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MEASUREMENTS OF THERMAL AND RESONANCE NEUTRON FLUENCE AND INDUCED RADIOACTIVITY INSIDE BUNKERS OF MEDICAL LINEAR ACCELERATORS IN THE CENTER OF ONCOLOGY IN OPOLE, POLAND*

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Emission of high-energy X-ray and electron therapeutic beams from medical linear accelerators is related to undesirable neutron production and to induction of radioactivity. In this work, measurements of thermal and resonance neutron fluence and induced radioactivity were performed inside two bunkers with medical linacs — Elekta in the Center of Oncology in Opole (Poland). The bunkers differ with a construction of their walls. The neutron measurements were performed by means of the induced activity method during emission of the 18 MV X-ray beam. The investigation of radioactivity induced by neutrons was based on the method of off-line gamma-ray spectroscopy measurements. This work has shown that the differences

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in the considered construction of bunkers do not influence significantly on the thermal and resonance neutron fluence as well as on the induced radioactivity. The greatest thermal neutron fluence (1.4×10^4 cm^{-2} MU^{-1}) as well as the resonance one (0.7×10^4 cm^{-2} MU^{-1}) was measured at the isocenter of a rotation of the accelerator head. The radioisotopes of ^{187}W, ^{56}Mn, ^{24}Na and ^{82}Br originating from the (n, γ) reactions were identified in the spectral measurements.

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1. Introduction

Contemporary medical linear accelerators applied in radiotherapy generate X-ray and electron beams with energies up to 20 MeV. Gammas and electrons of the therapeutic beams induce photonuclear and electronuclear reactions, in which neutrons are produced. The neutrons are undesirable in the X-ray/electron beam treatment. They are a contamination of therapeutic beams. The cross sections of photonuclear reactions [1] are about three orders of magnitude greater than those of electronuclear reactions [2] in the range of energies generated by therapeutic linacs. Therefore, the problem of the neutron contamination is particularly significant for therapeutic X rays [3, 4]. The main neutron sources are massive components of an accelerator head [5]. The produced neutrons have a broad energy spectrum with the high-energy end at more than 10 MeV [6]. In the concrete walls, ceiling and floor of the radiotherapy facility, the neutrons undergo elastic collisions with nuclei of hydrogen and lose their energy. The slowed-down neutrons may get out of the concrete and return to air, contributing to the specific distribution of neutron energy inside an accelerator bunker. The slowed-down neutrons induce simple capture reactions (n, γ) in the thermal and resonance energy range [7, 8]. In these reactions, radioisotopes are produced in objects located in the accelerator bunker [9–12]. The radioisotopes are also produced directly in photonuclear and electronuclear reactions. The purpose of this work was the measurement of the thermal and resonance neutron fluence inside two bunkers differing in the thickness of walls and materials used in their construction. The measurements were performed during emission of the high-energy 18 MV X-ray therapeutic beam from the new medical linear accelerator Elekta. Additionally, gamma-ray spectra were measured in the vicinity of the accelerators, to provide the empirical evidence that radioisotopes are produced in neutron reactions in components of the Elekta. The knowledge of the slowed-down neutron level and investigations of the induced radioactivity are significant for radiological protection of staff in medical centers. The measurements were performed in the Center of Oncology in Opole, Poland.

2. Materials and methods

The measurements of the thermal and resonance neutron fluence were carried out by means of the induced activity method, in which the dependence between the neutron activation detector activity and the thermal/resonance neutron fluence is applied. The neutron activation detectors were foils made of natural indium. The activated isotope was ^{115}In with abundance of 96%. Isotope ^{115}In has a (n, γ) cross section of 160 b for thermal neutrons, the high resonance of about 28000 b at 1.45 eV and a number of lower resonances yielding the resonance activation integral of 2700 b. The thermal and resonance neutrons activate the indium according to the following reaction: $^{115}\mathrm{In}(n, \gamma)^{116m}\mathrm{In}$. The unstable ^{116m}In disintegrates by β^- decay into the exited $^{116}\mathrm{Sn}^*$ producing gamma rays. The gamma-ray spectra from de-excitation of $^{116}\mathrm{Sn}^*$ were measured with use of a high-purity germanium detector by ORTEC. The activity of the indium foil was determined by net area of the photopeak at 1293.5 keV, using the calibration factor determined by means of a commercial ^{60}Co source. The cadmium cover method was applied to separate the thermal neutron fluence from the resonance neutron one. In this method, the measurement is performed twice in each measuring location *i.e.* using the indium foil placed in the 1 mm thick cadmium shield and without the shield. The cadmium shield absorbs almost all thermal neutrons but it lets through most of the resonance ones. The indium foil activity caused by the resonance neutrons is a product of the activity of the foil that was in the cadmium shield during the neutron measurement and the correction for the resonance neutron absorption in cadmium. The difference between the activity induced in the uncovered foil and the indium foil activity caused by the resonance neutrons provides information about the activity induced by the thermal neutrons. The details of the applied method were presented in [13]. The measurement locations are marked in Fig. 1.

The neutron measurements were performed in two bunkers during emission of the therapeutic 18 MV X-ray beam generated by the same type of the linac — Elekta. In this paper, the bunkers are called bunker 1 and bunker 2. Bunker 1 has concrete walls with a slab of lead. The thickness of the walls is 150 cm except for the 180 cm thick wall 1. Bunker 2 has thinner walls because it has been used for a cobalt apparatus and adapted for a high-energy X-ray linac. Bunker 2 has concrete walls of 94 cm to 98 cm, except for the 143 cm thick wall 1, in which a 210 cm × 330 cm × 11 cm steel plate is installed to increase absorption of gamma radiation. The measurements of the induced radioactivity were carried out by means of a high-purity germanium detector used also for the determination of the indium foil activity. The identification of the produced radioisotopes was based on the knowledge of materials applied in the construction of the considered linacs. The tables of isotopes [14] were used in this analysis.

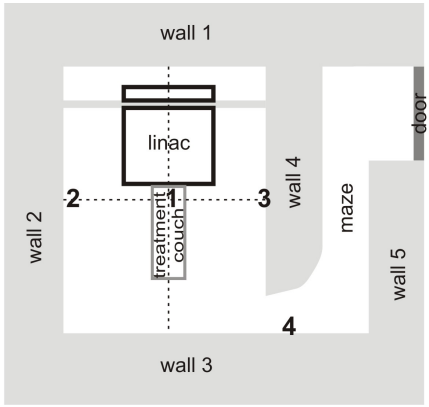

Fig. 1. The numbered locations of indium foils inside the bunker during measurements. The place 1 corresponds to the isocenter of the accelerator head rotation. In this location, the foils were placed on the surface of the treatment couch. In the remaining locations, the foils were placed on walls at about 1.0 m over the floor or on the shelf (bunker 1). The shelf was hanged on the wall 2 in the case of bunker 1 and on the wall 1 in the case of bunker 2.

3. Results and discussion

3.1. Neutron measurements

Comparison of the thermal and resonance neutron fluence is presented in Table I. The determined fluences were normalized to a monitor unit (MU). 1 MU corresponded to 1.004 cGy of a dose at the reference depth of 10 cm in water for the therapeutic 18 MV X-ray beam.

TABLE I

The thermal neutron fluence (ϕ_{ther}) and the resonance neutron fluence (ϕ_{res}) normalized to 1 MU.

	$\phi_{\text{ther}}\ 10^4$ [$\text{cm}^{-2}\,\text{MU}^{-1}$]		$\phi_{\text{res}}\ 10^4$ [$\text{cm}^{-2}\,\text{MU}^{-1}$]	
Measuring place	Bunker 1	Bunker 2	Bunker 1	Bunker 2
1	1.4	1.4	0.7	0.7
2	0.5	0.3	0.2	0.2
3	0.5	0.5	0.2	0.2
4	0.3	0.2	0.1	0.1

Similar values of the resonance neutron fluence were measured in both bunkers in all measuring places. In the case of thermal neutrons, the difference in the measured fluence is visible in the locations 2 and 4. The difference

observed in the location 2 can be caused by the shelf hanged on the wall 2 in bunker 1 whereas in bunker 2 the shelf was hanged on the wall 1 with no measuring place. The greatest thermal and resonance neutron fluence was measured at the isocenter. The uncertainty in the determined neutron fluences does not exceed 20% when the foils have been exposed to neutrons for 14 minutes (7000 MU) for the maximal efficiency of accelerators *i.e.* for 500 MU per minute. The main source of this uncertainty is the random error in the determination of the foil activity.

3.2. Induced radioactivity measurements

An example of a spectrum measured at the isocenter in bunker 1 after emission of 18 MV X rays is presented in Fig. 2. The similar spectrum was measured in bunker 2. In the vicinity of the isocenter, technicians preparing a radiotherapy treatment spent a lot of time. The identified radioisotopes of ^{187}W, ^{56}Mn, ^{24}Na and ^{82}Br indicate that simple capture reactions occur in the accelerator components. The photopeaks at 846.8 keV, at 1810.8 keV and at 2113.1 keV (Fig. 2) are a result of the decay of ^{56}Mn (a β^- decay, half-life $T_{1/2} = 2.58$ h). This radioisotope originates from the reaction: $^{55}\mathrm{Mn}(n,\gamma)^{56}\mathrm{Mn}$. Manganese is a fundamental component of stainless steel used in constructions of accelerators. The observed photopeaks at 479.5 keV, 618.4 keV and 685.8 keV are a consequence of the decay of the ^{187}W (a β^- decay, $T_{1/2} = 23.7$ h) nuclei originating from the reaction:

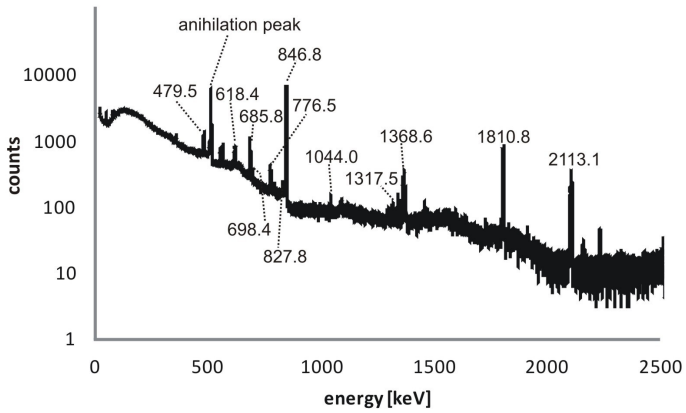

Fig. 2. The spectrum measured at the isocenter of the Elekta accelerator in bunker 1. The measurement was carried out by means of a high-purity germanium detector immediately after emission of the therapeutic 18 MV X-ray beam. The photopeaks denoted by energy (in keV) come from gammas emitted by radioisotopes originated from the simple capture reactions induced by thermal and resonance neutrons in components of the accelerator.

$^{186}W(n,\gamma)^{187}W$. Tungsten is applied in the collimation systems of a beam. The identified radioisotope of ^{24}Na ($T_{1/2}$ = 14.95 h) gives the photopeak at 1368.6 keV. It originates from the reaction: $^{23}Na(n,\gamma)^{24}Na$. Sodium is used in outer casing materials. The photopeak at 776.5 and several ones with small intensity (at 698.4 keV, 827.8 keV, 1044.0 keV and 1317.5 keV) originate from the reaction: $^{81}Br(n,\gamma)^{82}Br$ (a β^- decay, $T_{1/2}$ = 35.3 h). Bromine is added to materials of electronic modules of the linac. The remaining peaks visible in Fig. 2 are the escape/summation ones. The clear influence of the construction of bunkers on the gamma-ray spectra was not observed.

4. Conclusions

The differences in the constructions of considered bunkers do not influence on the thermal and resonance neutron fluence as well as on the measured gamma-ray spectra. The measured thermal/resonance neutron fluences are of the same order of magnitude as those for X-ray beams with the similar nominal potential from medical linacs by other manufacturer [13, 15]. The radioisotopes identified in this work appear also in massive components of other types of medical linacs [9–12]. The presented results can be used by constructors of therapeutic linacs for a reduction in the neutron and gamma radiation in bunkers which is significant to take the ALARA principle into consideration in all aspects with respect to minimizing the radiation dose to personnel operating medical linacs.

REFERENCES

[1] S.S. Dietrich *et al.*, *At. Data Nucl. Data Tables* **38**, 199 (1988).
[2] A. Polański *et al.*, *Prog. Nucl. Energ.* **78**, 1 (2015).
[3] A. Konefał *et al.*, *Phys. Med.* **24**, 212 (2008).
[4] K. Polaczek-Grelik *et al.*, *Appl. Radiat. Isot.* **68**, 763 (2010).
[5] X.S. Mao *et al.*, *Health Phys.* **72**, 524 (1997).
[6] H.R. Vega-Carrillo *et al.*, *J. Rad. Nucl. Chem.* **287**, 323 (2011).
[7] A. Konefał *et al.*, *Nukleonika* **50**, 73 (2005).
[8] A. Konefał *et al.*, *Radiat. Prot. Dosim.* **162**, 197 (2014).
[9] A. Konefał *et al.*, *Radiat. Prot. Dosim.* **128**, 133 (2008).
[10] K. Polaczek-Grelik *et al.*, *Appl. Radiat. Isot.* **70**, 2332 (2012).
[11] M. Janiszewska *et al.*, *Strahlenther Onkol.* **190**, 459 (2014).
[12] H.R. Vega-Carrillo *et al.*, *Appl. Radiat. Isot.* **102**, 103 (2015).
[13] A. Konefał *et al.*, *Rep. Pract. Oncol. Radiother.* **17**, 339 (2012).
[14] Tables of isotopes, version 1.0, edited by Firestone, 1996.
[15] Wen-Shan Liu *et al.*, *Rad. Phys. Chem.* **80**, 917 (2011).