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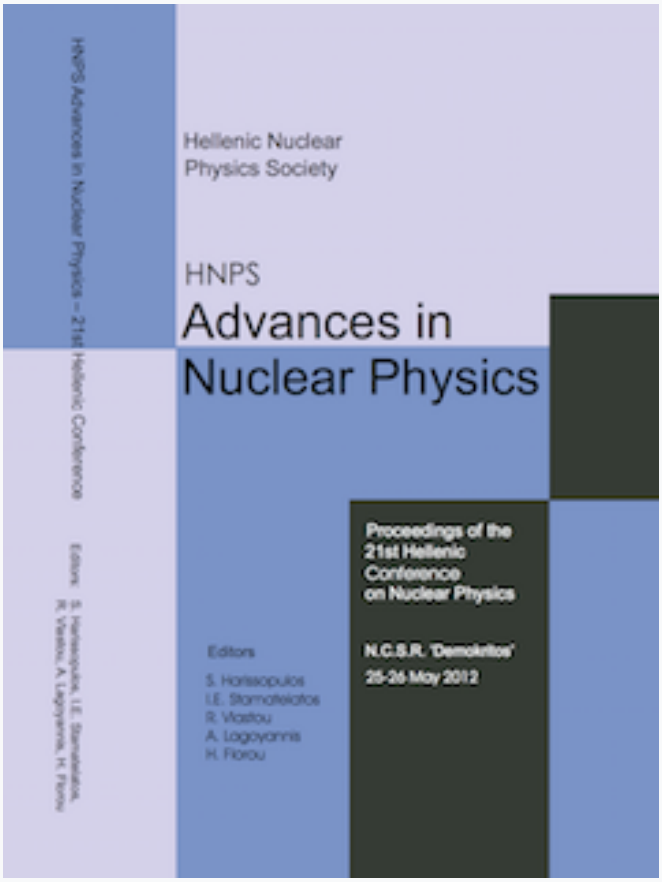

Induced Radioactivity in Medical Accelerators

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Abstract

Radiation-induced activation of patients and materials in radiotherapy treatment rooms may result in occupational radiation hazards due to in-room induced activity. Induced activation following 18 MV X-ray irradiations was assessed during commissioning and use of a medical linear accelerator at Ioannina University Hospital. Measurements were carried out using hand-held instruments at twenty locations in the accelerator bunker (three portable dose rate meters, a contamination meter were used). Temporal ambient dose rate data fitted with exponential functions and coupled with *in situ* spectroscopic data were used to characterize the post-irradiation field and develop detailed and practical site-specific work-plans to keep personnel doses secondary to radiotherapy as low as reasonably practical. The application of the suggested work-plans kept occupational exposure at very low levels during the first 2 y of clinical use of such beams.

Key words: Activation, linear accelerator, radiation therapy

1. Introduction

Radiation therapy is mostly carried out with high X-rays beams produced by electron accelerators. However, photonuclear threshold energies for most elements are between 8 and 20 MeV [1]. Therefore, accelerators operated at 8 MeV or higher for medical purposes, cargo inspection or other purposes, and mostly those operated above 15 MV, result in delayed nuclear activation of the treatment room mainly by photonuclear reactions in the target, the beam flattening filter, the primary and the secondary collimator as well as by interactions with matter of neutrons produced mainly by (γ,n) reactions with an average neutron energy of 1.0 -1.5 MeV [2,3]. The thus formed radioactive reaction products cause extra radiation dose to both patients and personnel.

The main sources of delayed radiation in medical linear accelerators (linacs) are the accelerator itself (e.g. target, bending magnets, flattening filter, collimators, treatment head shielding), the patient and his support system, the ambient air in the treatment room and any other material present in the room during irradiation, as well as the structural components of the bunker. The type of the radionuclides and their activity depend mainly on accelerator type, beam characteristics and room design and construction. For example, (γ,n) reactions in air, patient's body and target, result in the production among others of the short-lived neutron-deficient β^+ emitters ^{14}N, ^{15}O and ^{62}Cu, with energy thresholds of 10.6, 15.7 and 10.8 MeV, respectively [1,4-6]. Thermal neutron capture in materials, such as Al, Mn and W form mainly β^- emitters, such as ^{28}Al, ^{56}Mn and ^{187}W [4-6], that decay half-lives of 2.24 min, 2.56 h and 24 h, respectively. Fast neutron reactions may also result in formation of radionuclides, such as ^{24}Na and ^{56}Mn [4-6]. Thus the in-room radioactivity gradually accumulates resulting mainly in the emission of β- and γ- rays, which present an occupational hazard to those present in the room.

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The increase of patient radiation exposure due to activation is negligible compared to the therapeutic one. However, the decay of activation products may result in substantial internal and external occupational exposure to personnel entering the accelerator bunker, on-top to the one related to radiation leakage from the bunker shielding, while outside the treatment room. For example, radiation therapy technicians have to enter the bunker shortly after patient irradiation to facilitate his exit from the treatment room and the set-up the next patient to be treated, when some of the short-lived activation products have not yet decayed sufficiently. Some investigators [5, 6] assuming realistic working scenarios estimated 0.5 to 7 mSv annual doses to operators of modern 15 to 18 MV linacs, due to external irradiation with penetrating γ-rays related to their work inside the bunker under "beam OFF" conditions, neglecting their skin and eye lens doses by beta particles and doses due to inhalation ^{14}N, ^{15}O and ^{41}Ar, often considered to be of minor importance [7].

The purpose of the present study was to indentify the activation products and measure the dose rates at various locations in the bunker of a linear medical accelerator from induced activation following 18 MV X-ray irradiations. Accelerators providing other types of therapeutic beams, such as proton, heavy ion and neutron beams were not studied.

2. Material and methods

During commissioning at the Ioannina University Hospital (IUH) of a 20 MeV Clinac 2100 DHX linac by Varian equipped with a multileaf collimator and a portal inager, delayed activation was studied experimentally at twenty locations in the treatment room. The accelerator that produces both photon (6 and 18 MV) and electron beams (up to 20 MV), was installed in a ground floor bunker made of concrete and iron. Taking into account that shielding materials of the treatment unit, the main treatment room and its bunker are optimized for X-rays and inadequate to neutrons in some locations, extra neutron attenuating and capturing materials were installed in the maze and in the bunker door located at the outer maze entrance, thus made of 10 cm-thick boronated polyethylene plates and lead plates of 1.0 cm total thickness. Room ambient air was exchanged 12 times per hour, using a forced ventilation system with entrance of outdoor air, separate from that of the remaining hospital.

Successive measurements were carried out with three hand-held survey meters after the termination of 18 MV X-ray irradiations. One of the survey meters used, a IdentiFinder N by Target, was equipped with a GM detector and 3 cm x 4 cm NaI(Tl) scintillator allowing gross *in situ* γ-spectroscopy. For simplicity reasons all ambient dose rate values given in the present study refer to 20 s - long 10 cm x 10 cm irradiations at a 300 MU/min rate, resulting in open fields in a 3.0 Gy/min dose rate in water at 1.0 m distance from the target, made of W and Cu. The measured H*(10) rate data at each location were fitted by a number of exponential components to assess the corresponding half-lives The activation products of radiological interest were identified combining the spectroscopic data with the exponential components. A contamination monitor was also used to check for beta particles, which may contribute substantially to occupational shallow dose.

Dose rate measurements were also carried out during the clinical use of the linac using survey meters. These measurements were combined with long-term environmental and personnel dose measurements. Among others, personnel badges containing LiF:Mg,Ti,… thermoluminescent dosimeters (TLDs) measured by either the Greek Atomic Energy Commission (GAEC) or the University of Ioannina Medical Physics Laboratory (UIMPL) [8]

were used to monitor occupational and environmental radiological burden during the study period. The adequacy of the room shielding was tested my multiple dose rate measurements carried out at various locations around the treatment using various β, γ and neutron detectors.

3. Results and Discussion

Induced activity and dose rates

The spatial distribution of the induced activity in the bunker following 18 MV X-ray irradiations was found, as expected, non-uniform and depended on the beam utilization patterns. More specifically the ambient dose rate at each location and its temporal evolution depend among others on the machine 18 MV output, MU/min, irradiation field size, beam direction, materials in the path of the primary beam and irradiation history.

Initial H*(10) rates of almost 10 μSv/h were found about 2 cm from the centre of the beam exit window and the portal imager located at a distance of 140 cm from the target and a phantom in place (its irradiation with 18 MV X-ray beams is not recommended) after single 1.0 Gy 20 s-long 10 cm x 10 cm irradiations defined by the two classical pairs of collimator jaws, no field modifying devices in place and a rate 300 monitor units (MU) per minute. About 30% of the initial dose-rate reduced with a half-live ($T_{1/2}$) of about 2 min and most of the remaining with ~9.5 min. ^{15}O and ^{28}Al were considered to be the predominant γ-emitters that contribute to the first component and ^{13}N, ^{27}Mg and ^{62}Cu of the second one. ^{56}Mn, ^{57}Ni, ^{64}Cu and ^{187}W, radionuclides with $T_{1/2}$ between 2.6 and 36 h, were the main dose contributors close to the exit window about 1 h after termination of the irradiations.

Initial H*(10) rates of ~5 μSv/h per Gy were found along the central beam-axis at a 1.0 m distance from the target as well as between the patient couch and the portal imager, with no phantom in place. Measurements carried out in the vicinity of the treatment head away from the beam exit window indicated maximal rates between 1 and 3 μSv/h depending on the side of the head. Measurements carried out after a 3 month-long period during which no 18 MV X-ray irradiations were made, showed dose rates up to 0.4 μSv/h close to the treatment head, attributed mainly to the decay of the neutron capture product ^{124}Sb, ($T_{1/2}$: 60 d).

Initial H*(10) rates 1.5 to 2.5 μSv/h per Gy were found close to the patient couch and ~1.5 μSv/h in the vicinity of the directly irradiated laminated wall, made of 16 cm of iron and 235 cm of concrete, when a 270^{o} gantry angle was used. These rates were attributed mainly to ^{15}O, ^{38}K, ^{49}Ca, ^{53}Fe, ^{56}Mn ^{124m}Sb production, i.e., radionuclides that decay with $T_{1/2}$ in the range 1.5 to 9 min. Measurements after an 100 MU irradiation with the worst geometrical configuration indicated initial H*(10) rates in the maze 10 to 100 nSv/h per Gy, depending on maze location. Elevated dose rates were also found close the air exhaust pipe extended to ~3 m above the bunker terrace, i.e., a restricted area during accelerator operation.

Measurements carried out close to a 30^{o} wedge iron filter after its removal from the treatment head indicated an initial H*(10) rate γ-rays of ~17 μSv/h per Gy in water at 1.0 m distance along the main beam axis and a substantial dose rate from beta rays. Therefore, manipulations of filters made of iron compound may result in substantial β-γ dose to the hands of the therapy technicians. The dose rate data were fitted with two time-components of 2 and 8.5 min half-lives, respectively (the latter being attributed mainly to the β^{+}/γ emitter ^{53}Fe). The initial H*(10) rate in the vicinity of a 45^{o} lead wedge filter was lower, ~ 6 μSv/h per Gy, with the fast decaying nuclides ^{124m}Sb and ^{207}Tl considered to be the main dose contributors.

No evidence of substantial delayed activation of materials outside the treatment room was found, such as close to the external surfaces of the walls bombarded by the primary beam and the heavily shielded door of the bunker (478 keV prompt γ-rays due to thermal neutron capture in ^{10}B was the main dose contributor close the door during irradiation). Moreover, the activation of the patient's body after his exit from the treatment room was not found to present a radiation hazard to personnel, care givers and relatives (the delay between the end of irradiation and his exit from the bunker allows for substantial decay of ^{15}O in his body).

Management of the potential radiation hazards

Based on dose rate mapping of the treatment room and the on its temporal evolution, detailed and realistic work-plans were developed to keep personnel doses as low as reasonably practical [4]. For example, a delay of half a minute before staff starting to open the door of the bunker following clinical 18 MV irradiations was proposed (the delay time is increased following longer irradiations, often carried out for accelerator testing, maintenance and dosimetry). Such delays allow for some decay of the short-lived radionuclides and partial exchange of the activated air in the room (linac operation is not allowed if the forced ventilation system is not functioning). Treatment plans are carried out in a way that excluded the use of the heavily activated wedge filters made of iron. No equipment or material is removed from the treatment room for storage or disposal without previous check for activation by a health physicist. Calculations carried out during the linac testing and commissioning period, indicated that the application of the proposed work-plan by the radiation therapy technologists which carry out the clinical irradiations, will result in a 1.2 to 1.7 mSv collective annual dose due to in-room induced activation, depending on the assumptions made.

The adoption of the developed site-specific dose reduction plans for daily clinical operation, dosimetry, equipment testing, maintenance and repair, combined with the appropriate design of the bunker and staff training resulted in non-reportable doses by GAEC to the IUH staff that offered services at the Radiation Therapy Department during the study period. Taking into account that the minimum monthly dose by GAEC is 0.1 mSv, personnel dosimeters were issued by UIMPL to the medical radiation physicists in charge of the IUH linear accelerators over three time periods of about 9 months each. These dosimeters failed to indicate doses higher than those registered by environmental dosimeters used at the nearby UIMPL at indoor locations free of artificial sources of ionizing radiations.

4. Conclusions

The majority of radionuclides of radiological importance formed during 18 MV X-ray irradiations undergo either β^- or β^+ decay, followed with γ-rays with $T_{1/2}$ not exceeding 10 min. At the majority of the studied locations close to the treatment field, β^+ emitters, such as ^{13}N, ^{15}O, ^{53}Fe, and ^{62}Cu, were the main short-term dose contributors, with rates approaching a saturation level after about 30 min of continuous 18 MV X-ray machine operation. Radionuclides of longer $T_{1/2}$, such as ^{56}Mn, ^{64}Cu, ^{57}Ni and ^{187}W, produced by either photon or neutron interactions mainly at the treatment head, build-up their activity during the workday. Over the course of a treatment day when the various modes of machine operation are used, the dose rate in the bunker starts from a low level at the beginning of the day, goes

though cycles of increased and decreased rate according to the treatment schedule, usually reaches its peak by the end of the day, followed by an overnight drop or during weekends.

In conclusion, personnel is exposed whenever enters a treatment room after the termination of a high MV linac run and not only immediately after irradiations with high energy X-ray beams. The application of the work-plans developed at IUH following the ALARA principle resulted in minimal occupational burden due to activation products secondary to 18 MV X-ray irradiations.

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