ADDITIONAL DOSE ASSESSMENT FROM THE ACTIVATION OF HIGH-ENERGY LINEAR ACCELERATORS USED IN RADIATION THERAPY

by

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It is well known that medical linear accelerators generate activation products when operated above certain electron (photon) energies. The aim of the present work is to assess the activation behavior of a medium-energy radiotherapy linear accelerator by applying *in situ* gamma-ray spectrometry and dose measurements, and to estimate the additional dose to radiotherapy staff on the basis of these results. Spectral analysis was performed parallel to dose rate measurements in the isocenter of the linear accelerator, immediately after the termination of irradiation. The following radioisotopes were detected by spectral analysis: ^{28}Al, ^{62}Cu, ^{56}Mn, ^{64}Cu, ^{187}W, and ^{57}Ni. The short-lived isotopes such as ^{28}Al and ^{62}Cu are the most important factors of the clinical routine, while the contribution to the radiation dose of medium-lived isotopes such as ^{56}Mn, ^{57}Ni, ^{64}Cu, and ^{187}W increases during the working day. Measured dose rates at the isocenter ranged from 2.2 μSv/h to 10 μSv/h in various measuring points of interest for the members of the radiotherapy staff. Within the period of 10 minutes, the dose rate decreased to values of 0.8 μSv/h. According to actual workloads in radiotherapy departments, a realistic exposure scenario was set, resulting in a maximal additional annual whole body dose to the radiotherapy staff of about 3.5 mSv.

Key words: linear accelerator, activation, radioisotopes, photonuclear reaction, gamma spectroscopy

INTRODUCTION

Linear accelerators have become the megavoltage treatment units of choice in modern radiotherapy departments [1, 2]. Due to recent developments, such as multi-leaf collimators and intensity modulated radiotherapy units, many older devices are being substituted by high-energy accelerators with photon energies over 10 MV [3, 4]. At present, the majority of external radiotherapy is carried out using high-energy X-rays and electrons from electron accelerators. When X-ray beams are used and the photon energy exceeds the binding energy of a nucleon, which is approximately 8 MeV to 10 MeV, radioactive isotopes can be produced due to photonuclear reactions. Depending on the photon energy and on the irradiated material, a number of radionuclides will be created in the accelerator itself, in the construction material and objects present in the room, as well as in the patient's body. These activation products may give rise to an increased exposure of the radiotherapy staff [5]. The effect is more pronounced after prolonged irradiations [6].

Several studies have identified isotopes and measured or calculated resulting dose rates, and from these findings it is an accepted fact that resulting doses for the staff are not negligible [5, 7-9]. The annual dose burden derived from other studies ranged from 0.5 mSv to 5 mSv [6, 10, 11]. Although the problem has been known for de-

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cades, little is known about the spatial distribution of the induced activity. Whilst it can be easily demonstrated that the treatment head, the target and flattening filter regions are dominant radiation sources, it has also been shown that treatment accessories such as wedges or block trays are activated as well [12]. These studies were predominantly concentrated on the problem of radioactive waste handling after accelerator decommissioning. According to the results of previous studies, activation products have a short half-life [3, 6, 7]. However, depending on the exact composition of the accelerator head, radionuclides with a longer half-life could also be found, but no systematic dependence on machine properties or manufacturer was observed [13]. In addition, due to the difficulties in performing gamma-ray spectrometry in a hospital environment and the relative unavailability of therapy machines for experiments due to high patient workload, very little information is available about the specifics of these radioisotopes which may contribute to occupational exposure.

In order to obtain additional knowledge on activation processes and the materials in which they take place, a study was performed to determine the activation products and resulting dose rates for the linear accelerator of the Siemens Primus type operating at 18 MV electron energies and to assess the additional dose to radiotherapy staff due to activation products.

MATERIALS AND METHODS

Background physics

In a medical linear accelerator operating in a photon mode, the bremsstrahlung radiation is produced in the target. The photons have an energy distribution with the maximal energy equivalent to the energy of the generating electrons. The photons emitted from the target in the photon mode or as side effect in the electron mode, interact with the electron shell of atoms in their path and with the nuclei when the energy is high enough. In the energy range of medical linear accelerators, two major processes are involved in the generation of activation products. The first process is the nuclear photo effect, *i. e.* (γ, n) reaction, resulting in neutron emission. The produced neutron is able to initiate nuclear reactions itself and give rise to another process - neutron capture, *i. e.* (n, γ) reaction which is essentially the absorption of a neutron by a nucleus, followed by the emission of binding energy in the form of photons [5].

At sufficiently high energies, neutrons are principally produced by means of the giant dipole resonance mechanism (GDR) in the nuclear reaction between photons and target nuclei. The reaction threshold energy decreases with the increase in the target's atomic number (Z). In the energy region of the GDR, the (γ, n) cross section for high-Z elements is a factor ten times higher than for low-Z materials [14].

Neutron production in medical linear accelerators arises from photonuclear reactions of high-energy photons with high-Z material components in the accelerator head and greatly depends on its isotope composition. The absorption cross-sections of the material present in a linear accelerator are very low for generated neutrons. Thus, neutrons are not shielded by the collimators and can be found throughout the treatment room, contributing to the extra dose to the patients and radiotherapy staff. In addition, it can be expected that the activation products created by neutron capture are distributed over the whole treatment room, whereas the isotopes produced by nuclear photo-effect events concentrate in the region of the maximum flux of high energy photons, *i. e.* in the primary collimator, target and jaws [12].

Linear accelerator incorporated into this study

All medical linear accelerators have the same basic operation principle; however, they may differ considerably in construction details; even when of same accelerating voltage, the may differ in the electron current, which ultimately determines the activation flux [7]. According to the results of previous studies, induced radioactivity in a high-energy treatment room arises mainly from the accelerator itself and its components, and in a lesser extent, from walls, floor, ceiling and the patient [3, 12]. In order to obtain additional knowledge of the impact of the activation process on the radiation burden of occupationally exposed individuals in radiotherapy, a study was undertaken to determine the activation products and assess the additional dose to the operating staff for a particular linear accelerator.

The linear accelerator model chosen for this experimental study is a Siemens Primus (Siemens Medical Solutions, Malvern, Penn., USA) operated in a 18 MV configuration that was installed in 2004. For this particular accelerator model and photon energy, no activation data have been reported so far.

Gamma-ray spectroscopy

In situ gamma-ray spectroscopy was performed using a calibrated gamma-ray spectrometer consisting of a high purity germanium detector of 25% relative efficiency and battery driven hardware (InSpector 2000, Canberra, Meriden, Conn., USA). The recorded data were analyzed using the gamma spectrometry software Genie 2000 (Canberra, Meriden, Conn., USA).

Although the results of gamma-ray spectrometry can under certain geometry and absorption assumptions be used for quantitative activity assessment [7], here the peaks were used only for radionuclide identification.

Dose rate measurements

Dose measurements from induced activity in terms of the photon equivalent dose rate (H_X) were performed using a calibrated portable scintillation measuring unit 6150 ADB (Automess, Ladenburg, Germany), consisting of a scintillation probe 6150 AD-b and a dose rate meter 6150 AD 6. The energy range of the instrument is 23 keV to 7 MeV, while the dose rate range is 0.01 µSv/h to 99.9 µSv/h, making it suitable for measurements of gamma radiation predominantly in the MeV range [15]. The detector was placed adjacent to the spectrometer crystal, within a 20 cm   20 cm field size, as defined by the accelerator light field. Due to the logging capability of the instrument, the time dependence of the dose rate was recorded. Dose rate values were recorded every second.

The dose rate distribution was measured around the therapy couch, at points where the staff is likely to stand, and in front of the door at the end of the maze.

Measurement set-up

All the measurements in this study were performed for a 20 cm   20 cm field at the isocenter (source-to-skin distance 100 cm) at 0º gantry angulations. This geometry corresponds to a reference filed in most relevant dosimetry protocols and treatments [2].

The measurements were performed at midnight, at the end of a working day. The linear accelerator workload is very high, encompassing treatment of more than 60 patients in 150 fields per working day. Induced activity at 18 MV was generated and measured with a 20 cm   20 cm open field, chosen to be representative of a typical clinical treatment field, having in mind that around 20% of the patients are treated using 18 MV photons.

Since the induced dose rate increases with the size of the field, the selected field size is a reasonable conservative choice. The measuring points are selected to represent the dependence of irradiation modality (isocenter and front face), since positions behind the shielding of the treatment head remain unaffected by irradiation modality, due to strong attenuation in the shielding material [9].

A maximal dose rate of 500 monitor units (MU) per minute was delivered over a period of 2.20 minutes, which corresponds to the absorbed dose of 10 Gy at a normal treatment distance.

The spectrometer and the dosemeter were installed on a trolley and put in operational mode outside of the treatment room to avoid radiation damage during beam on. The sensitive volume of the detector and the dosemeter were positioned at the isocentre of the accelerator, not later then 1 minute after beam termination. The detectors were positioned in the region of the light

Figure 1. Experimental set-up, showing a gamma-ray spectrometer and a dose rate meter with accessories

field, allowing a direct view of the target and the flattening filter. Spectra acquisition and dose measurements were performed simultaneously over 1000 s. The experimental set-up is presented in fig. 1.

The measurements were repeated five times for the same irradiation conditions, in order to follow the effects of activity build up. Also, both gamma-ray spectroscopy and dose rate measurements were performed for both the open jaws and the 30º wedge in position.
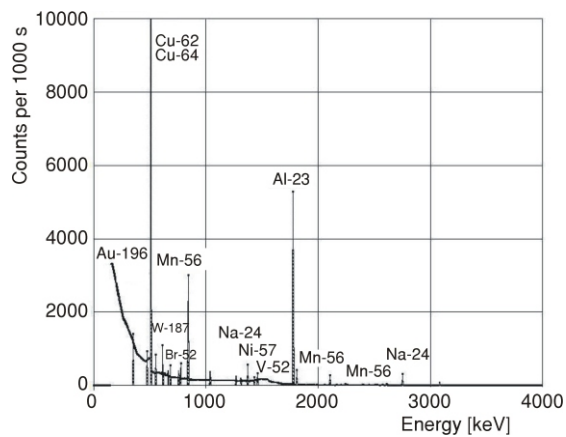
RESULTS AND DISCUSSION

Major activation products identified in the room are listed in tab. 1, along with their basic properties. The identified radionuclides are consistent with other studies [6, 7, 9, 11]. Radiologically, the most significant isotopes are ^{28}Al, ^{62}Cu, ^{56}Mn, ^{64}Cu, ^{187}W, and ^{57}Ni. Figure 2 shows the obtained spectra as an example.

The short-lived isotopes as ^{28}Al and ^{62}Cu are the most important ones in the clinical routine, while the contribution to the radiation dose of medium-lived isotopes as ^{56}Mn, ^{57}Ni, ^{64}Cu, and ^{187}W increases during the working day. To assess the maximum activity, the experiment was carried out at the end of the working day. Other long-lived isotopes contribute to dose build-up on a weekly or even yearly basis. These isotopes are likely to be in equilibrium, since this linear accelerator has been operating for more than 4 years.
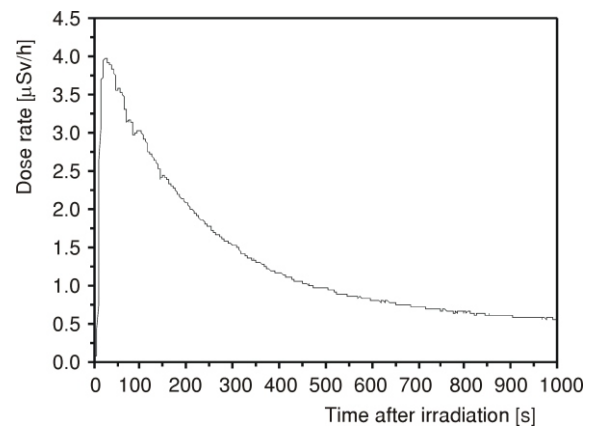
Table 1. Activation products found in the radiotherapy room of a Siemens Primus linear accelerator operating at 18 MV photons

Radionuclide	Half life	Decay mode	Photon energy used for identification [keV]	Probable nuclear reaction
^{28}Al	2.3 min	β^-, γ	1779	^{27}Al(n, γ)^{28}Al
^{56}Mn	2.6 h	β^-, γ	846, 1811, 2114	^{55}Mn(n, γ)^{56}Mn
^{24}Na	15 h	β^-, γ	1369, 1731, 2755	^{23}Na(n, γ)^{24}Na
^{54}Mn	312 d	β^-, γ	834	^{54}Fe(n, p)^{54}Mn
^{57}Ni	36 h	β^+, γ	1378	^{58}Ni(γ, n)^{57}Ni
^{82}Br	35.3 h	β^-, γ	554, 776, 1044, 1318	^{81}Br(n, γ)^{82}Br
^{187}W	24 h	β^-, γ	479, 617, 685	^{186}W(n, γ)^{187}W
^{62}Cu	9.7 min	β^+		^{63}Cu(γ, n)^{62}Cu
^{64}Cu	12.7 h	β^+		^{65}Cu(γ, n)^{64}Cu
^{52}V	3.75 min	β^-, γ	1434	^{51}V(n, γ)^{52}V
^{196}Au	6.2 d	β^+, β^-, γ	355	^{197}Au(n, 2n)^{196}Au

Figure 2. Gamma-ray spectrum obtained at the linear accelerator's isocenter after irradiation, using 18 MV photons and a field size of 20 cm   20 cm

Figure 3. Dose rate time dependence at the linear accelerator's isocenter after irradiation using 18 MV photons and a 20 cm   20 cm field size

The isotope ^{28}Al is produced by neutron capture in ^{27}Al, while ^{187}W and ^{56}Mn are produced in reactions ^{186}W(n, γ)^{187}W, ^{58}Ni(γ, n)^{57}Ni, and ^{55}Mn(n, γ)^{56}Mn. ^{54}Mn was identified using the 834 keV line. It should have been produced in a reaction ^{54}Fe(n, p)^{54}Mn. The isotope ^{24}Na probably originates from the activation of concrete by thermal neutrons. The peak at 511 keV is due to the annihilation from positron emitters. According to the time evolution of the peak, it was attributed to the positron emitting radionuclides ^{62}Cu and ^{64}Cu. However, their contribution to the radiation dose is not significant. A gamma line of 355 keV was used for ^{196}Au detection. It is likely that the activation of stable gold occurs in the wave-guide of the linear accelerator. The absence of ^{198}Au speaks of the non-thermal character of neutrons at points where the gold is activated. No presence of Co, Fe, Sb, and Cr isotopes, which were reported by other authors, was found [11, 13].

The linear accelerator itself is subject to considerable activation, particularly the target, flattening fil-

ter, and the collimators. Figure 3 represents the behavior of dose rates in the isocenter at the level of the treatment coach, following irradiation. The curve is a rather complex sum of several exponential decay curves. The steep increase in the part of the curve corresponds to the movement of the detector through the maze, while the maximum corresponds to the beginning of measurements in the isocenter. It is likely that the personnel stand close to the aperture in both vertical and horizontal beam configuration. In that case, the dose to the staff would be higher, as presented in tab. 2. This is particularly important for operations of positioning the patient or treatment aids such as wedges, shielding blocks or electron applicators in the beam. The dose rate measured at collimator jaws ranges from 2.2 µSv/h to 10 µSv/h and becomes uniform with the increase in the distance from the accelerator head, as presented in tab. 2. The dose distribution indicates that the accelerator head is a major source of induced activity. The dose from the activation of other accelerator

Table 2. Results of dose rate measurements, 2 minutes following the irradiation, using 18 MV photons and a 20 cm 20 cm field size

Position	Photon equivalent dose rate in the center of the beam [μSv/h]	Photon equivalent dose rate 50 cm laterally from the beam center [μSv/h]
Front face	10	4.0
Under jaws (15 cm)	7.0	2.8
Under jaws (50 cm)	4.0	2.6
Isocenter	2.7	2.3
Floor	2.3	2.2

components is also of concern to the staff that performs maintenance operations soon after treatments.

In the energy interval commonly used in medical accelerators (10 MV to 20 MV), the photonuclear cross-section increases with the atomic number [4]. High-Z materials included in the components of the linear accelerator produce significantly more neutrons than the biological tissues of the patients, making the accelerator itself the dominant source of an additional dose to the staff.

There was no significant difference in dose rate and spectra obtained with the wedge in place or without it. Thus, one can consider the activation of the wedge to be negligible.

Gamma-ray spectroscopy was used only for radionuclide identification, since the activity could not be reliably estimated, due to its dependence on the history of accelerator use and a very complex geometry of the accelerator itself, the room, and objects present in the room.

DOSE ASSESSMENT

Every radiotherapy machine presents a potential hazard due to the primary radiation transmitted through the patient, scattered photons from the patient and surroundings, and leakage radiation through the accelerator shielding. Also, neutrons produced in photonuclear reactions require particular attention, as well as high-energy gamma radiation produced in eventual neutron capture. The radioactivity induced in the accelerator, patient, the structure of the room, and accessories is a significant additional source of radiation dose to the radiotherapy staff.

Clinical practice involving the machine showed that a typical patient spends 10 minutes in the room, receiving 18 MV 4-field treatments, with an average of 100 MU delivered per field. The fields are delivered 1 minute apart. It was assumed that operators do not enter the room between two fields. The maximal dose rate after the termination of irradiation in the front face and the isocenter was 10 μSv/h and 4 μSv/h, respectively, for a therapist's time in the room of 10 minutes

per patient, standing next to the treatment head. For a realistic dose assessment, the following equation was used, adopted from Fisher *at al.* [7]

$$E \quad N_d N_p f \int_{t_0}^{t_1} \dot{H} dt \qquad (1)$$

where N_d is the number of working days per year , N_p – the number of patients treated per day, f – the fraction of high-energy fields, and $\dot{H}$ – the measured dose rate, while parameters t_0 and t_1 define the time interval which the radiotherapy staff spends in the room between two treatments.

According to the above presented results of dose rate measurements (fig. 3 and tab. 2) and the mentioned typical workload, the estimated annual whole body dose is 3.5 mSv, assuming a total of 250 working days per year and a 20% accelerator operation using 18 MV photons. The estimated dose to the hands of the operator is 5 mSv per year, using a similar exposure scenario. The dose to the skin from both beta and gamma radiation is significant for wedge and filter positioning operations. Such dose assessment is based on "the worst case scenario", assuming constant and maximal dose rates for the duration of the exposure. The maximum annual whole body dose of 3.5 mSv is slightly higher than suggested by results of other studies [6, 9], due to a higher workload assumed in this study. In order to obtain a more realistic dose assessment using eq. (1), taking into account the dose rate decrease for the same workload pattern, the annual dose was estimated to be 1.5 mSv. The applied integration limits take into account the exposure of the individual from the moment of entering the maze, as presented in fig. 3.

Although high-energy fields are not often used in clinical practice (10-20%), the radiotherapy staff receives doses from activation almost continuously, following each treatment, as a result of the previous high-energy activation. The uncertainty of these results is affected by the presence of the patient, use of different gantry angles, field sizes and accessories, as well as by the sharing of responsibilities among operators. The location of the operator in the treatment room and number of high-energy fields are another source of uncertainty.

POTENTIAL FOR DOSE REDUCTION

Transmission measurements of the induced radiation in the vicinity of the accelerator have shown that the half-value layer is at least 2.5 mm of lead, which makes the use of personal protective devices unfeasible [16]. However, it was found that the dose to the staff could be significantly reduced by closing the jaws or using suitable filters, since radiations from

radionuclides activated by the copper and nickel used in the construction inside the head of the accelerator emanate directly through the open collimator.

In part, dose reduction can be achieved by removing unnecessary objects from the treatment room and, thus, eliminating sources of activation, particularly aluminum. Also, dose reduction may be achieved by scheduling high-energy field treatments for the end of the working day or delaying entry into the treatment room after irradiation using high photon energies.

Due to significant variations in working habits, in order to obtain a more realistic occupational dose assessment, the use of electronic personal dosimeters (EPD) for radiotherapy staff is to be considered.

FURTHER EXPERIMENTS

Although all medical linear accelerators have a similar construction and operating principles, there are certain construction details that may influence dose rates differently, due to induced activities. Further investigations should focus on different accelerator models and a more detailed assessment of induced activity distribution in the radiotherapy treatment room.

CONCLUSIONS

High-energy accelerators expose both patients and personnel to radionuclides created by neutrons and gamma-ray activation of material within the treatment room. At photon energies of 18 MV, the principal radionuclides are produced in (n, γ) reactions. Major dose contributors are ^{28}Al, ^{56}Mn, and ^{24}Na. Dose rates are significant in the first ten minutes after the termination of irradiation, dominated by the 2.3 minutes half-life ^{28}Al for short-treatment times. For typical clinical practice involving this machine, an estimated maximal annual individual dose for radiotherapy staff members of 3.5 mSv has been calculated, while the dose to the hands can be even higher, up to 5 mSv per year. This dose is well below regulatory limits [17], however, it is far from negligible and extremely dependent on local practice. Thus, it is of utmost importance to perform gamma-ray spectroscopy and dose rate measurements at each particular radiotherapy installation and to suggest the tools for dose reduction if we are to keep occupational doses in radiotherapy As Low As Reasonably Possible in practice.

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ПРОЦЕНА ДОДАТНЕ ДОЗЕ КАО ПОСЛЕДИЦА АКТИВАЦИЈЕ КОД ЛИНЕАРНИХ АКЦЕЛЕРАТОРА ВИСОКХ ЕНЕРГИЈА У РАДИОТЕРАПИЈИ

Линеарни акцелератори који се користе у медицини на високим енергијама генеришу продукте активације. Циљ рада је процена активационог понашања линеарног акцелератора у радиотерапији на основу гама спектроскопских и дозиметријских мерења. Користећи разултате мерења процењена је додатна доза за професионално изложена лица у радиотерапији. Спектроскопска мерења и мерење дозе реализовано је истовремено у изоцентру линеарног акцелератора тренутно након престанка озрачивања. Најзначајнији детектовани радиоизотопи били су: ^{28}Al, ^{62}Cu, ^{56}Mn, ^{64}Cu, ^{187}W и ^{57}Ni. Кратокоживећи радиоизотопи (^{28}Al и ^{62}Cu) најзначајнији су чинилац у клиничкој пракси са становишта тренутног доприноса дози, док средњеживећи радиоизотопи (^{56}Mn, ^{64}Cu, ^{187}W и ^{57}Ni) постају значајнији током радног дана и радне недеље, посебно у случају великих радних оптерећења. Измерена јачина дозе кретала се у интервалу од 2.2 μSv/h до 10 μSv/h, у различитим мерним тачкама од интереса за процену дозе за професионално изложена лица у радиотерапији. Након 10 минута од престанка озрачивања јачина дозе износила је 0.8 μSv/h. Користећи податке о типичном радном оптерећењу процењена је максимална додатна доза за професионално изложена лица од 3.5 mSv на годишњем нивоу.

Кључне речи: линеарни акцелераȗор, акȗивација, радиоизоȗоȗи, фоȗонуклеарна реакција, ȓама сȗекȗроскоȗија