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Measurements of neutron radiation and induced radioactivity for the new medical linear accelerator, the Varian TrueBeam

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HIGHLIGHTS

- The investigation of secondary radiation was performed for the new medical accelerator, the Varian TrueBeam.
- Secondary neutrons were measured using a helium chamber and the induced activity method.
- The identification of produced radioisotopes was based on measurements of the gamma spectra.
- The correlation between the neutron fluence and the mode and energy of the therapeutic beam was observed.
- 11 radioisotopes resulting from the neutron production were identified.

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ABSTRACT

Contemporary linear accelerators applied in radiotherapy generate X-ray and electron beams with energies up to 20 MeV. Such high-energy therapeutic beams induce undesirable photonuclear (γ,n) and electronuclear (e,e'n) reactions in which neutrons and radioisotopes are produced. The originated neutron can also induce reactions such as simple capture, (n,γ), reactions that produce radioisotopes. In this work measurements of the non-therapeutic neutrons and the induced gamma radiation were carried out in the vicinity of a new medical accelerator, namely the Varian TrueBeam. The TrueBeam is a new generation Varian medical linac making it possible to generate the X-ray beams with a dose rate higher than in the case of the previous models by Varian. This work was performed for the X-ray beams with nominal potentials of 10 MV (flattening filter free), 15 MV and 20 MV, and for a 22 MeV electron beam. The neutron measurements were performed by means of a helium chamber and the induced activity method. The identification of radioisotopes produced during emission of the therapeutic beams was based on measurements of the energy spectra of gammas emitted in decays of the produced nuclei. The gamma energy spectra were measured with the use of the high-purity germanium detector. The correlation between the neutron field and the mode and nominal potential was observed. The strongest neutron fluence of 3.1×10^6 cm^{-2} Gy^{-1} and 2.0×10^6 cm^{-2} Gy^{-1} for the thermal and resonance energies, respectively, was measured during emission of the 20 MV X-ray beam. The thermal and resonance neutron fluence measured for the 15 MV X-rays was somewhat less, at 1.1×10^6 cm^{-2} Gy^{-1} for thermal neutrons and 6.7×10^5 cm^{-2} Gy^{-1} for resonance neutrons. The thermal and resonance neutron fluences were smallest for the 10 MV FFF beam and the 22 MeV electron beam and were around two orders of magnitude smaller than those of the 20 MV X-ray beam. This work has shown that the neutron reactions are dominant because of relatively high cross sections for many elements used in the accelerator construction. The detailed analysis of the measured spectra made it possible to identify 11 radioisotopes induced during TrueBeam delivery. In this work the following radioisotopes were identified: ^{56}Mn, ^{122}Sb, ^{124}Sb, ^{131}Ba, ^{82}Br, ^{57}Ni, ^{57}Co, ^{51}Cr, ^{187}W, ^{24}Na and ^{38}Cl.

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1. Introduction

Contemporary linear accelerators applied in radiotherapy generate X-ray and electron beams with energies up to 20 MeV (Sheikh-Bagheri and Rogers, 2002; Francois et al., 1997). Such energies are enough to induce undesirable photonuclear (γ,n) and electronuclear (e,e'n) reactions in which neutrons and radioisotopes are produced (Chen et al. 2006; Konefał et al. 2008a; Mesbahi, 2009; Polaczek-Grelik et al. 2012; Thomadsen et al. 2014). These reactions occur with a therapeutic beam. The photonuclear cross section has a resonance character. Its maximum value depends on an atomic number and it is in the range from several millibarns for light nuclei to several hundred millibarns for heavy nuclei (Dietrich and Bermab, 1988; Naseri and Mesbahi, 2010). Moreover, the maximum photonuclear cross section corresponds to a gamma energy of about 22 MeV for light nuclei and about 12 MeV as the atomic number increases. Therefore, the main neutron sources are massive components of an accelerator head (Mao et al. 1997). The energy threshold of the photonuclear reactions is about 8 MeV for most isotopes. In the case of the therapeutic electron beams the majority of neutrons is produced in the collimation system, applicators and scattering foils. The cross sections of electronuclear reactions are about three orders of magnitude less than those for photonuclear reactions in the range of energies generated by medical linacs (Scott et al. 1955; Polański et al. 2015). Therefore, the problem of the neutron and radioisotope production is particularly significant for therapeutic X-ray beams. The produced neutrons have a broad energy spectrum with a high-energy endpoint of greater than 10 MeV (Facure et al. 2005; Esposito et al. 2008; Amgarou et al. 2011; Vega-Carrillo and Baltazar-Raigosa, 2011; Chu et al. 2011). The majority of the neutrons reach the concrete walls, ceiling and floor of the radiotherapy facility. In the concrete the neutrons undergo elastic collisions with nuclei of hydrogen and they lose their energy. The slowed down neutrons may escape from the concrete and return to air, contributing to the specific distribution of neutron energy inside a radiotherapy facility (Konefał et al. 2005; Polaczek-Grelik et al., 2010; Wen-Shan Liu et al 2011a,b). The slowed down neutrons can easily induce the simple capture reactions (n,γ) in the thermal and resonance energy range and additional radioisotopes are produced (Konefał et al. 2008a; Polaczek-Grelik et al. 2012; Janiszewska et al. 2014; Konefał A et al. 2014, Thomadsen et al. 2014).

The TrueBeam accelerator is a new generation medical linac. This linear accelerator makes it possible to generate the X-ray beams with a dose rate higher than in the case of the previous models by Varian. The dose rate increase was reached by changes in the treatment head construction. The purpose of this work was to check if these changes affect the induced activity and the neutron field. The neutron radiation level and the radioisotopes induced during emission of the therapeutic beams from the TrueBeam were compared with those for Clinacs - the older type of accelerators by Varian. Additionally, the detailed information about the cross sections of the identified nuclear reactions was presented in this paper. The included data are significant for manufacturers of medical linacs and for the radiological protection of staff in medical centers (Guo and Ziemer, 2004).

2. Materials and methods

The TrueBeam studied for this work can generate five X-ray beams and six electron beams. This work was performed for the beams capable of generating nuclear reactions, i.e., X-ray beams with nominal accelerating potentials of 10 MV (flattening-filter-free), 15 MV, 20 MV, and the 22 MeV electron beam. The choice of the beams was made taking into account their maximal energy and cross sections of the neutron production in materials of the TrueBeam head. In the case of the chosen X-ray beams the high-energy end of their spectra is above the energy threshold of the photonuclear cross sections for all of the main materials used in the accelerator head.

2.1. Neutron measurement methods

The neutron fluence was measured at the measurement locations denoted in Fig. 1. These measurements were performed by means of the commercial helium chamber with an 8 cm active length and with a gas pressure of 2 atm (additional equipment for the InSpector1000 detection system by Canberra). The helium chamber was used outside a therapeutic beam. The helium chamber was connected to the InSpector1000 digital handheld multichannel analyzer. The sensitivity of this system was about 1% for an unmoderated ^{252}Cf fast neutron source. The helium chamber also provides information about the thermal neutron flux because the signal produced in the chamber is a sum of signals from recoil protons and products of the reactions of the slowed down neutrons with nuclei of ^{3}He: n(^{3}He,p)^{3}H.

In this work the helium chamber was used to obtain the relative neutron flux in the measurement location for a comparison of the neutron fields associated with the chosen therapeutic beams. The determination of the absolute neutron flux needs an effective calibration based on the knowledge of the absolute neutron spectrum. This information was unavailable. However, the absolute neutron fluence was determined in the thermal and resonance energy range. The thermal and resonance neutron fluence was measured by means of the induced activity method. This method was applied for the neutron measurements inside a therapeutic beam. The indium foils (^{115}In) in the shape of a circle with a radius of 0.75 cm and with the detector material thickness of 98–110 mg/cm^2 were the activated material. The foils were inside a 1 cm × 1 cm paper cover shielding the foil against mechanical damage. Indium can be activated by thermal and resonance neutrons in the following reaction:

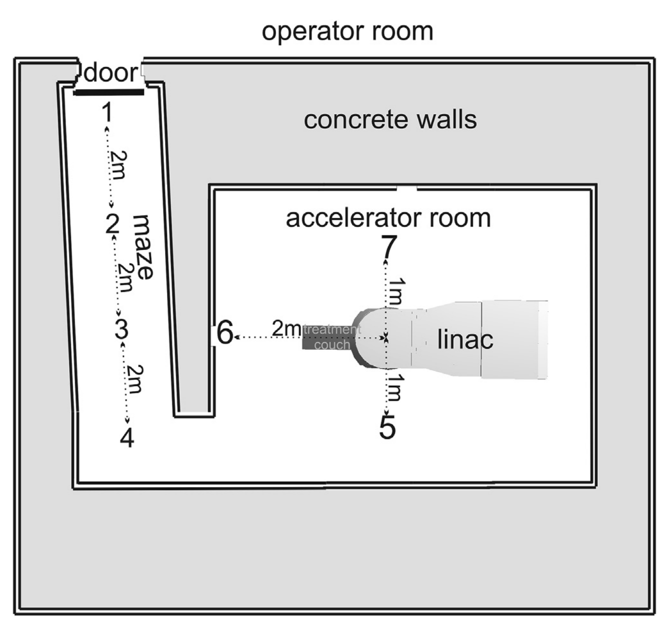

Fig. 1. The schematic of the treatment room with the numbered measurement locations for measurements with the use of the helium chamber.