NUKLEONIKA 2016;61(1):23–28
doi: 10.1515/nuka-2016-0006

ORIGINAL PAPER

DE GRUYTER
OPEN

Ambient dose equivalent measurements in secondary radiation fields at proton therapy facility CCB IFJ PAN in Krakow using recombination chambers

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Abstract. This work presents recombination methods used for secondary radiation measurements at the Facility for Proton Radiotherapy of Eye Cancer at the Institute for Nuclear Physics, IFJ, in Krakow (Poland). The measurements of $H^*(10)$ were performed, with REM-2 tissue equivalent chamber in two halls of cyclotrons AIC-144 and Proteus C-235 and in the corridors close to treatment rooms. The measurements were completed by determination of gamma radiation component, using a hydrogen-free recombination chamber. The results were compared with the measurements using rem meter types FHT 762 (WENDI-II) and NM2 FHT 192 gamma probe and with stationary dosimetric system.

Key words: recombination chambers • workplace monitoring • proton therapy

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Received: 27 August 2014
Accepted: 7 July 2015

Introduction

Proton therapy is an effective form of radiation therapy for many types of tumors and it is often considered as being the most advanced radiation therapy available today. The main difference between proton therapy and the use of standard X-ray radiation is that protons deposit much of their energy directly in the tumor and then stop. This allows delivering higher doses to the tumor, while reducing damage to surrounding healthy tissues [1, 2]. The most significant benefits of proton therapy over standard X-ray radiation are [3–9]: reduced risk of damage to healthy tissue, fewer short- and long-term side effects, improved quality of life, and lower incidence of secondary tumors.

The first hospital-based proton center was opened in 1990 at Loma Linda University Medical Center. Since that time, the technology and medical experience have greatly improved, and about 100 000 people worldwide have received proton therapy at centers in United States, Europe, and Asia.

The first proton eye radiotherapy facility operating in Poland was built at the Institute of Nuclear Physics of the Polish Academy of Sciences (IFJ PAN) in Krakow, based on the AIC-144 isochronous cyclotron designed and constructed at IFJ PAN in the early 1990s to accelerate light ions for research in nuclear physics. The radiotherapy facility [10, 11] was fully activated in 2009 in collaboration with the Department of Ophthalmology and Ocular Oncology (Collegium Medicum of the Jagiellonian University--CMUJ and the Centre of Oncology in Krakow.

Following this, the Bronowice Cyclotron Centre (in Polish – Centrum Cyklotronowe Bronowice, CCB) has been organized, as a part of IFJ PAN [12]. In 2012, the Proteus C-235 cyclotron, produced by IBA (Ion Beam Applications S.A., Belgium), with energy selector and rotating arm (gantry), was installed in its new building. CCB will provide both proton ocular and scanning beam proton radiotherapy.

Proton dose to the irradiated organ can be planned and verified with high precision. There is, however, a radiation protection issue, associated with the fact that high-energy proton beams generate complex radiation fields, with neutrons and gamma radiation being the largest contributors to the out-of-field doses in the vicinity of irradiated organs. This includes an extra secondary radiation dose generated by proton therapy machines, proton line with collimator and impossible to avoid secondary radiation produced in the patient's body [13]. This unwanted radiation contributes to the summary dose delivered to the patient and may also affect the medical staff at the therapy room. The assessments of both effective dose and doses at different parts of the body are important due to the possible development of secondary cancers and for better characterization of different workplaces [14–17].

Neutrons have a greater effect on tissue than electrons and photons. This is included in the definitions of quantities used in radiation protection. The two most important are the operational quantities ambient and personal dose equivalent, which are defined as the product of the energy deposited (i.e., the absorbed dose, and a qualifying factor that allows for the radiobiological effects of the same dose when delivered by different radiation types). These are the quantities in terms of which survey instruments and personal dosemeters, respectively, are calibrated and in terms of which their responses are usually expressed [18, 19].

The biological impact dependent on neutron energy is peaking at about 1 MeV and the ideal neutron detector should have a similar response across the energy spectrum as equivalent dose in tissue. In practice, most detectors have response, which depends strongly on neutron energy but the peak is not at 1 MeV.

One of the most significant features of neutron fields is the very wide range of possible neutron energies. Especially difficult are the measurements near high-energy accelerators, where neutrons occur with energies from those of thermal neutrons at a few meV to the upper end of the available energy. This enormous range sets a challenge for designing measuring devices and uncertainty of the calibration factor in a radiation field of unknown neutron energy is usually the main factor determining the total uncertainty of the measurements. Usually, more than one instrument is used for characterization of high-energy neutron radiation fields and final conclusions are drawn based on the comparison and analysis of all the results.

The most common instruments for real-time field measurements of neutron dose equivalent are neutron rem meters. These devices are designed so that their response per unit fluence approximates an appropriate fluence-to-dose conversion function. Typically, a polyethylene moderator surrounds a thermal neutron detector, such as a BF_3 counter tube. Internal absorbers may also be used to further fine-tune the detector response to the shape of the desired fluence conversion function. All models using a pure polyethylene moderator have no useful high-energy response, which makes them inaccurate around high-energy accelerator facilities.

Another possible method is the use of recombination chambers, which are high-pressure, tissue-equivalent ionization chambers, designed in such a way that the initial recombination of ions occurs when the chamber operates at polarizing voltages below saturation, and the initial recombination is much greater than volume recombination [20]. The amount of recombination is related to linear energy transfer (LET), so also to radiation quality [21]. This property can be used for the determination of dose-equivalent quantities [22]. Recombination chambers are specially suitable for beam dosimetry and workplace measurements at high-energy accelerators, because of relatively flat energy response of the instrument over whole neutron energy range and linear response in pulse radiation fields even at high dose rates [23–26].

In this work, the recombination chamber of REM-2 type (developed in the former Institute of Nuclear Research and manufactured by POLON Bydgoszcz) has been used in IFJ PAN for determination of ambient dose equivalent, $H^*(10)$, at ocular therapy facility operating with AIC-144 cyclotron and in vicinity of the new Proteus C-235 cyclotron. The results recorded at AIC-144 were compared with the measurements performed using a FHT 762 WENDI-II rem meter and FHT 192 probe (Thermo Electron Corporation).

Materials and methods

Recombination chamber of REM-2 type [22] contains 25 parallel-plate tissue-equivalent electrodes, with a total mass of 6.5 kg. The effective wall thickness of the chamber is equivalent to about 1.8 cm of tissue and the gas cavity volume is of about 2000 cm^3. The chamber is filled with a gas mixture consisting of methane and 5% of nitrogen, up to a gas pressure of about 1 MPa. The chamber roughly approximates dosimetric parameters of the ICRU sphere and can be used for determination of $H^*(10)$ in mixed radiation fields without additional moderators. The chamber has similar sensitivity to neutrons and photons, so contrary to most instruments, it measures total value of $H^*(10)$.

Generally, the output of the recombination chamber is the ionization current (or collected charge) as a function of polarizing voltage. Measuring methods are based on determination of the dose rate as being proportional to the saturation current (an appropriate calibration factor is used) and of radiation quality from the amount of initial recombination.

Recombination chambers are always calibrated in neutron and gamma radiation fields. Calibration factor N, determined in neutron radiation field, is then used for measurements of the total absorbed dose. In this work, the chamber was calibrated with ^{239}Pu-Be radiation source in the calibration hall of National Centre for Nuclear Research.

The method used for determination of radiation quality involves measurements of two ionization currents i_S and i_R at two properly chosen polarizing voltages U_S and U_R. A certain combination of these two currents, is called recombination index of radiation quality Q_4 and may serve as a measurable quantity which depends on LET in a similar way as the radiation quality factor does [20, 21].

Polarizing voltage U_S = 1200 V is the high voltage, the same as for the measurements of the absorbed dose. The lower voltage U_R = 50 V, called the recombination voltage, has been determined during calibration of the chamber in gamma radiation field. U_R is the voltage at which the ion collection efficiency in ^{137}Cs gamma radiation field equals 0.96 (i.e., 4% of ions, generated in sensitive volume of the chamber, recombined before they were collected). The value of Q_4, is calculated as:

(1) $$Q_4 = (1 - f_R)/0.04$$

where f_R is ion collection efficiency measured in investigated radiation field at the voltage U_R.

Finally,

(2) $$H^*(10) = (i_s/N)\cdot Q_4$$

The same method has been successfully used in our earlier measurements at proton therapy facilities [27, 28].

Measurements of total $H^*(10)$ were completed with determination of gamma component of the value. Measurements were performed using high-pressure hydrogen-free ionization chamber of the same design as REM-2, but with aluminum electrodes and filled with carbon dioxide. The chamber (marked as GW-2) was calibrated in gamma radiation field of ^{137}Cs source and can be considered as neutron insensitive.

Results of measurements with recombination chambers were compared with data obtained using rem meters type NM2 and WENDI-II. The wide energy neutron detection instrument (WENDI-II) is a rem meter with a ^{3}He counter tube located in the center of a cylindrical polyethylene moderator assembly. Tungsten or tungsten carbide (WC) powder is added to a polyethylene moderator for the purpose of generating spallation neutrons in tungsten nuclei and thus enhance the high-energy response of the meter beyond 8 MeV. Tungsten's absorption resonance structure below several keV was also found to be useful in contouring the meter's response function [29, 30]. NM2B is a moderated BF_3 proportional counter, whose response is considered acceptable for neutron energies between thermal limits and ~10 MeV.

All the measurements with recombination chambers result in mean values of the measured quantities over the measuring time of few minutes. For WENDI-II and NM2, the minimum and maximum of measured values were recorded (at the same time as for REM-2). In order to account for radiation intensity variations, all the measured values have been normalized to the reference monitor readings.

At Proteus C-235 cyclotron, the measurements were performed also with LB-6411 and LB-6360 dosimetric probes, which constituted parts of local dosimetric system. The LB-6411 neutron probe (Berthold Technologies) consists of a polyethylene moderator sphere with a ^{3}He counter tube at its center. It can be used for monitoring of neutron radiation fields with energy up to 10 MeV. For higher energies, its sensitivity considerably decreases. The Low Dose Rate – Gamma Probe LB 6360 (Berthold Technologies) is a proportional counter tube calibrated in terms of ambient dose equivalent.

Measurements

The aim of the measurements was determination of secondary radiation generated in the therapy room and corridors close to the cyclotron hall of AIC-144 cyclotron with maximum energy of 60 MeV and Proteus C-235 cyclotron with maximum energy 230 MeV.

Measuring positions at 60 MeV proton therapy facility based on AIC-144 cyclotron are sketched in Fig. 1, where X is the position on the patient chair, P is on the floor near the patient chair and A2 is the position in the corridor near the entrance to the treatment room. It is located on the wall opposite the door, mounted at a height of 2 m (the same position as a dosimetric system mounted at the facility). Point B is the position behind the door to the experimental hall with a separate therapy room, point L is located at the corridor on the wall (the same position as dosimetric system mounted in the facility) at the height of 2 m. Point E is in the corridor with the access only to the staff.

The maximum width of modulation of proton beam (28.3 mm) was used during the measurements because it was expected that doses of stray radiation would be maximum at such a configuration. The patient's head, which is an additional source of stray radiation during the treatment, has been simulated by a poly(methyl methacrylate) (PMMA) phantom, placed on the patient chair. The mean dose

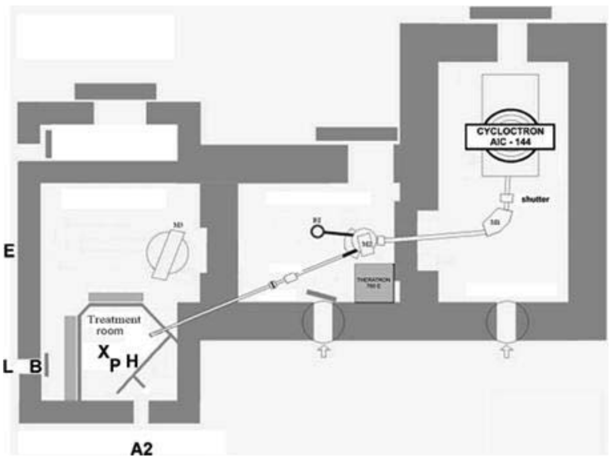

Fig. 1. Measuring positions at ocular therapy facility.

rate of the proton beam in the eye ball phantom was 0.2 Gy·s^{-1}.

The measurements of second series were performed at facility equipped with Proteus C-235 cyclotron, which is able to accelerate protons to 230 MeV. An energy degrader and selector allow for downgrading the beam energy continuously to 70 MeV, with intensities up to 500 nA. In this work, the measurements were performed in the treatment room and at the door to the cyclotron hall, at proton energies of 70, 76 and 100 MeV.

Results and discussion

The results of $H^*(10)$ measurements at ocular proton therapy facility are shown in Table 1. The accuracy of Q_4 is of about 10% and accuracy of $H^*(10)$ is estimated to be of about ±20% for both instruments.

All the values of $H^*(10)$ in the treatment room are at the level of few mSv per hour (from about 0.9 mSv/h to about 2.6 mSv/h) and do not cause any considerable hazard for the patient. Radiation hazard in corridors is also negligible. There are no permanent workplaces in the area and time of the accelerator operation is strongly limited.

The results of REM-2 and WENDI-II are in good agreement for the measuring points outside the treatment hall, while inside the room the REM-2 values are considerably higher than those of WENDI-II. The first possible reason could be the photon contribution, as REM-2 measures the total $H^*(10)$ while WENDI-II only the neutron component. However, in this case, a high value of Q_4 clearly suggests that the gamma radiation contribution to $H^*(10)$ does not exceed few percent of the total value. The difference is, therefore, due to different energy dependence of the instrument response.

In neutron dosimetry, the energy dependence of the instrument response is expressed as the ratio of the instrument reading $r\Phi(E)$ to fluence to ambient dose equivalent conversion factors $k\Phi(E)$. In such presentation, the energy dependence of the REM-2 chamber response does not significantly differ from unity. For the chamber calibrated with ^{241}Am-Be source, there is a slight overestimation in the region of 1 MeV, with the maximum value of about 1.6 and narrow minimum in the region from 10 to 15 MeV with minimum value of about 0.8. At 19 MeV, the chamber response is again close to unity and remains at this level up to more than 100 MeV [23].

The energy dependence of WENDI-II response is flat within ±30% in the neutron energy range from 0.1 to 10 MeV. Below 0.1 and over 100 MeV, the instrument overestimates the $H^*(10)$ value. Important for this work is the fact that in the neutron energy range from 10 to 100 MeV, there is underestimation, with minimum value of about 0.5 in the range from about 15 to about 40 MeV [29, 30]. Monte Carlo simulations of the proton therapy facility [31] have shown that about 70% of total $H^*(10)$ value is due to neutrons of energy from the range between 10 and 30 MeV. Slightly higher energy response of REM-2 chamber in this energy region well explains the ob-

Table 1. Results of $H^*(10)$ measurements at ocular proton therapy facility

Measuring position	REM-2 (mean value)		WENDI-II (minimum÷maximum values)
	$H^*(10)$ [μSv/h]	Q_4	$H^*(10)$ [μSv/h]
X	2586	7.3	1211÷2098
P	877	7.6	567÷653
H	1532	7.4	590÷680
A2	<4.4	6.4	3.8÷4.3
B	11.5	6.4	10.0÷11.8
L	<4.4	6.4	1.4÷1.8
E	<2.2	6.4	0.1÷0.3

Table 2. Results of the $H^*(10)$ measurements at proton facility with Proteus C-235 cyclotron

Position	Proton energy [MeV]	REM-2		GW-2	FHT 762 (WENDI-II)	FHT 192
		Q_4	$H^*(10)$ total [mSv/h]	$H^*(10)$ gamma [mSv/h]	$H^*(10)$ total [mSv/h]	$H^*(10)$ gamma [mSv/h]
'Patient'	70	5.6	2.78	0.2	3.2	0.8
	76	5.7	5.00	0.3	4.2	1.2
	100	6.0	26.53	1.5	24.0	8.6
'Electronic equipment'	70	4.9	1.11	0.1	0.8	0.06
	76	5.3	1.67	0.2	1.3	0.07
	100	5.4	6.11	0.6	5.3	0.3
'Floor' (beside patient)	70	6.5	0.89	0.1		
	76	6.5	1.22	0.1		
	100	6.9	6.11	0.4		
'Entrance to the cyclotron hall'	100	5.0	$2.33\cdot10^{-3}$		$0.4\cdot10^{-3}$	$0.2\cdot10^{-3}$
					CCB stationary dosimetric system LB 6411/LB 6360	

served differences in measured values of $H^*(10)$ in the treatment room, while energy response in more degraded neutron energy spectrum in the corridor becomes similar to both instruments.

The results of the measurements at proton facility with Proteus C-235 cyclotron are shown in Table 2. In this case, the gamma radiation contribution to $H^*(10)$ was directly measured with the GW-2 chamber.

The values of $H^*(10)$ measured in the treatment room of the new facility at 70 MeV are only slightly higher that at AIC-144 ocular therapy facility and, as it could be expected, rapidly increase with increase of the proton beam energy. The values of Q_4 are slightly lower than at AIC-144 cyclotron and gamma radiation contribution to the $H^*(10)$ is about 10% of the total value for all measuring positions.

Conclusions

The measurements described in this work have been performed for radiation protection purposes. The aim of such measurements is to achieve the sufficient accuracy of radiation monitoring for radiation safety. However, the accuracy requirements for neutron radiation protection are not clearly laid down by any international body. The latest European Commission guidance [32] gives recommendations for personal dose equivalent as: "For a measurement of the operational quantity $H_p(10)$ for a single field component for a quantity value equal to or greater than 1 mSv (annual dose limit for effective dose for members of the public) in proportion to the wear period, the combined standard uncertainty should be less than 30% for photon/electron workplace fields and less than 50% for neutron fields". This rather high level of acceptable uncertainty presumably reflects the difficulty of measuring this quantity, especially in high energy radiation fields. The accuracy of the measurements with recombination chambers in complex stray radiation fields is usually within 20%, so such measurements may provide additional information leading to considerable improvements of radiation monitoring.

Measurements at proton facility CCB IFJ PAN for beam energy from 60 to 100 MeV (energy for eye cancer radiotherapy) confirmed that hazard for the patient due to stray neutron radiation is statistically insignifant. Radiation hazard to staff and visitors is also negligible.

Acknowledgment. The work was partly supported by Warsaw University of Technology, the Faculty of Physics as a part of Human Capital Operational Programme no. 4.1.1 "Preparing and realization of medical physics faculty".

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