PREGNANCY AND RADIOTHERAPY - IS THERE AN ISSUE FOR FEMALE STAFF MEMBERS OCCUPATIONALLY EXPOSED TO RADIATION?

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Abstract

When medical linear accelerators are operated at bremsstrahlung energies higher than 10 MeV-X, the radioactive materials produced by photonuclear reactions can cause an internal and external exposure to the staff.

This survey includes measurements on medical linear accelerators of one major vendor. Photon energies range from 4 to 18 MeV-X. By means of photonuclear effects, radioactive substances are produced inside of the treatment head of the linear accelerator, in the walls, ceiling and floor of the vault, in air and in the patient itself. The actual dose rates, caused by the radioactive decay of the radioactive materials, is measured by commercially available ion chamber survey meter after switching off the beam in a timeline with respect to daily routine. Depending on energy of the bremsstrahlung and different daily routine procedures, the annual exposure for staff members, can add up to 3.5 mSv. Especially for pregnant and breast feeding female staff members it is important to avoid incorporation of radioactive material and to limit the external exposure. Working conditions have to be organized to keep the Radiation Protection Regulations with respect to prohibition of incorporation and limitation of exposure to the fetus as low as 1 mSv.

Keywords : radiation protection, annual dose, pregnancy, permissible exposure

I. INTRODUCTION

Places of work in the departments for radiotherapy, nuclear medicine and diagnostic radiology are due to radioprotection survey with respect to national and international legal rules, because special equipment and materials are in use [1, 2]. According to radioprotection regulations, occupationally exposed staff members have to wear specific badge detectors (i. e. film, TLD, OSLD) for dose determination. Because of possible harmful effects of ionizing radiation on human beings and the environment, the exposition is strictly limited. The maximum permissible effective dose to the public is 1 mSv per year, to occupationally exposed staff members 20 mSv per year.

Passive facilities, radiation protection equipment, and controlled access guarantee compliance with the regulations. Access to nuclear medicine departments and X-ray suites during imaging is prohibited according to national and international regulations. Radiotherapy departments and vaults are special cases : During beam-on in patient treatment, dosimetrical measurements and QA, radioactive material is produced by nuclear photo effect in the treatment head, walls, ceilings, floor, air, as well as in the patient itself and the dosimetrical equipment, when bremsstrahlung energy is higher than 10 MeV-X [3, 4]. The induced activity has to be accounted for, when estimating exposure doses to the public and to the staff, especially to pregnant members of the staff.

The maximum permissible values of the effective dose for the public is 1 mSv/y, for a fetus, which receives a radiation dose because of the occupation of the mother, the maximum permissible dose is 1 mSv per 9 months. This number includes external and internal radiation doses.

To estimate or determine low dose values at the surface of the body as well as internal dose measurements are critical of several reasons (see Chapter V.). Therefore external occupational doses have to be determined by indirect measurements : a) by dose rate measurements, b) by calculations, depending on parameters of the radioactive source. The internal dose is determined using physical and biological parameters of incorporated radioactive material and time of exposition.

II. MATERIAL AND METHODS

This investigation was carried out on two medical linear accelerators of one vendor. Both units produce two different maximum photon energies: 15 and 18 MeV-X. Even if different vendors realize different design features in their products, the resulting dose rates based on production of radioactive materials by photo nuclear effects and the subsequent decay, is not that different : The standardized exposure doses per year vary from 1 to 4 mSv [5, 6, 7, 8].

Table 1 shows a list of induced radioactive isotopes, grouped according to position of production : treatment head; floor, wall and ceiling; air. The

Table 1 Radioactive Nuclides (selection)

Group	Nuclide	HL	Eth [MeV]	Process	Mode of Decay
I. Linear	^{28}Al	2.31 min	-	(n, γ)	β-, γ
accelerator	^{53}Fe	8.51 min	13.4	(γ, n)	β+, EC, γ
(treatment head,	^{60}Co	5.28 a	-	(n, γ)	β-, γ
couch,	^{62}Cu	9.8 min	10.8	(γ, n)	β+, EC
base frame)	^{64}Cu	12.9 h	9.9	(γ, n)	β-, β+, EC, γ
	^{185m}W	1.6 min	7.2	(γ, n)	IT, γ
	^{187}W	23.9 h	-	(n, γ)	β-, γ
	^{196}Au	6.18 d	8.1	(γ, n)	β-, β+, γ
	^{198}Au	2.693 d	-	(n, γ)	β-, γ
	^{203}Pb	2.16 d	8.2	(γ, n)	EC, γ
II. Air	^{13}N	2.04 min	10.6	(γ, n)	β+
	^{15}O	9.97 min	15.7	(γ, n)	β+
III. Building	^{28}Al	2.31 min	-	(n, γ)	β-, γ
(walls, ceiling,	^{15}O	9.97 min	15.7	(γ, n)	β+
floor)	^{24}Na	15 h	-	(n, γ)	β-, γ
	^{34m}Cl	32 min	12.7	(γ, n)	β+, γ

Explanations: HL physical half life; Eth activation threshold energy; E(γ) energy of emitted photons; Ann. Rad. annihilation radiation; β-, β+ beta decay; EC electron capture; IT isomeric transition energy of the emitted gamma radiation ranges from 174 keV up to 1.8 MeV. The mean free path length in air is larger than about 60 m. Therefore a separation of the contributions by components is impossible : each dose rate measurement reflects all activated components (9-12).

Two different survey meters have been used: TOLF (Berthold Techn., Bad Wildbad, Germany) and Victoreen 451 (Fluke Corp., Cleveland, USA). Both instruments are using the principle of air ionization. The dose rate scales range from 0.1 µSv/h to 10 mSv/h and 0 mSv to 500 mSv/h, respectively. As calibration source for both instruments, ^{137}Cs is used: The response over the whole energy range is characterized by ± 30 %, the accuracy of the readings on any dose rate range is ± 10 %. In integral mode, both survey meters show an extremely high linearity : regression coefficient r = 0.99998 ; the standard deviation of estimation $\sigma \leq 1.4$ %.

To determine the dose to uterus or fetus, three different substitute positions have been realized: 1) exit window at the treatment head; 2) isocenter; 3) position of the radiotherapist/technologist: 45 cm beside isocenter, and 100 cm above floor ("gonades' position").

One cycle of dose rate measurements consists out of the following single measurements for the three above described positions: 1. dose rate prior to application of 2 Gy; 2. dose rate after delivering 2 Gy at a timeline according to daily routine (1, 2, 3, 5, 10, and 15 min after beam off). The following cycle starts again with the application of 2 Gy at a gantry angle of 0º (beam directed to floor), a field size of 20 x 20 cm^2, and a standard dose rate of 600 MU/minute.

This survey was carried out on a 15 MeV-X unit (unit I) and an 18 MeV-X unit (unit II). Test measurements on 4, 6 and 10 MeV-X units confirmed the theoretical findings, that threshold energies for activation are higher than 10 MeV, i. e. Eth(^{14}N) = 10.5 MeV. This introductory measurements included "dose rate mapping" of the treatment room, to estimate the influence of the position of the radiotherapist during patient set up and preparation of the treatment on annual dose to the staff.

For estimation of external radiation exposure the following parameters are taken into account:
- time dependency of dose rate;
- 30 patients per day;
- 236 days per year;
- 2 Gy per fraction;
- cycle time 15 minutes;

Table 2 Air activation parameters and consequences

Nuclid	^{13}N	^{15}O
$T_{(1/2)}$ [h]	0.167	0.0344
C (15X) [Bq/m^3]	243	-
C (18X) [Bq/m^3]	816	1781
DF [Sv/Bq•h]	$7.0 \cdot 10^{-12}$	$8.9 \cdot 10^{-12}$
Annual activity uptake [Bq]		
Unit I	$0.6 \cdot 10^{6}$	-
Unit II	$2 \cdot 10^{6}$	$4.3 \cdot 10^{6}$
Annual internal exposure [µSv]		
Unit I	1.0	-
Unit II	3.3	1.9

Assumptions: annual breathing volume 2400 m^3;
high photon energy use only ; C concentration of nuclides in air ;
$T_{(1/2)}$ effective half life; DF dose factor [1, 15, 17].

- time spending per patient in the vault 1-14 minutes;
- usage of higher photon energy only (15 MeV-X for unit I and 18 MeV-X for unit II).

A second scenario is based more on European conditions, i. e. German basic conditions:
- 50 patients per day;
- 220 days per year;
- cycle time 10 minutes;
- time spending per patient in the vault (set up time) 1-9 minutes.

For the final determination of the radiation exposure a worst case scenario is assumed: set up time is 9 minutes (unit I) or 14 minutes (unit II). Beside external exposure an internal exposure has to be assumed, because air activation (^{16}O and ^{14}N) is possible (Table 1 and Table 2). Additional to routine treatments on both units special treatments are carried out, i. e. total body irradiation with about 5400 MU per fraction twice a day. For unit I about 25 patients per year, for unit II 12 patients per year are treated by this special procedure. On 75 days and 36 days per year, respectively, a significantly higher activation rate and subsequently a higher annual dose to the staff can be assumed.

III. LEGAL BACKGROUND AND REGULATIONS

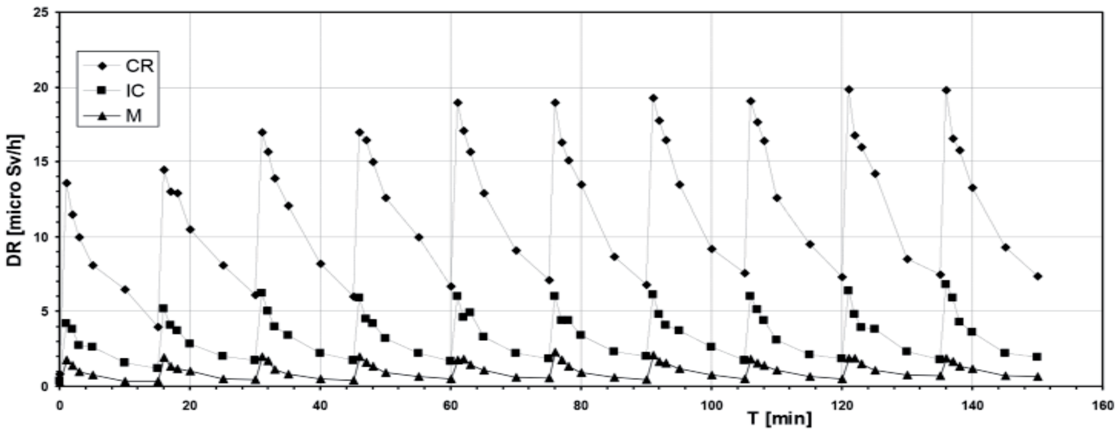
If radiation protection regulation provide for access and employment prohibition, then radiation exposure with respect to incorporation of activated air can be neglected, because of low concentration and dose factors.

Should incorporation of radioactive material be totally avoided, pregnant or breast feeding female staff members are not allowed to have access to linear accelerator vaults, despite the radiation dose resulting. This solution guarantees, that dose limits to the fetus are always kept, based on measurements by official exposure detectors, i. e. film, TLD, OSLD. In ICRP 103 Report [13, 14] a maximum external dose to the fetus of 1 mSv is stated, the incorporation should be kept "extremely low". This statement doesn't prohibit access and working in linear accelerator vaults. Employers, radiation protection officers and radiation protection commissioners have to guarantee by organizational procedures the compliance with regulations, to keep maximum permissible doses for pregnant and breast feeding staff members.

IV. RESULTS

Detailed measurements of the local dose rate have been carried out on the distinctive positions on two medical linear accelerators. In Figure 1 the dose

Figure 1 Time - Dose Rate Characteristic (18 MeV-X unit).



Measuring points: CR crosshair/treatment head; IC isocentre (field size 20 x 20 cm2); M RT position (45 cm beside IC, 100 cm above floor; beam-on and set-up time: ≤ 1 min; measuring interval 14 min; number of simulated fractions: 10.

rate dependency on time is shown for the three relevant positions: isocentre (IC), exit window or cross hair (CR) and position of radiotherapist (M). The peak dose rate is increasing according to number of simulated fractions, activation formula and photon fluence. For the positions IC and CR the saturation dose rates are achieved after application of 5 fractions and 3 fractions, respectively.

For the position M already after one fraction, the saturation dose rate is achieved: 1.96 µSv/h. Both positions, IC and CR, are not seen as realistic sites for pausing of the radiotherapist. For further evaluation only data measured at the position M are taken. The effective physical half life of the induced radioactivity shows a short- term and a longer component : T(short) ≈ 2 minutes; T(long) > 43 minutes. A separation and identification of isotopes based on dose rates is impossible, because of the minimum mean free path length of photons is about 60 m in air. Therefore each individual measurement shows contributions of all components, i. e. linear accelerator, floor, walls, air, etc.

Mathematical integration of dose rate curve (sum of two exponential functions) within the limits t1 and t2 (t1: entering treatment room; t2 leaving treatment room) adds up to the dose to a member of the staff with respect to one fraction. On days with TBI treatments the dose rate is increased by a factor of 3.8 (Table 3). The calculated dose at position M per fraction is 0.16 µSv (unit I) and 0.2 µSv (unit II). Accounting for the basic conditions (see above) the annual dose to the uterus is 3.5 mSv (unit I) and 2.1 mSv (unit II). For a 9-months-period (pregnancy) and without any special treatments (i. e. TBI), the fetal doses are still above the limit of 1 mSv (Table 4) for both units.

Table 3 Annual external exposures

Unit	I	II
Scenario 1 [mSv/a]	1.8	1.4
Scenario 2 [mSv/a]	3.5	2.1
Scenario 3 [mSv/a]	1.1	0.9
Scenario 4 [mSv/a]	0.3	0.2
Scenario 1 [mSv/a] (no TBIs)	1.4	1.1

Explanations: Scenario 1 und 2 (see text); Scenario 3: normal routine (3 min. break and 11 min. resp. 6 min. set-up time); Scenario 4: normal routine (1 min. set-up time and 13 min. resp. 8 min. break); Beam on time for all scenarios: ≤ 1 min.

Table 4 Dose-Reduction-Factors

Modality	k_i
MU(HIGH EBS) vs. MU(total) :	* 0.4
Number of RTs/Technologists :	* 0.5
Number of patients per day :	* 0.8
Set-up time :	* 0.67
Position of RTs/Technologists :	* 0.86
kred :	≈ * 0.09
⇨ Dred ≤ 0.32 mSv	

V. DISCUSSION AND CONCLUSIONS

Radiation protection recommendations, such as ICRP, EURATOM [13, 14, 15], and subsequently national regulations[1], have lowered continuously the limits of protection for ionizing radiation for the public as well as for pregnant occupationally exposed female workers. Especially protection of fetus became more and more a higher priority. The latest recommendation is 1 mSv for external exposure to the fetus and the internal exposure should be "reasonable low". Although this consideration of the worst-case scenario results in a non-negligible annual dose to members of the staff of radiotherapy departments, the monthly or quarterly film dosimetry records (or for other detectors) show no detectable doses. From a practical point of view some dose reduction factors come into effect, i. e. usage of high energy photon beams (40 %), number of radiotherapists and technologists (at least two radiotherapists), practical set-up times (t < 14 min. and 9 min., respectively), position during set-up of the patient (Table 5 and Table 3), number of patients per day (about 80 % of the worst-case assumption). The overall reduction factor kred is the product of the individual factors ki : kred = Πki = 0.09. Taking this factor into account, the annual doses might be reduced by about 90 %: Dred = 3.5 mSv • kred = 0.32 mSv. Additionally, it has to be accounted for the threshold levels, accuracy and

Table 5 Mean local dose rate values (after routine treatment day) for treatment unit II.

Position	Dose rate* [µSv/h]	Rel. Dose rate [%]
Treatment head (CR)	3.88	626
Isocentre ** (IC)	0.61	98
Isocentre *** (IC)	1.32	213
Treatment head (100 cm) (S)	0.51	82
Cover of treatment head (5 cm) (C)	0.99	160
Turn table (T)	0.93	150
RT/technologist position (M)	0.62	100
RT (upper trunk/front) (M)	0.75	121
Walls (W)	0.24	39
Floor (F)	0.37	60
Maze/door (S/T)	0.15	24
Counter (A)	0.34	55
Control console ("Beam On") (K)	0.81	131

* *ca. 20 min after treatment end;*
** *closed jaws;*
*** *field size 20 x 20 cm²*

reproducibility of the detector systems (film, TLD, OSLD), as well as for possible rounding errors in data evaluation and reporting: The non-detectability of doses smaller than 0.32 mSv per year is obvious. But with respect to the dose minimizing dictate of national and international regulations and recommendations, steps have to be taken to guarantee optimal protection of pregnant and breastfeeding staff members.

This can be accomplished by prohibiting access to treatment rooms/vaults for work-related groups. All linear accelerator vaults, where a unit with higher photon energy than 10 MeV-X is in operation, are affected. The affected group of staff members includes therapists, technologists, physicians, and physicists. A total avoidance of the linear accelerator area/vault for pregnant staff members is the absolute safest and most satisfying solution to keep internal and external doses below limits 1. Accuracy of external dose detection at this low level, rounding errors and limited knowledge about internal dose distributions support this statement [16]. The integrity of the fetus should have priority over economic considerations [2, 12, 17].

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