TEST OF PRODUCTION OF ^{99}Mo/^{99m}Tc BY MEANS OF TYPICAL MEDICAL LINEAR ACCELERATORS USED IN TELERADIOTHERAPY*

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The test of production of the ^{99}Mo/^{99m}Tc complex by means of Varian medical linear accelerators used in teleradiotherapy was performed. The targets made of the natural molybdenum were irradiated by high-energy therapeutic 20 MV X-ray beam. ^{99}Mo was produced mainly in the photonuclear reaction of ^{110}Mo$(\gamma, n)^{99}$Mo. The obtained specific activities are relatively small in the saturation state (from 155.4 kBq/g to 163.2 kBq/g) because only the high-energetic part of the spectrum of 20 MV X-ray beam covers the energy range of the ^{110}Mo$(\gamma, n)^{99}$Mo reaction cross section. The new application of the ^{99}Mo/^{99m}Tc complex of the low activity was suggested using the molybdenum nanoparticle technology.

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1. Introduction

Most of the radiopharmaceuticals used nowadays are based on ^{99m}Tc. The main sources of the ^{99}Mo/^{99m}Tc complex are nuclear reactors [1]. The main advantage of using reactors to produce ^{99}Mo/^{99m}Tc generators is a very intense neutron flux. However, in the last decade, several independent reactor shutdowns and outage extensions significantly disrupted global ^{99}Mo supplies. These unplanned events, combined with other planned outages created a worldwide ^{99}Mo supply crisis. Therefore, new methods of production of technetium are required. The methods based on cyclotrons [2, 3] and dedicated electron linear accelerators [4, 5] are used more and more often.

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The aim of this work was to test a possibility of ^{99}Mo/^{99m}Tc production by means of the Varian medical linacs used in teleradiotherapy. The targets made of the natural molybdenum were irradiated by a high-energy therapeutic 20 MV X-ray beam. The ^{99}Mo radioisotope can be produced in the photonuclear reaction: $^{110}\mathrm{Mo}(\gamma, n)^{99}\mathrm{Mo}$ induced by gammas of the therapeutic beam. The reactions: $^{110}\mathrm{Mo}(n, 2n)^{99}\mathrm{Mo}$ induced by fast neutrons and $^{98}\mathrm{Mo}(n, \gamma)^{99}\mathrm{Mo}$ were also considered. The neutrons are a contamination of the therapeutic X rays. They originate from the photonuclear reactions occurring mainly in the massive components of the medical accelerator head [6–8]. The irradiations were performed at the Maria Skłodowska-Curie Memorial Cancer Centre and Institute of Oncology in Gliwice (Poland). The activities of the produced radioisotopes were measured at the Department of Nuclear Physics and Its Applications of the Institute of Physics of the University of Silesia in Katowice (Poland).

2. Materials and methods

The molybdenum targets of the 1 cm × 1 cm × 1 mm size were located on the accelerator window during irradiation. In such location, the molybdenum target is irradiated by gammas and neutrons. As the performed simulations showed, the gamma flux was 10^{10} cm^{-2}s^{-1} whereas the neutron flux was 10^5 cm^{-2}s^{-1} in the target for the maximal efficiency of the accelerators. The gamma energy spectra and those of neutrons at the accelerator window are presented in Fig. 1. The cross sections for the possible reactions in which the ^{99}Mo radioisotope can be produced are shown in Fig. 2. The activities of the produced radioisotopes of ^{99}Mo and ^{99m}Tc were determined using the energy spectra of gammas emitted by these radioisotopes. The spectra were measured by means of the Ge(Li) semiconductor detector. The efficiency calibration of the detector was performed with the use of the commercial sources of ^{152}Eu and ^{133}Ba. The activity of ^{99}Mo was determined on the base of the net area of the photopeak at 181.1 keV, whereas that of ^{99m}Tc was related to the photopeak at 140.5 keV.

The radioisotope of ^{99}Mo originates mainly from the $^{110}\mathrm{Mo}(\gamma, n)^{99}\mathrm{Mo}$ reaction because the photon flux at the target is 5 orders of magnitude greater than the neutron flux. The $^{110}\mathrm{Mo}(n, 2n)^{99}\mathrm{Mo}$ reaction is of minor importance, because at the target only 0.4% of all neutrons have energy greater than 8 MeV. The contribution of thermal neutrons is also small. The thermal neutrons constitute 27% of all neutrons at the target. However, the maximum cross section of the $^{98}\mathrm{Mo}(n, \gamma)^{99}\mathrm{Mo}$ reaction is about 6 times lower than the maximum photonuclear cross section of the $^{110}\mathrm{Mo}(\gamma, n)^{99}\mathrm{Mo}$ reaction (253 mb). This observation was verified experimentally by the comparison of the ^{99}Mo activities induced in the photon and neutron field and in the neutron field exclusively.

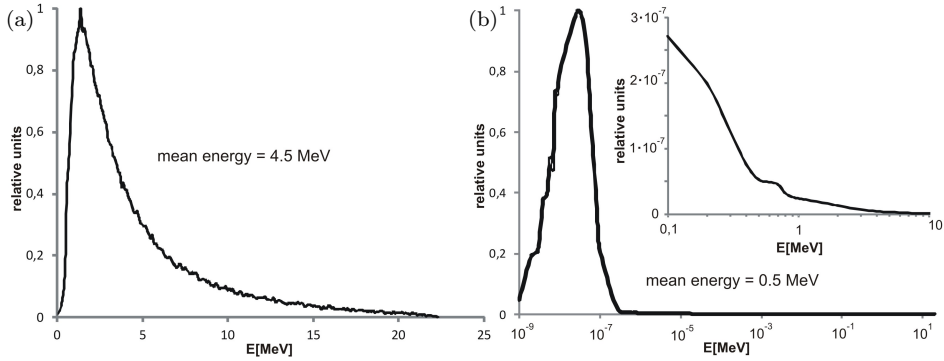

Fig. 1. (a) The gamma energy spectrum of the therapeutic 20 MV X-ray beam used in this work. (b) The energy spectrum of neutrons originating from photonuclear reactions induced by the mentioned therapeutic X rays. The zoom of the spectrum in the energy range from 0.1 MeV to 10 MeV is presented in the insert. The spectra were derived from the Monte Carlo simulations based on the Geant4 code.

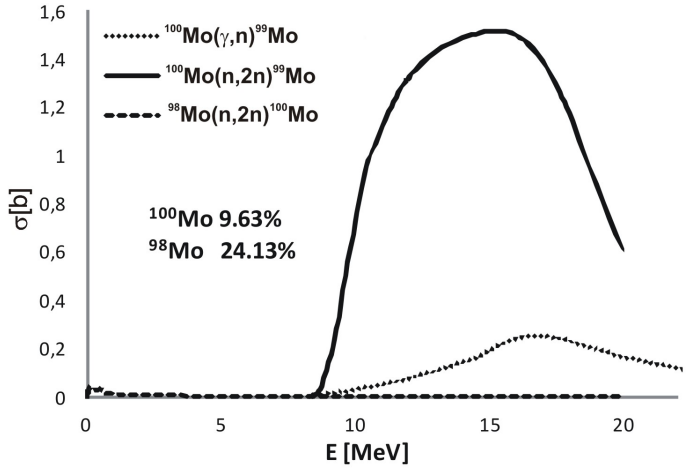

Fig. 2. The cross sections of the following reactions: $^{110}\mathrm{Mo}(\gamma, n)^{99}\mathrm{Mo}$, $^{110}\mathrm{Mo}(n, 2n)^{99}\mathrm{Mo}$ and $^{98}\mathrm{Mo}(n, \gamma)^{99}\mathrm{Mo}$ considered as possible ways of production of ^{99}Mo (from the ENDF data base).

3. Results and discussion

The molybdenum targets were irradiated by means of the therapeutic 20 MV X rays from two Varian linear accelerators: Clinac 2300 and TrueBeam. The irradiation time was between 10 and 20 minutes. The irradiations were carried out under various conditions. The irradiation conditions differed in a radiation field size and a location of the target in relation to the

central axis of the beam. The radiation fields determined at SSD = 100 cm were 3 cm × 3 cm, 10 cm × 10 cm and 40 cm × 40 cm. The irradiations were performed using the mode with the maximal efficiency of 600 monitor units (MU) per minute. 1 MU corresponded to 1 cGy of the therapeutic X-ray dose at the reference depth of 10 cm in water. The exemplary gamma-ray spectrum for the irradiated molybdenum target is presented in Fig. 3.

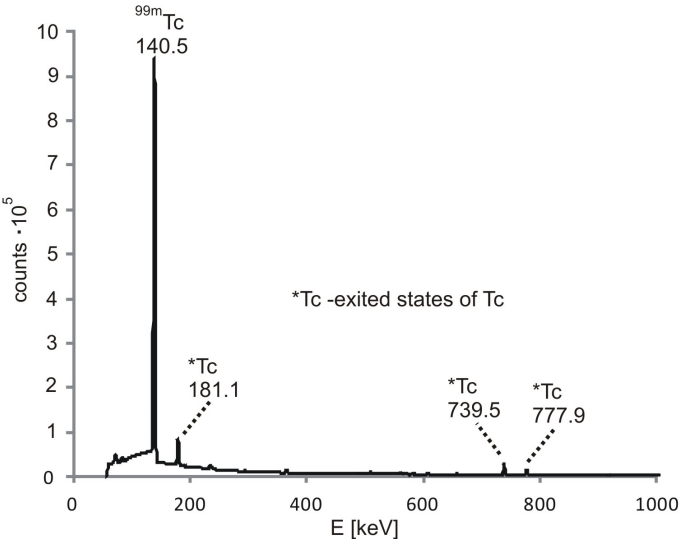

Fig. 3. The gamma-ray spectrum for the natural molybdenum target irradiated by means of the therapeutic 20 MV X-ray beam from the medical linear accelerator (TrueBeam). The photopeaks from the decays of ^{99}Mo are denoted. Duration of the spectrum measurement was 260 h (Ge(Li) detector).

The saturation curves were determined for the targets irradiated under various conditions. The chosen saturation curves determined on the base of the activities of the produced ^{99}Mo radioisotope are presented in Fig. 4. Obviously, the activity of ^{99m}Tc is equal to the activity of ^{99}Mo in the saturation state. In general, the differences between the saturation curves obtained under the various irradiation conditions are small, *i.e.* the specific activities in the saturation state differ by less than 3%. The saturated specific activities fall in the range of 155.4 kBq/g–163.2 kBq/g and their uncertainties are less than 1%. An attempt to increase the induced activity was carried out by means of the 5 cm thick slab of lead located behind the molybdenum target in the X-ray beam: the slab was an additional source of fast neutrons originating from photonuclear reactions with nuclei of lead. It made it possible to increase significantly (by 50%) the activity of ^{99}Mo. The details of this approach will be presented in the subsequent paper.

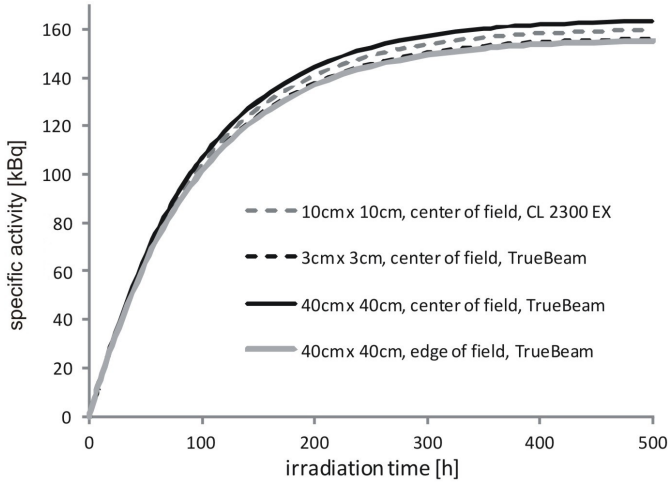

Fig. 4. The saturation curves determined for the produced radioisotope of ^{99}Mo, for various irradiation conditions.

Though the obtained specific activities are too small for the tested method to be applied in the large scale production of the $^{99}Mo/^{99m}Tc$ generator, however, one can consider a novel application of the described method in the radiotherapy treatment based on a use of nanoparticles. Many studies indicate that the dose enhancement is obtained when the high atomic number metal nanoparticles are introduced to a target volume [9, 10]. This dose enhancement is caused by the increase of the photoelectric effect due to irradiation with the therapeutic megavoltage X rays. The methods for the synthesis of Mo nanoparticles are already well-known [11–17]. Such nanoparticles are used in lithium-ion batteries [18], hydrogen evolution catalysis [19], transistors [20], photodetectors [21], sensors and biosensors [22, 23] and memory devices [24], *etc.* We suggest a new application of the nanoparticles with the radioactive molybdenum of ^{99}Mo as an additional dose enhancement tool. The local dose enhancement is expected to be caused not only by photons from the disintegration of the excited state of ^{99}Tc but also by electrons from the β^- decay of ^{99}Mo. Additionally, the radioactive molybdenum will be produced during irradiation of a patient. In such therapy, the dose enhancement depends on many factors: a concentration of nanoparticles, an activity of the radioisotope, a time of irradiation, a distribution of nanoparticles in a target volume, *etc.* In the suggested method, a dose is delivered even after the irradiation séance, however, due to the relatively low energy of photons and the low activity of the radioisotopes, it does not cause a radiological risk. We believe that suggested in this work application of ^{99}Mo as a dose enhancement tool is worthy of consideration but requires further investigation.

4. Conclusions

A long time of irradiation of the target (about several hundred hours) is needed to obtain the saturation state due to a relatively long half-life of ^{99}Mo (65.9 h). The radioisotopes with shorter half-lives reach the saturation state in a shorter irradiation time and generally, the obtained specific activities are greater. The relatively small activities of ^{99}Mo were obtained, because only 16% of photons from the 20 MV X-ray beam have sufficiently high energy to cause the $^{110}\mathrm{Mo}(\gamma, n)^{99}\mathrm{Mo}$ reaction. In order to obtain greater activities, beams with higher energies have to be used because the mean energy of the beam should be close to that related to the maximum of the photonuclear cross section. Attempts to increase the induced activity of ^{99}Mo are in progress.

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