ± 1.1
481	^{187}W	480	23.7 h	27.7	29.6 ± 1.6
567	^{82}Br	554	35.3 h	34.6	36.9 ± 1.7
695	^{187}W	686	23.7 h	27.7	27.3 ± 1.1
794	^{82}Br	777	35.3 h	34.6	31.5 ± 3.8
848	^{54}Mn ^{56}Mn	835, 847	312 d, 2.6 h	28.3*	28.5 ± 2.6
1387	^{57}Ni	1378	35.6 h	34.7	35.1 ± 0.4
1915	^{57}Ni	1920	35.6 h	34.7	39.0 ± 7.3

*: 28.3 is calculated by the ratio of 0.45: 0.55 = ^{54}Mn: ^{56}Mn

IV. Conclusion

In this study, we identified the radioactive nuclides induced by medical LINAC heads operated in high-energy photon mode. We measured the energy spectra of γ-rays from activated nuclides and compared the measured values of peak energy and half-life with them of candidates. The energy resolution was also helpful to identify by removing the interference between peaks and the irregularity of background shapes. The activated nuclides were identified as ^{203}Pb, ^{187}W, ^{82}Br, ^{54}Mn, ^{56}Mn and ^{57}Ni. Our isotope identification method, using two decay energy spectra of different DAQ times would be a reliable tool to resolve peak energy not only for inorganic scintillation detectors but also for high purity Ge detectors.

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