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DETERMINATION OF ELECTRON BEAM PARAMETERS ON RADIATION-TECHNOLOGICAL FACILITY FOR SIMULATION OF RADIATION PROCESSING

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It was performed the practical approval of special computational method PFSEM for reconstruction of EB characteristics on the base of two-parametric fitting of semi-empirical model for the depth-dose curves (DDC) of electrons beam. The measurement of DDC of electrons into standard dosimetric wedge were performed in the process of radiation sterilization of medical devices on the radiation facility with EB accelerator into INCT, Warsaw, Poland. It was shown that satisfactory agreement between the measurement results and simulation of the DDC of electrons beam with using PFSEM method is observed.
KEY WORDS: electron beam energy, dosimetric wedge, semi-empirical model, computational method PFSEM, Monte-Carlo method

ОТРИМАННЯ ПАРАМЕТРІВ ПУЧКУ ЕЛЕКТРОНІВ НА РАДІАЦІЙНО-ТЕХНОЛОГІЧНИХ УСТАНОВКАХ ДЛЯ МОДЕЛЮВАННЯ ПРОЦЕСІВ ОПРОМІНЕННЯ

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Проведена апробація спеціального розрахункового методу PFSEM для відновлення характеристик пучку електронів (ПЕ) на основі двопараметричної підгонки напівемпіричної моделі для глибинної залежності дози (ГЗД) ПЕ. Вимірювання дози електронів в стандартному дозиметричному клині проводилось в процесі радіаційної стерилізації медичних виробів на радіаційному обладнанні із прискорювачем електронів в Інституті Ядерної Хімії та Технологій, Варшава, Польща. Спостерігалося задовільне узгодження між результатами вимірювання та моделювання ГЗД ПЕ із використанням PFSEM методу.
КЛЮЧОВІ СЛОВА: енергія пучку електронів, дозиметричний клин, напівемпірична модель, розрахунковий метод PFSEM, метод Монте-Карло

ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ ПУЧКА ЭЛЕКТРОНОВ НА РАДИАЦИОННО-ТЕХНОЛОГИЧЕСКИХ УСТАНОВКАХ ДЛЯ МОДЕЛИРОВАНИЯ ПРОЦЕССОВ ОБЛУЧЕНИЯ

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Проведена апробация специального вычислительного метода PFSEM для восстановления характеристик пучка электронов (ПЭ) на основе двухпараметрической подгонки полуэмпирической модели для глубинной зависимости дозы (ГЗД) ПЭ. Измерения дозы электронов в стандартном дозиметрическом клине проводились в процессе радиационной стерилизации медицинских изделий на радиационном оборудовании с ускорителем электронов в Институте Ядерной Химии и Технологий, Варшава, Польша. Наблюдалось удовлетворительное согласие между результатами измерений и моделирования ГЗД ПЭ с использованием PFSEM метода.
КЛЮЧЕВЫЕ СЛОВА: энергия пучка электронов, дозиметрический клин, полуэмпирическая модель, вычислительный метод PFSEM, метод Монте-Карло

The process of radiation sterilization of medical devices refers to “critical technologies”. These technologies are conducting under continuous dosimetric control of all basic parameters of radiation facility and process irradiation. Control parameters on the EB accelerators are the following: energy and EB current, scanner characteristics, velocity of conveyer line, and value of EB absorbed dose on the surface of irradiated target – so called as sterilization dose. EB energy in time irradiation is controlled with dosimetric wedge or stack that together with irradiated products overpass all cycle irradiation. Sterilization dose control is realized with dosimetric calorimeter. The measurement of EB absorbed dose distribution in an irradiated product in detail is performed with dosimetric films.

Determination of the electron beam (EB) characteristics on the base of measurement results was performed with use of standard [1] and special [2-7] computation methods. Computer simulation of irradiation process allows profitably to perform dose mapping for EB and gamma irradiation, determination of location for maximal and minimal values of absorbed doses (D_{min} and D_{max}) into containers with irradiated products, calculates productivity of irradiated product [8]. In this case the volume of routine dosimetric measurements essentially decreased.

Quality factor of the computation methods of EB characteristics determination was based on calculation of the mean square deviation between measurement results and Monte Carlo (MC) simulation results for the DDC into standard dosimetric wedge. Determination of parameters that are necessary for correct computer simulation the irradiation process of product by EB, X-rays and gamma rays on radiation facility are actual tasks.

Available standard computational methods [1] do not allows correctly reconstruct spectral and angular EB characteristics. As a result, there are no possibility correctly simulate the absorbed depth-dose distribution of electrons into standard dosimetric devices such as wedge and stack.

Goal of the present work is investigation of possibility determination the electron beam characteristics on the base of measurement results of the absorbed depth-dose distribution of electrons into standard dosimetric wedge or stack. These results should be obtained with necessary accuracy for correct simulation the processes irradiation on the real EB radiation facility into practical activity of the radiation-technological centers.

PROCEDURE AND MEASUREMENT RESULTS

Irradiation of 2 standard Al wedges with PVC, CTA and B3 dosimetric films was performed on the electron linear accelerator Elektronika 10/10 at INCT, Warsaw with electron beam energy of 10 MeV [9]. Two Al wedges with PVC, CTA and B3 dosimetric films in form of strips were located in one Al box irradiated with a scanned electron beam of energy 10 MeV, pulse duration 5.6 µs, pulse frequency 370 Hz, average beam current 1.04 mA, scan width 58 cm, conveyer speed was in the range 1-0.1 m/min, scan frequency 5 Hz. Electron beam energy was measured with two Al wedges. Control of dose delivered to the wedges in time irradiation was performed with RISO polystyrene calorimeter [10].

The absorbed dose of irradiated materials was delivered in the range of 10-50 kGy. The maximum of combined uncertainty related to dose determination in the Al wedges with PVC, CTA and B3 dosimetric films for values of doses greater than 5 kGy did not exceed 8% (k=2). The uncertainty is a combination of the uncertainties related with dosimetric film calibration, in reproducibility of the series of experiments, the dose given at electron accelerator, spectrophotometer reader variability. The uncertainty of the length value measurement of dosimetric strips is 0.1cm.

PVC, CTA and B3 dosimetric films were calibrated against alanine dosimeter which is traceable to National Physical Laboratory, Teddington, Middlesex, UK [11].

Characteristics of dosimetric films are the following:CTA- Cellulose Triacetate film: density 1.32 g/cm^3, thickness 0.125mm, width 8mm; PVC - Polyvinylchloride film: density 1.3 g/cm^3, thickness 0.26mm, width 8mm or 16 mm; B3 – Polyvinylbutyral film: density 1.12 g/cm^3, thickness 0.02mm, width 10-15mm.

The SEMCO S/E_c spectrophotometer in automatic mode was used for reading the optical density at a wavelength of 394 nm from PVC strip films with a step of 0.1 cm along the film length. The FDR001 spectrophotometer in automatic mode was used for reading the optical density for CTA strip films using a wavelength 280 nm. The RISO flat-bed scanner was used for processing B3 dosimetric films.

Comparison of experimental and simulation results will be illustrated on the CTA dosimetric films located into standard Al wedges and irradiated with scanned EBs. The CTA films into wedges were irradiated with electrons in two regimes: at dose of sterilization – 35 kGy (regime 1), and 28 kGy (regime 2).

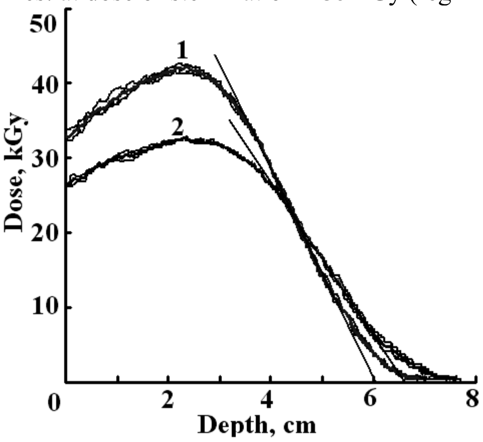

Fig.1. The depth-dose curves of electrons in CTA dosimetric films located in standard dosimetric wedges. Curves 1 – irradiation regime 1, curves 2 – irradiation regime 2.

Preliminary processing of measurement results was performed. Initial points of the absorbed depth-dose curves in CTA dosimetric films located in dosimetric wedges were determined. The systematic inaccuracies for values of absorbed dose were eliminated. Results of preliminary processing of experiments data for the depth-dose curves of EBs into CTA dosimetric films are presented in Fig. 1. Curves 1 –corresponds to irradiation regime 1, curves 2 – irradiation regime 2. The tangent curves were used for determination the practical range R_p of electrons and the most probably energy - E_p for electrons of beam.

As it is seen from the Fig.1 the changes of working regimes irradiation into electrons beam accelerator can be lead to essential changes of electrons beam characteristics and respectively the changes of the depth-dose curves for electrons in the dosimetric wedges.

Investigation of results repeatability for the depth-dose curves of electrons in CTA, PVC and B3 dosimetric films located into standard Al wedges were performed in set of experimental measurements. The measurement results repeatability was estimated on the base of the mean square deviation for each pair of measurement results and relatively averaged data of the absorbed depth-dose distribution curves into measurement series.

As result of estimations - repeatability of measurement results for absorbed dose EB is good. For example, the deviation for average value of absorbed dose for CTA dosimetric films did not exceed 1%**.** Relatively of repeatability for the absorbed dose measurements in separate spatial points – the mean square deviation did not exceed 2%.

STANDARD METHODS FOR DETERMINATION OF ELECTRON BEAM CHARACTERISTICS

The possibilities of computational methods which are realized of standard methods for determination of electron beam characteristics on the base of the depth-dose curves measurements into standard dosimetric wedge were investigated.

The various computational methods for determination of standard EB characteristics such as most probably energy - E_p and average energy - E_{av} for electrons of beam were analyzed.

First of all, the methods difference related with possibility to use into Standard [1] two various functions for approximation of dependence $E_p(R_p)$ for most probably energy of electron beam as function of the practical range R_p of electron:

- linear function

$$E_p = 5.09 \cdot R_p + 0.2. \quad (1)$$

- square-law function

$$E_p = 0.423 + 4.69 \cdot R_p + 0.0523\, R_p^2. \quad (2)$$

Furthermore, the method for determination of value R_p demands processing results of measurements with using approximation of discrete data for which the function type is not determined into standard. Therefore, both of linear function [1,7] and fourth polynomial [2,3] are used in practice.

In calculations, based on set of measurement results, it was shown that at determination of value R_p, calculation results with use linear interpolation [1, 7] - and fourth polynomial [2] are putted to values difference that exceed 2%. Some calculations results are presented in the Table 1. Else more greater differences appears off use above empirical dependences $E_p(R_p)$ on the base of linear (1) or square-law approximations (2) and, for set of measurement results, they can exceed 5%.

In accordance with R_p, value the most probably energy - E_p was calculated with use linear dependence (1) (column E_p, (1)) and square-law dependence (2) (column E_p, (2)). Most probably energy - E_p and average energy - E_{av} for electrons are presented in Table 1 for comparison.

Table 1.

Electron beam parameters calculated with various computational methods on the base experimental data A_v, that were obtained by averaging results in measurement series for irradiation regime 1

Computational methods	R_p, cm.	E_p(1), MeV	E_p(2), MeV	E_{av}, MeV
A_v, [2]	1.70	8.54	8.86	7.88
A_v, [1]	1.66	8.35	8.67	-

Data of experimental results A_v (separated points), received by averaging of a set of measurements in CTA dosimetric films for first irradiation regime and simulation results of the depth-dose curves of EB into CTA dosimetric films on the base of semi-empirical model [6] with using of parameters EB from Table 1 are presented in Fig. 2.

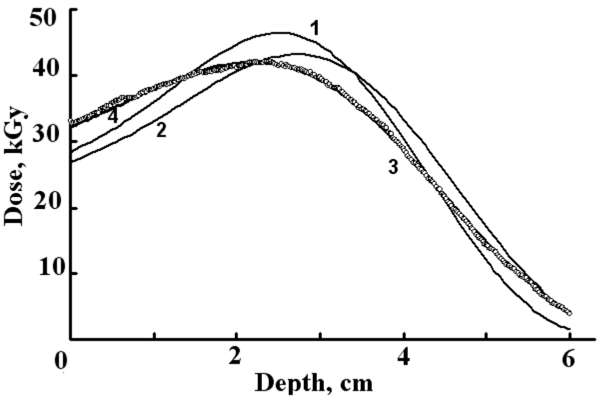

Fig.2. Comparison of experimental results- separate points - curve 3, with simulation results for the depth-dose curves of EB in CTA dosimetric films located into dosimetric wedge on the base of semi-empirical model - continuous curve 4.

The depth-dose curves for mono-energetic electron beams of various energies for comparison are presented in Fig. 2:

- E_{av} – average energy, calculated with use standardized procedure (curve -1);
- E_p – most probably energy, calculated with use standardized procedure on the base of square-law dependence from R_p (curve -2).

These curves are normalized in a such way, that absorbed dose of electrons into target is fixed (do not depend from energy of electrons) and corresponds to measurement results.

As it is seen on Fig. 2. the back decline of the absorbed depth-dose distribution curves can be described using standard parameters of EB. But the results will be received with big value of uncertainty. Relatively the depth-dose curves in the region of target from entrance surface up to thickness, where observe maximum of dose (D_{max}) - utilized models for determination of EB parameters are do not satisfactory. Indeed, relation for dose value on the target surface D(0) to maximum dose value into irradiated target - D_{max} for semi-empirical models approximately equal 0.62, that differs from experimental data - 0.77.

Accordingly, standard computation methods for processing of measurement results obtained into dosimetric wedge or stack do not allow to receive EB parameters, that will be sufficient for correct computer simulation the absorbed depth-dose distribution into standard dosimetric wedge and stack.

It seems that difference between measurement and simulation results testify about essential role of angular distribution of electrons in the process of dose field formation into irradiated target. Furthermore, it is necessary to take into consideration the electron beam spectrum. But today, there are absent the methods and facilities for control of spectral and angle characteristics of EB in the process of target irradiation.

DETERMINATION OF ELECTRON BEAM CHARACTERISTICS ON THE BASE OF TWO-PARAMETRIC SEMI-EMPIRICAL MODEL

For control of spectral and angle characteristics of EB it is proposed to use two-parametric semi-empirical model for EB. In this model it is supposed that spectral and angular characteristics of EB falling on the target surface coincides to characteristics of mono-energy and mono-directional EB, which cross some material layer.

Model parameters are the following: electron energy (E_0) of mono-energy EB and thickness (X_0) of material layer which is located before target. Model parameters can be determined by fitting of semi-empirical model parameters for the depth-dose dependence of mono-energy EB into semi- infinite area to experimental results obtained with dosimetric wedge. Herewith, fitting parameters of semi-empirical model are the following: electron beam energy (E_0) and displacement of initial point (dX) on depth-dose curve.

Into computational scheme, the method of coordinate descent was used for determination with prescribed accuracy the value of EB energy and depth displacement of the initial point on the depth-dose curve. These characteristics ensure of minimum square deviation between data calculated into model and normalized measurement data.

Thereby, accounting of spectral and angular characteristics of EB falling on the target surface is defined by selection of model EB energy and thickness of material layer located before target which allows correctly simulate the depth-dose curve into irradiated target.

Some results calculations of EB characteristics with standard methods and with use of two-parametric model are presented in the Table 2. It was assumed that model layer was made by aluminum also as dosimetric wedge. It should be note, that for all set of experimental data, the energy values simulated with various methods are correlated, but also can be greatly differs by values (Table 2).

Table 2.

Results calculations of EB characteristics with standard methods and with use of two-parametric model

Regimes irradiation	R_p, cm	$E_p(2)$, MeV	E_0, MeV	X_0, cm
Regime 1	1.72	8.63	9.96	0.31
Regime 2	1.89	9.43	11.39	0.42
Regime 1A_v	1.70	8.54	10.01	0.32

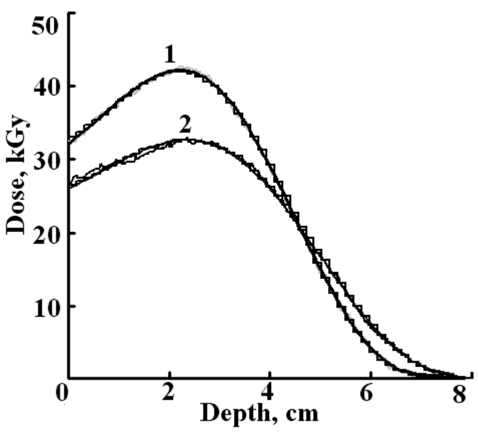

Fig. 3. The depth-dose curves of electrons in CTA dosimetric films. Curves 1 – irradiation regime 1, curves 2 – irradiation regime 2.

Practical approval results of parametric fitting of semi-empirical model (PFSEM) method for determination of electron beam characteristics on the base of two parametric model are presented in Fig.3. Electron beams parameters for which represented results simulation are presented in the Table 2. It should be note that row of Table 2 (regime 1A_v) include of EB parameters for which results simulation are shown in Fig.2.

Package of Curves 1 include the following information: experimental curve which was measured in regime 1; smooth curve corresponds to results simulation with two-parametric semi-empirical model; histogram curve – result simulation with Monte Carlo method using RT-Office software [8]. Package of Curves 2 include the same information only related with irradiation regime 2.

As it is seen from Fig. 3 and from comparison of averaging measurement results with semi-empirical model results (curve 4) on the Fig.2. – agreement between measurement and simulation results is good. Difference of model approximation from measurement results for all set of experimental data is less 1%.

INVESTIGATION RESULTS

• The measurement results of the depth-dose curves of electrons into standard dosimetric wedge were performed. Changes of working regimes irradiation into electrons beam accelerator can be lead to essential changes of electrons beam characteristics and respectively the depth-dose curves of electrons in dosimetric wedge.

• Repeatability estimation of measurement method the depth-dose curves into dosimetric wedge was performed. The measurement results repeatability was estimated on the base of the mean square deviation for each pair of measurement results and relatively an averaging curve. Estimates for these two methods were agreed and measurement errors were less than 2% of average value for absorbed dose in an irradiation area.

• Investigations of possibility for utilization of electron beam characteristics, that were obtained by standard dosimetric wedge, for computer simulation of process irradiation were performed. It was shown that these characteristics are insufficient for correct simulation of the depth-dose curves into dosimetric wedge and stack. The reasons of essential difference between results simulation and measurement were established.

• The practical approbation of two-parametric semi-empirical model for determination of EB characteristics on the base of measurement results, obtained with standard dosimetric wedge, was performed. The errors of PFSEM method were estimated on the base of the mean square deviation between measurement and simulation results. Approximation error did not exceed 1% from average value for absorbed dose in an irradiation zone. It means that irradiation regimes, that corresponds to performed experiments, can be adequately simulated on the base of obtained parameters EB.

CONCLUSIONS

It was proposed and tested the computational methods for processing of measurement results obtained with dosimetric wedge for determination of electron beam parameters on the base of which it is possible to realize of correct computer simulation of the depth-dose curves of electrons in wide diapason of target depth.

It should be interesting to perform the verification and validation methods into wide diapason of EB energy and on the various types of EB accelerators.

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