Activation Processes in Medical Linear Accelerators and Spatial Distribution of Activation Products

Helmut W Fischer[1,3], Ben E Tabot[1,2] and Björn Poppe[2]

1 University of Bremen, Dept. of Physics, 28359 Bremen, Germany
2 University of Oldenburg, Institute of Physics, 26111 Oldenburg, Germany

E-mail: hfischer@physik.uni-bremen.de

Abstract
Activation products have been identified by in situ gamma spectroscopy at the isocenter of a medical linear accelerators shortly after termination of a high energy photon beam irradiation with 15 x 15 cm field size. Spectra have been recorded either with open or with closed collimator. Whilst some activation products disappear from the spectrum with closed collimator or exhibit reduced count rates, others remain with identical intensity. The former isotopes are neutron-deficient and mostly decay by positron emission or electron capture, the latter have neutron excess and decay by β^- emission. This new finding is consistent with the assumption that photons in the primary beam produce activation products by (γ,n) reactions in the treatment head and subsequently the neutrons created in these processes undergo (n,γ) reactions creating activation products in a much larger area.

PACS classification: 87.56.By; 87.52.-g

Keywords
Medical linear accelerator, activation products, induced activity, in situ gamma spectroscopy

1. Introduction

Medical linear accelerators are known to generate activation products when operated above a certain energy. Several studies have identified isotopes and measured or calculated resulting dose rates (Ewen and lauber-Altmann 1987, Almen et al. 1991, Rawlinson et al. 2002), and from these findings it is an accepted fact that resulting doses for the staff are not neglegible. However, little is known about the spatial distribution of the induced activity. Whilst it can be demonstrated easily that the treatment head, and inside of it the target and flattening filter regions are dominant radiation sources, it has been shown that treatment accessories like wedges or block trays are activated as well (Fischer and Peick 1999). Rawlinson *et al.* (2002) assume the treatment couch and the treatment room walls to be also major sources of radiation. No systematic study, theoretical or experimental, has been published to date which would allow to combine radiation properties (like particle type, energy and flux) and material properties (like nuclear reaction cross sections) to predict kind, quantity and location of activation products.

In order to obtain additional knowledge on the activation processes and the materials in which they take place, a study was performed comparing activation products and resulting dose rates from linacs in different radiotherapy centres and from different manufacturers (Fischer et al. 2006). In one installation the experimental protocol was modified by closing or re-opening the collimator between acquisition of successive spectra. The aim was to distinguish between contributions arising from inside the treatment head and from outside of it. The present article reports about the results of this special experiment.

2. Materials and Methods

2.1 Physical Background

In a medical linear accelerator operating in photon mode, Bremsstrahlung is produced in the target. The energy of the resulting photons has a spectral distribution, with the maximal energy equivalent to the energy of the generating electrons. The photons emitted from the target will interact with the

[3] to whom correspondence should be addressed

electron shell of material on their path, and with the nuclei in case the energy is high enough. The most important reaction in the energy range covered by medical accelerators, i.e. up to 25 MeV, is the nuclear photo effect. It leads to the expulsion of a neutron from the nucleus, leading to a, in most cases radioactive, nucleus with neutron deficit, and a fast neutron. The reaction can be formalized as

$$ {}^{A}_{Z}A_{N}\,(\gamma,n)\,{}^{A-1}_{Z}B_{N-1} \tag{1} $$

with A = number of nucleons, Z = nuclear charge and N = number of neutrons. The reaction can take place if the photon energy exceeds the binding energy of the neutron, i.e. above 8 MeV for medium mass nuclei. If radioactive, the produced nucleus, due to the neutron deficit, will be a positron emitter or decay by electron capture in most cases.

The produced neutron is able to undergo nuclear reactions itself. In the energy range encountered in medical accelerators, the most important reaction is the neutron capture:

$$ {}^{A}_{Z}A_{N}\,(n,\gamma)\,{}^{A+1}_{Z}B_{N+1} \tag{2} $$

with the same notation as above. The produced nucleus is again radioactive in most cases and will most probably decay in β^- mode due to its excess in neutrons.

The neutrons generated by the nuclear photo effect contaminate the treatment beam (Karzmark et al. 1993) and are not well shielded by the high Z materials surrounding the treatment head. Neutrons can thus be found throughout the treatment room, requiring extra shielding of the door with low Z materials in many cases. Therefore 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 maximum flux of high energy photons, i.e. in the treatment head.

2.2 Experimental Setup

The experiments were performed on a linear accelerator with high photon energy of 15MV and equipped with MLC (Clinac 2100 C/D , Varian Medical Systems, Palo Alto, CA, USA). On a Friday evening, after the end of the weekly clinical routine, the machine was programmed to deliver 400 MU in the high photon stage at the maximum dose rate of 400 MU/min. The gantry angle was set to 0 degrees IEC scale, the field size was 15 x 15 cm and no accessory was used. Directly after termination of the beam, a previously setup and calibrated gamma spectrometer consisting of a portable high purity germanium detector of 10% relative efficiency (DC1018, Canberra Eurisys GmbH, Rüsselsheim, Germany) and associated portable, battery-driven spectrometer hardware (Inspector 2000, Canberra Eurisys GmbH, Rüsselsheim, Germany) was placed on the treatment couch top, with the sensitive volume of the detector close to the isocenter and inside the region covered by the light field, i.e. in direct view of the target and the flattening filter. Spectra were recorded over a period of two hours, in the beginning with 1 min. per spectrum, and later with increasing accumulation time. Five times during this sequence, before recording the spectrum, the collimator x and y jaws were closed completely, leading to a field size below 1 x 1 mm. After recording of these spectra, the field size was again set to 15 x 15 cm. This procedure leads to five open/closed collimator spectra pairs.

In order to obtain more information on long-lived isotopes, two days later another spectrum pair with open and closed collimator was recorded, the accelerator not having been used in between. The data were then analyzed using the Genie2000 gamma spectroscopy software (Canberra Eurisys GmbH, Rüsselsheim, Germany). Whilst the results can also be used to obtain activity values under certain geometric assumptions, we consider here the net peak areas only and refer to the complete study for details on activity and dose rates (Fischer et al. 2006).

Additional dose rate data were obtained by means of a portable dose rate meter with data logging capability (LB 123, Berthold Technologies, Bad Wildbad, Germany). The sensor of the instrument was placed adjacent to the germanium detector and inside of the radiation field. Figure 1 shows the experimental setup.

Figure 1. Experimental setup for the in situ gamma spectroscopy and dose rate measurements. The photo shows the gamma detector with its cryostat on the top of the treatment couch. Besides, also close to isocenter, the dose rate meter can be seen. Spectrometer electronics and computer are visible in the front.

3. Results

3.1 Measured spectra and dose rates

Figure 2 shows two gamma spectra recorded before and after closing the collimator as one example of the obtained data. The visible gamma lines, all originating from isotopes undergoing β^- decay in this case, show little or no difference in amplitude between both spectra. The 511 keV line from positron-electron annihilation, originating from positron-emitting radioisotopes, is reduced to about 10 per cent of its original amplitude. The recorded dose rate is shown in figure 3. The diagram indicates that with closed collimator the radiation level is still significant.

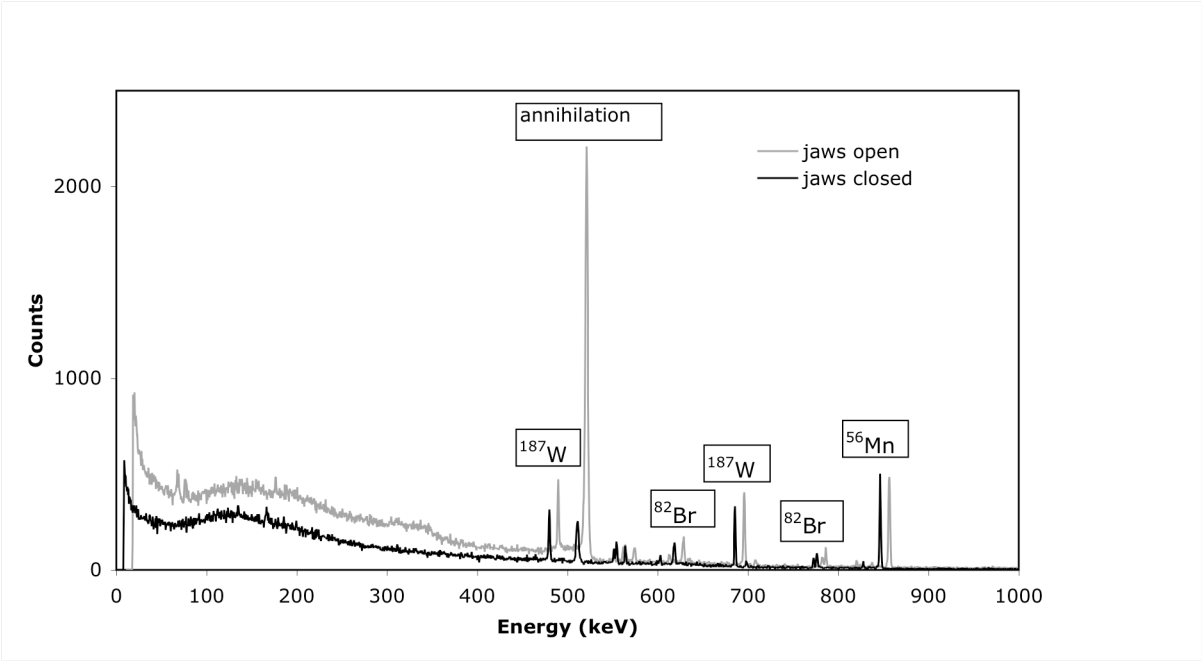

Figure 2. Gamma spectra obtained at the linac isocenter 15 min. after beam-off with a field size of 15 x 15 cm, before and after closing the collimator. Some lines are marked with the corresponding isotopes. The spectrum obtained with open jaws has been shifted by +10 keV for clarity. For the same reason the energy range has been restricted to 0 – 1000 keV.

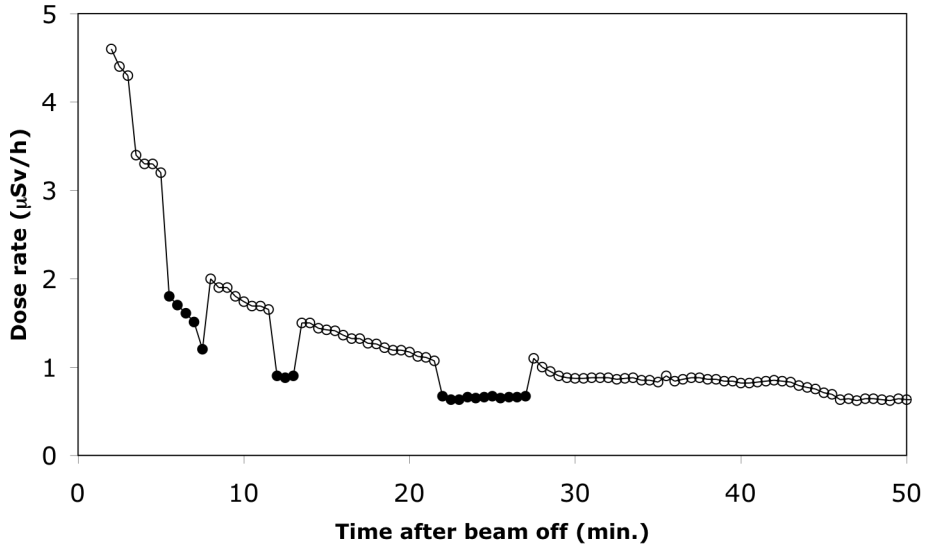

Figure 3. Dose rate recorded during the experiment. Filled symbols indicate the intervals with closed collimator.

3.2 Identified isotopes

Table 1 shows the identified radioisotopes, some characteristic data, the activation reaction suitable to produce the isotope from stable material as available in the web version of the Table of Isotopes (TOI 2006), and the relative reduction of the count rate after closing of the collimator. ^{62}Cu ($ß^+$ decay, no gamma emission) was identified from the time evolution of the 511 keV annihilation peak by its characteristic half life. From the six open/closed collimator spectrum pairs the data with the lowest statistical error are used. Only those isotopes are listed which could be identified in both open and closed blades spectra. The same data are presented graphically in *Figure 4*, this time grouped according to the effect of blade closing on the count rate, expressed by the count rate reduction factor $r_{i.}$ as defined below.

3.3 Effects of closing the blades

The effect of blade closing on the spectra was quantified by defining a nuclide-specific reduction factor r_i according to (3):

$$r_i = \frac{R_{closed,i}}{R_{open,i}} \tag{3}$$

with $R_{closed,i}$ = peak count rate with closed blades, $R_{open,i}$ = peak count rate with open blades and i = isotope index.

Table 1. Detected isotopes and count rate reduction factor r_i at isocenter after closing of the collimator

Isotope	$T_{1/2}$	Gamma energy (keV)	Decay mode	produced by	Reduction factor r_i
Na-24	15.0 h	1369	e^-	(n,γ)	1.03 ± 0.14
Al-28	2.24 min	1779	e^-	(n,γ)	1.12 ± 0.07
Mn-54	312.3 d	835	e^+	(γ,n)	0.33 ± 0.07
Mn-56	2.58 h	847, 1811	e^-	(n,γ)	1.02 ± 0.07
Co-57	271.8 d	122	e^+	(γ,n)	0.18 ± 0.02
Co-58	70.9 d	811	e^+	(γ,n)	0.19 ± 0.05
Co-60	5.27 y	1173, 1333	e^-	(n,γ)	1.00 ± 0.12
Ni-57	35.6 h	1378	e^+	(γ,n)	0.03 ± 0.01
Cu-62	9.74 min	-	e^+	(γ,n)	0.10 ± 0.06
Zn-65	244.3 d	1116	e^+	(n,γ)	1.30 ± 0.40
Br-82	35.3 h	619, 777	e^-	(n,γ)	1.02 ± 0.05
Sb-122	2.72 d	1141	e^-, e^+	(n,γ)	0.98 ± 0.08
Sb-124	60.2 d	603	e^-	(n,γ)	1.03 ± 0.08
W-187	23.7 h	480, 686	e^-	(n,γ)	0.78 ± 0.07
Au-196	6.18 d	356	e^+, e^-	(γ,n)	0.60 ± 0.12

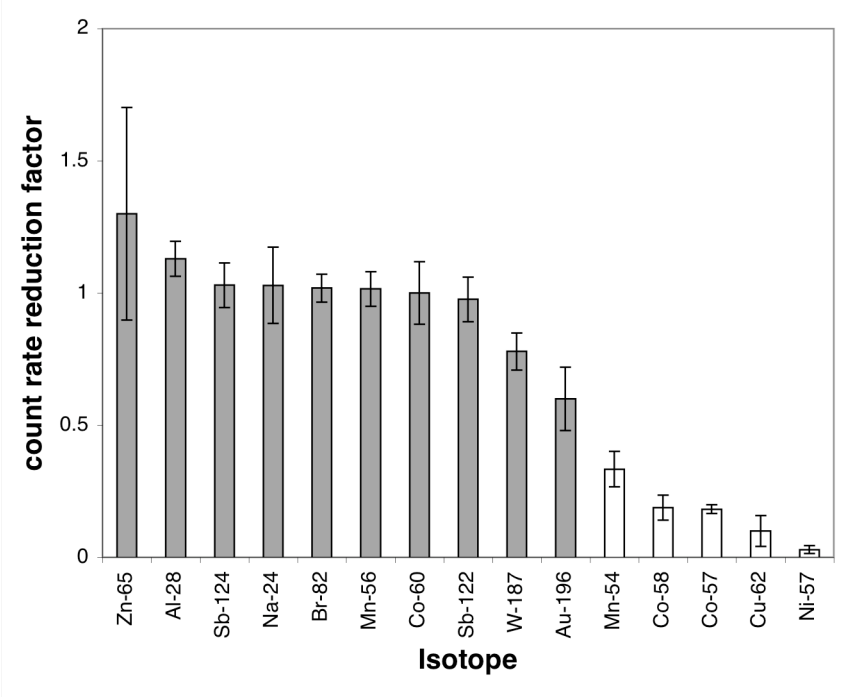

Figure 4. Isotope-specific count rate reduction factor r_i due to closing of the collimator (open collimator = 1), sorted in descending order of numerical value of r_i. Grey bars indicate beta emitting isotopes, produced by neutron capture, whilst white bars stand for positron emitting or EC decay isotopes produced by nuclear photo effect. Error bars indicate the statistical counting error (one standard deviation).

4. Discussion

The data indicate clearly and for the first time a different effect of closing the blades on those isotopes produced by the nuclear photo effect and those emerging from neutron capture by the following arguments:

- the count rate in the 511 keV annihilation peak, due only to positron emitting isotopes, is reduced to about 10 per cent of its initial amplitude after closing of the collimator jaws;
- amplitudes of spectral lines from $ß^-$ decaying isotopes are almost unaffected by blade position;
- amplitudes of spectral lines from $ß^+$ and EC decaying isotopes decrease after collimator closing.

These findings prove a different location of these two classes of activation products – nuclear photo effect products are found mainly inside the treatment head, and their radiation is effectively shielded

by the collimator jaws. Products of neutron capture are mainly located outside of the treatment head, and their radiation is little affected by jaw position. The dose rate data indicate a significant contribution to induced activity dose rate from regions outside of the treatment head. The location of the contributing isotopes is still unclear, it could be the treatment room walls, construction materials of the accelerator, or other objects. The effect could gain importance due to application of modern treatment methods like intensity modulated radiation therapy (IMRT), which often require enhanced MU numbers for the same patient dose, leading to a higher neutron production inside the treatment head.

5. Conclusion

Our results show a clear distinction between activation products according to their creation mechanism: the nuclear photo effect produces isotopes located mainly inside the treatment head, whilst neutron capture leads to induced activity outside of it. This suggests an enhanced contribution of the neutron-generated isotopes to staff dose, as these isotopes might be distributed throughout the treatment room. This finding may have importance for radiation protection of the staff in radiotherapy centers.

References

Almén A, Ahlgren L and Mattsson S 1991 Absorbed dose to technicians due to induced activity in linear accelerators for radiation therapy *Phys. Med. Biol.* **36(6)** 815-822

Ewen K and Lauber-Altmann I 1987 Aktivierung fester Materialien an einem medizinischen Elektronenlinearbeschleuniger *Röntgen-Blätter* **(40)** 185-190

Fischer H W and Peick K 1999 Activation Products in a Medical Linear Accelerator *Radiotherapy and Oncology* **51 Suppl.1** S59

Fischer H W, Tabot B E and Poppe B 2006 Comparison of Activation Products in different High-Energy Medical Linear Accelerators *(in preparation)*

Karzmark C J, Nunan C S and Tanabe E 1993 *Medical Electron Accelerators* (New York: McGraw-Hill)

Rawlinson J A, Islam M K and Galbraith D M 2002 Dose to radiation therapists from activation at high-energy accelerators used for conventional and Intensity-modulated radiation therapy *Med. Phys*. **29(4)** 589-608

TOI 2006 WWW Table of isotopes (http://ie.lbl.gov/toi/)

Acknowledgements

The authors wish to thank Mrs. Katja Popp, Radiotherapy Department, Sankt Marien Hospital, Vechta, Germany, for providing us access to the accelerator and for assisting in the experiments.