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OUT-OF-FIELD DOSIMETRY OF THE JINR RADIOTHERAPEUTIC PROTON BEAM USING THERMOLUMINESCENT DETECTORS

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Дозиметрия рассеянных дозных полей с помощью термолюминесцентных детекторов в кабине радиотерапевтического протонного пучка ОИЯИ

Описаны результаты экспериментов, проведенных на клиническом протонном пучке в Лаборатории ядерных проблем ОИЯИ (Дубна). Эксперименты были направлены на определение поглощенной дозы в непосредственной близости от облучаемой мишени и оценку средней величины линейной передачи энергии (ЛПЭ). Измерения были проведены с использованием нескольких различных типов термолюминесцентных детекторов (ТЛД), которые расположены в фантоме из органического стекла. Средняя величина ЛПЭ была оценена на основании различной зависимости отклика различных типов ТЛД от величины ЛПЭ. Мы определили, что относительная величина поглощенной дозы вокруг мишени уменьшается до 0,01 % от максимальной дозы, поглощенной в мишени. Также мы оценили, что средняя величина ЛПЭ не превышает 6 кэВ/мкм. Эксперименты показали, что происходит рассеяние частиц в системе транспортировки пучка, которое вносит вклад в поглощенную дозу вокруг мишени. Рассеяние пучка придает несимметричность распределению дозы от вторичных частиц вокруг мишени. Однако уровень фона поглощенной дозы вокруг облучаемой мишени в результате рассеяния пучка не является опасным для пациента.

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Out-of-Field Dosimetry of the JINR Radiotherapeutic Proton Beam Using Thermoluminescent Detectors

We describe results of experiments performed at the clinical proton beam of the Laboratory of Nuclear Problems of JINR (Dubna, Russia). The experiments were focused on determination of the out-of-field doses in the near vicinity of the irradiated target volume and estimation of the linear energy transfer (LET) distributions. Measurements were performed using several types of thermoluminescent detectors (TLD) placed in the polymethylmethacrylate phantom. The average value of the LET was estimated using knowledge of the relative response of the TLD to the radiation with different LET. It was found that the relative out-of-field dose values decline up to 0.01% of the dose delivered to target and that the average value of the LET in the vicinity of the target does not exceed 6 keV/μm. Further we revealed scatter of the radiation in the collimation system causing the nonsymmetry of out-of-field distribution. Fortunately, we found out that it does not pose a hazard for the patient.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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INTRODUCTION

Radiotherapy is based on principles of maximal dose delivery into a target volume and minimal radiation load of surrounding healthy issues. Naturally, these two conditions are opposite to each other. Redundant radiation load of healthy tissues increases probability of second primary malignancies induction. Moreover, radiation initiated cell can remain dormant during several decades until new damage is inflicted on genome or a decrease in defence mechanisms efficiency occurs [1].

This work is primarily focused on measurement of out-of-field dosimetric characteristics in the clinical proton beam of the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research. Experiments were focused on determination of 2-dimensional absorbed dose and linear energy transfer distributions using only properties of the thermoluminescent detectors. Furthermore, results are planned to be used for verification of the beam transport system of Monte Carlo model. Measured profiles show that out-of-field doses in homogeneous phantom are not distributed in symmetric way and that there is a source of scattered radiation causing the nonsymmetry of the profiles. In spite of the changes performed in the beam transport system, the effect has been eliminated only partially. Therefore we performed additional experiments, which allowed us to estimate scattered radiation source and the radiation quality of the scattered radiation.

MATERIALS AND METHODS

As we mentioned in Introduction, we decided to use thermoluminescent dosimeters (TLDs). The TLDs combine advantages of the «point-like» and high sensitivity passive detectors, allowing integration of very low dose rates and detection of low dose gradients. Totally, we used 4 various types of highly sensitive TLDs, namely Al_2O_3:C, $CaSO_4$:Dy, MCP6 (^{6}LiF:Mg, Cu, P, Harshaw TLD600H equivalent) and MCP7 (^{7}LiF: Mg, Cu, P, Harshaw TLD700H equivalent). Disadvantage of TLDs is that their response depends on the radiation quality. In case of TLDs used in our work, their response decreases with increasing LET.

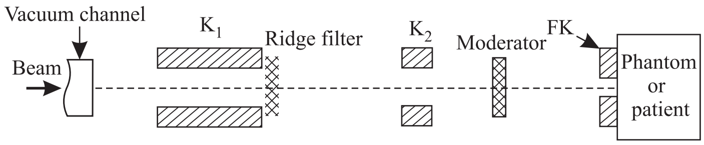

Fig. 1. Schematic drawing of the beam collimation system in the treatment room No. 1. K_1 and K_2 represent primary and intermediate collimators, FK represents the shaping collimator

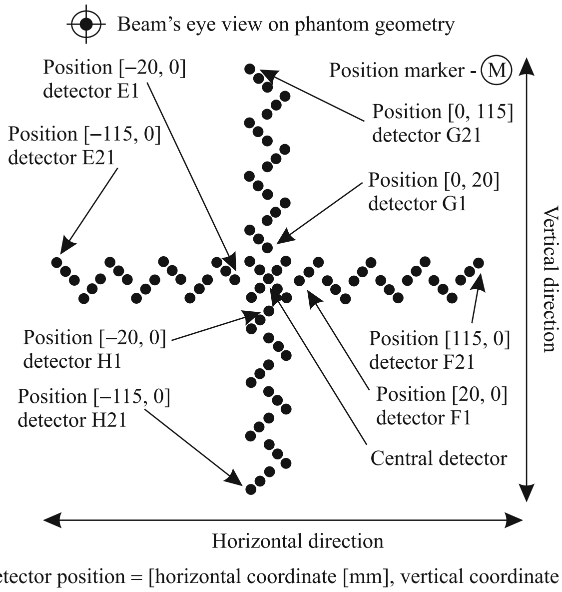

Fig. 2. Schematic drawing of the phantom. Detectors were placed in the way minimizing their reciprocal shielding. Black dots represent position of detectors. Introduced system of coordinates allows exact determination of the spatial phantom orientation and the position of all TLDs

Let define relative sensitivity of the TLD R_Y to the radiation of the quality Y using the equation

$$R_Y = (TL_{\text{reading}})_Y \big/ (TL_{\text{reading}})_{\text{Co}-60\gamma},$$

where $(TL_{\text{reading}})_Y$ resp. $(TL_{\text{reading}})_{\text{Co}-60\gamma}$ is response of the TLD to the same dose delivered imparted to the mater by radiation of quality Y and by ^{60}Co photons. Then, reversely, the dependence can be used with advantage to determine radiation quality of the field, which the detectors were exposed to. More information can be found in [2, 3].

Detectors were calibrated in ^{60}Co in terms of absorbed dose to water. Relative dose values were acquired as a ratio of dose measured with respective detector and dose delivered to the target volume. In case of the combined measurements with MCP6 and MCP7 TLDs, the response was evaluated only relatively as a ratio of the signal of the respective detector to the signal of the detector placed in the target volume. Individual sensitivity of the detectors was corrected using additional irradiation of the ^{60}Co beam.

Combined uncertainty of the calibration is lower than 8% and was estimated summing up the uncertainty of the determination of the activity of the calibration source (1.18%), calibration geometry uncertainty (1.3%), uncertainty of TLD response (5%) and uncertainty introduced by evaluating process (4%). Combined uncertainty estimation of the average LET value in water from response of different types of TLDs on the same dose is given by uncertainty of the calibration function (15%) and dose determination (5%), and is lower than 17%.

Expositions were realized in the treatment room No. 1, which is primarily used for brain radiotherapy and radiosurgery. The average energy of the entering proton beam was 171 MeV. In the room, the beam passed further through three collimators, additional moderator and the Bragg peak was spread out to 6 cm

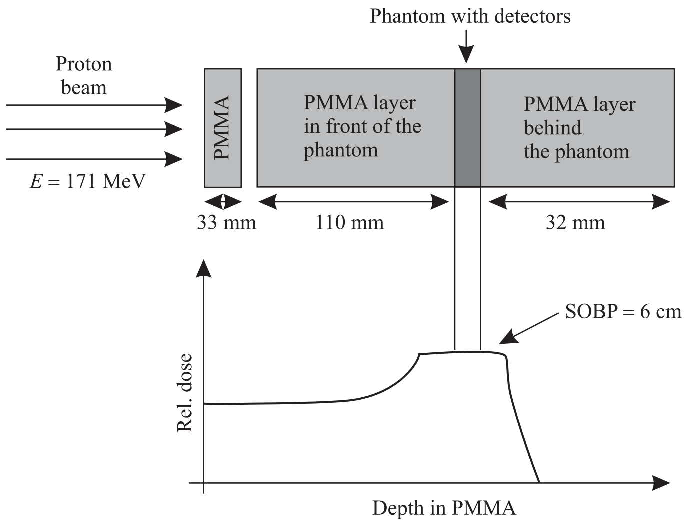

Fig. 3. Schematic drawing of the experiment, in which the phantom was positioned between two PMMA layers and measuring the dose in the middle of the spread-out Bragg peak area. There were two other experimental arrangements, both differing only in placement of the phantom. In the first one, the phantom was placed in front of both PMMA layers and measured dose distributions at the beam enter. In the second one, the phantom was placed behind both PMMA layers and measured dose in the area behind the range of the primary protons

plateau using ridge filter. Schematic drawing of the beam collimation system in the treatment room No. 1 is shown in Fig. 1.

TLDs were placed in a polymethylmethacrylate (PMMA) phantom, which schematic drawing is shown in Fig. 2. The phantom was placed in three positions: *a*) at the enter of the beam having additional PMMA layers behind it; *b*) between two PMMA layers at SOBP region; and *c*) behind the both additional PMMA layers. Additional PMMA blocks simulated scatter of the primary beam in the patient body. Schematic drawing of the experiment is shown in Fig. 3.

Because we used the beam impinging only from one direction, the target volume was defined with the beam dimensions and the spread-out Bragg peak length. Absorbed dose delivered to the target volume was equal to 30 Gy except of the irradiations, in which we combined MCP6 and MCP7 TLDs. In those cases, the dose delivered to the target volume was equal to 50 Gy.

RESULTS

First Set of the Measurements. Phantom with detectors was placed between two PMMA plates. We found out that out-of-field doses around the target volume area are distributed in nonsymmetric way. Although the dose profiles were obtained for four different dimensions of the beam, nonsymmetric way of dose distribution was not influenced with it. Horizontal and vertical dose profiles are shown in Fig. 4. Collimation system changes, as schematically shown in Fig. 5, lead to partial improvement of the situation but the effect has not been fully eliminated. Dose distributions measured after the changes have been performed is shown in Fig. 6.

To acquire further information about the radiation field, we estimated average value of the LET at specific points. For this purpose, we used two types of TLD

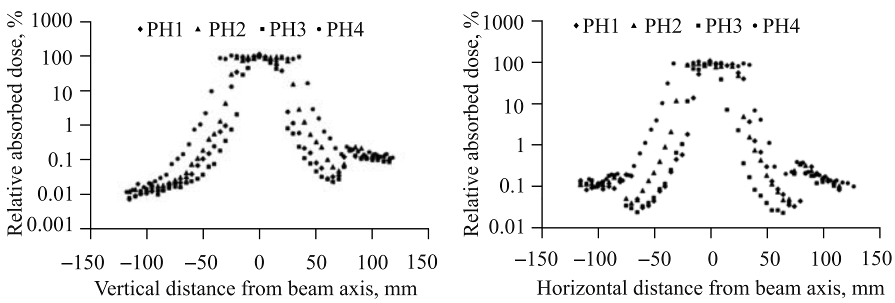

Fig. 4. Horizontal and vertical dose profiles measured during the first set of the experiments. Beam dimensions are as follows: PH1 — circle field diameter of 3 cm; PH2 resp. PH3 resp. PH4 — square fields with side of 4 resp. 5 and 8 cm

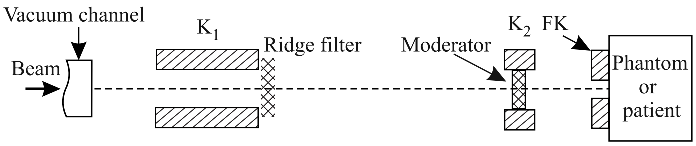

Fig. 5. Schematic drawing of the beam collimation system after the changes have been performed. Position of collimator K_2 and moderator has been changed

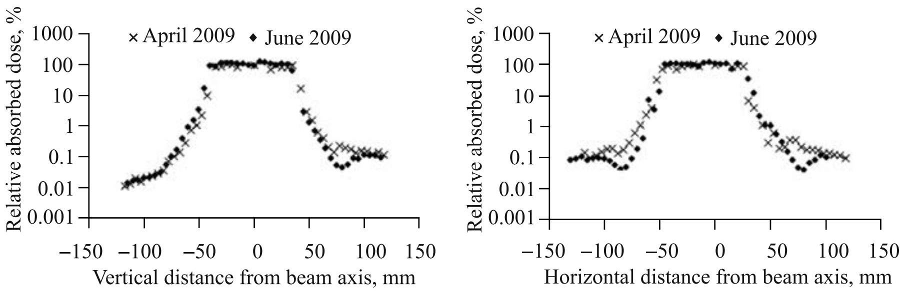

Fig. 6. Relative out-of-field doses measured after the changes of the beam transport system has been made. Crosses represent doses measured before the changes were made, black diamonds represent measurements performed after the changes to the beam transport system has been made

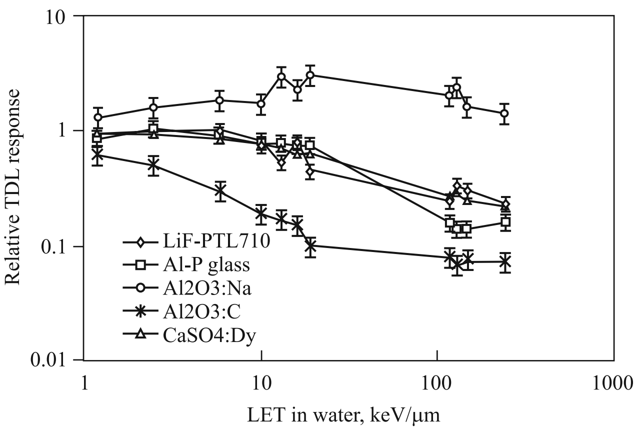

Fig. 7. Dependence of the relative response of the thermoluminescent dosimeters on the LET. Responses are normalized to the response of detectors to the ^{60}Co beams. Figure was taken from [4]

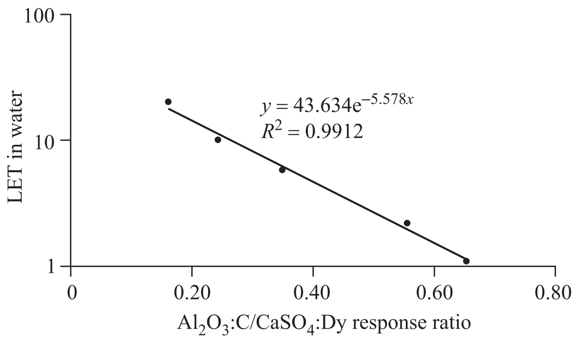

Fig. 8. LET as a function of Al_2O_3:C and $CaSO_4$:Dy response ratio. Uncertainty of LET estimation according to [4] is lower than 15%

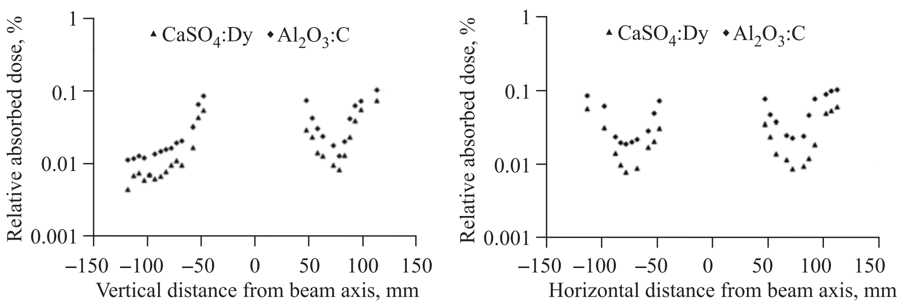

Fig. 9. Relative values of absorbed dose measured with two different types of detectors. Diamonds represent values obtained from $CaSO_4$:Dy TLDs, triangles represent values obtained from Al_2O_3:C TLDs. During the experiment, the square field with a side of 8 cm was used. Response of Al_2O_3:C rapidly decreases with increasing LET. Ratio of responses of both detectors was used to estimate average LET value

detectors: $CaSO_4$:Dy and Al_2O_3:C. Dependence of $CaSO_4$:Dy TLD response on the LET differs in comparison with dependence of Al_2O_3:C; it is shown in Fig. 7 (picture was taken from (Spurný, 2004)). Al_2O_3:C/$CaSO_4$:Dy response ratio can be used to estimate average value of LET of the impinging radiation. The calibration curve is shown in Fig. 8. LET distribution calculated from the dose distributions (Fig. 9) is shown in Fig. 10.

In the next experiment we focused on measurement with MCP6 detectors, which were primarily focused on the estimation of the thermal neutron flux near the target volume. Because we could not calibrate MCP6 in the neutron source, we compared only their relative responses normalized to the response of the detector placed in the target volume. Results are shown in Fig. 11. In contrary to dose profiles, thermal neutron fluxes profiles are distributed symmetrically.

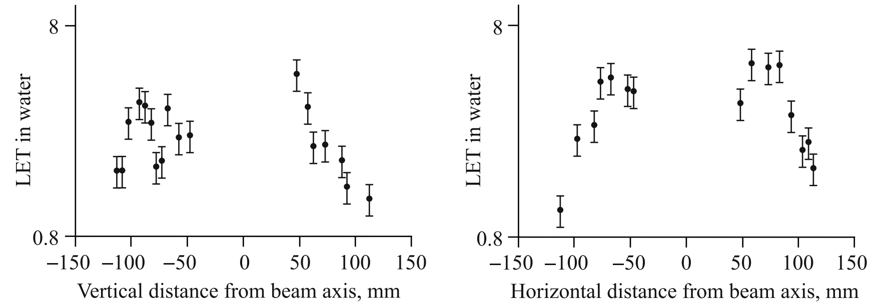

Fig. 10. Average value of the LET in water calculated from Al_2O_3:C/$CaSO_4$:Dy response ratio

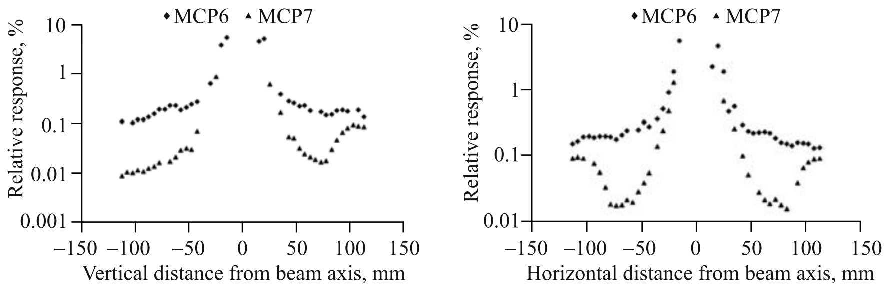

Fig. 11. Relative response of the MCP6 and MCP7 TLD detectors around the target volume. During the experiment, a circle field with a diameter of 3 cm was used and the absorbed dose delivered to the target volume was equal to 50 Gy

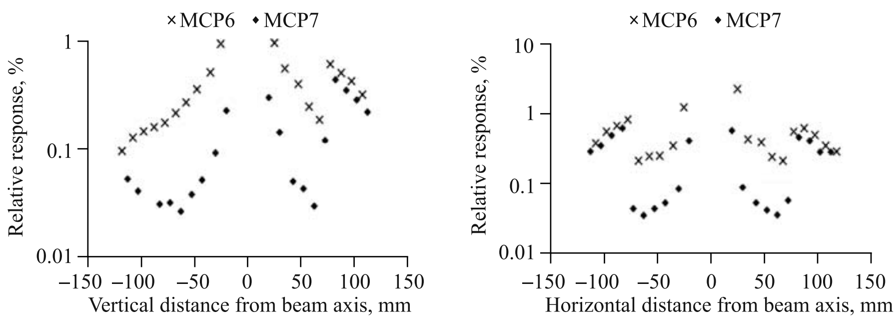

Fig. 12. Relative response of the MCP6 and MCP7 TLD detectors around the target volume. During the experiment, a circle field with a diameter of 3 cm was used, the absorbed dose delivered to the target volume was equal to 50 Gy

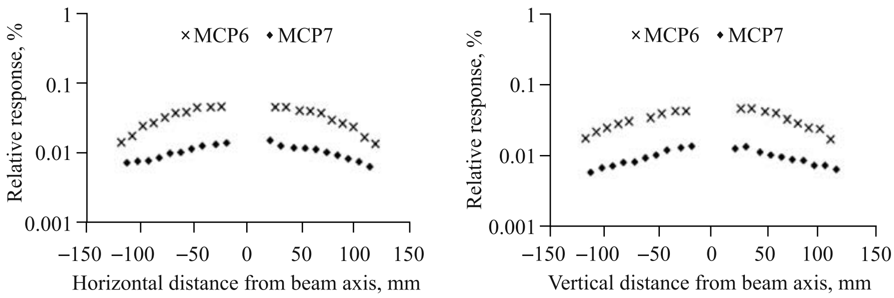

Fig. 13. Relative response of the MCP6 and MCP7 TLD detectors around the target volume. During the experiment, a circle field with a diameter of 3 cm was used, the absorbed dose delivered to the target volume was equal to 50 Gy

Second and Third Set of Measurements. To obtain more information about the nature of the effect causing the nonsymmetric distribution of doses, measurements were also performed having phantoms placed at the beam entrance and behind the spread-out Bragg peak. Experiment was performed in the same way as experiment, which results are shown in Fig. 12. Dose delivered to target volume was equal to 50 Gy, beam was circle shaped having diameter of 3 cm. Results are shown in Figs. 12, 13.

DISCUSSION

Dose Distributions and Their Shape. At first, we will discuss the shape of the out-of-field dose profiles. Figures 4, 5, 10 and 11 show that dose distributions are not symmetric. Expected dose distribution is measured only in negative vertical direction. We suppose that in this case the collimator tray absorbs scattered radiation. In remaining directions, sharp decrease is followed by subtle increase. The cause of the effect most probably lies in the scatter of the primary beam on one of the collimators in the collimation system. After the rearrangements of the beam collimation system, as shown in Fig. 5, improvement is observed. Despite of the improvement, effect has not been fully eliminated and is observed in further measurements.

Source of the Scattered Radiation. To determine source and types of the scattered radiation, we had to estimate type of the particles contributing to the observed effect. Figure 9 shows that dose distributions shape is similar for two different types of TLDs. Hence it follows that the unexpected shape of the dose profiles cannot be a result of the variation of the TLD sensitivity with respect to the LET of the radiation. Profiles shown in Fig. 11 show that the effect cannot be caused with thermal neutrons because response of the detectors enriched with ^{6}Li decreases in all directions. In Fig. 12 we can observe, that the thermal neutron flux decreases constantly in negative vertical direction but it is follows distribution measured with ^{7}Li type detectors in remaining directions. Taking into account collimator tray shielding effect, these results again support hypothesis that the effect is cased with scattered charged particles. Scattered particles are most probably produced in the collimation system or in the vacuum channel system. Finally, this hypothesis is also supported with results shown in Fig. 13 in which no nonsymmetry of the distributions behind the Bragg peak is observed.

Out-of-Field Doses in Comparison with Similar Experiments. It is difficult to compare similar results of our experiments with the results of other experiments because the proton beam therapy facility in Dubna is unique. Despite of this, we tried to compare our results with the similar experiments. One of them, described in [5], was performed in the clinical proton therapy facility of the Loma Linda University Medical Center (USA). Authors measured out-of-field dose equivalents during irradiation of anthropomorphic phantom with prostate cancer patient treatment plan. If we take into account that dose equivalent is defined via multiplication of absorbed dose with quality factor of order of two, we can make approximate comparison of the results. Comparison shows the agreement of the results is within one order.

Increased Out-of-Field Doses and Risk for the Patient. Increase of out-of-field doses in the positive vertical and both horizontal directions should be discussed in connection with second primary malignancies (SPM) radiation induction. Generally, as discussed in extensive study on SPM topic [1], it is very difficult to ascribe SPM induction to radiation load with low doses. Due to this paper, cancerogenesis is not simply the result of mutation of stem cell, because there are potent defence mechanisms in humans. Cancers are due to the failure of defence mechanism at the level of cell. If we take into account that typical prescribed doses in fractionated radiotherapy are equal to about 30 Gy, we get that the scattered radiation increases out-of-field doses by about 30 mGy. According to [1], during fractionated beam therapy, no clinically significant effect has been detected for doses per fraction below 120 mGy. Thus, we can conclude that measured effect does not pose a hazard for patients.

CONCLUSIONS

We have measured out-of-field dose profiles and estimated average LET value using methods of thermoluminescent dosimetry. Properties of the thermoluminescent detectors allowed us to detect nonsymmetric distribution of the radiation in the collimation system and to estimate type and source of the scattered radiation. Our further work will be focused on comparison of the results obtained with track-etch detectors and Monte Carlo simulations of the beam. Finally, we would like to conclude that the radiation load of healthy tissues represented with increase of out-of-field doses in positive vertical and both horizontal directions can be assumed to be negligible.

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