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DETERMINATION OF THE STANDARD CHARACTERISTICS OF DEPTH-DOSE DISTRIBUTIONS ON THE BASE OF SEMIEMPIRICAL MODEL OF ELECTRONS ENERGY DEPOSITION

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In this paper it was performed a comparison the standard characteristics of depth-dose distributions of electrons such as practical range R_p and half-value depth R_{50}, which were calculated with the semi-empirical model (SEM) and Monte Carlo (MC) method using the detailed physical model. It was shown, that SEM of electrons energy deposition allows with good accuracy (<2%) to determine in aluminum target the values of standard characteristics for depth dose distributions in the energy range of electrons that provides the main practical interest for industrial radiation technologies. On the base of the SEM of electrons energy deposition, it was calculated a systematic set of values the standard characteristics of $R_p(E)$ and $R_{50}(E)$ in an aluminum target in the area of relativistic energies - from 1 MeV to the border of the estimated accuracy of the semi-empirical model – 20 MeV. These data were approximated using linear and quadratic functions and obtained empirical formulas for dependences $R_p(E)$ and $R_{50}(E)$ as function of electrons energy E. It was performed approbation of empirical formulas at processing the measurement results for depth dose dependencies obtained in the radiation-technological center – Institute of Nuclear Chemistry and Technologies, Warsaw, Poland.

KEY WORDS: electron beam energy, dosimetry wedge, semi-empirical model, Monte-Carlo method.

ВИЗНАЧЕННЯ СТАНДАРТНИХ ХАРАКТЕРИСТИК ГЛИБИННИХ РОЗПОДІЛІВ ДОЗИ НА ОСНОВІ НАПІВЕМПІРИЧНОЇ МОДЕЛІ ПОГЛИНЕННЯ ЕНЕРГІЇ ЕЛЕКТРОНІВ

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У роботі проведено порівняння стандартних характеристик розподілів поглиненої дози електронів, таких як практичний пробіг R_p і глибина половинного зменшення дози R_{50}, розрахованих в напівемпіричної моделі (ПЕМ) і методом Монте-Карло (МК) з використанням детальної фізичної моделі. Було показано, що ПЕМ поглинення енергії електронів дозволяє з хорошою точністю (<2%) визначати значення стандартних характеристик глибинних розподілів дози електронів в алюмінієвій мішені в діапазоні енергій електронів, який забезпечує основний практичний інтерес для промислових радіаційних технологій. На основі ПЕМ поглинення енергії електронів був розрахований систематичний набір величин характеристик R_p (E) і R_{50} (E) в алюмінієвій мішені в області релятивістських енергій від 1 МеВ до кордону оцінки точності напівемпіричної моделі – 20 МеВ. Ці дані були апроксимовані з використанням лінійної та квадратичної функцій, у результаті були отримані емпіричні формули для залежностей цих характеристик R_p (E) і R_{50} (E) від енергії електронів E. Проведено апробацію емпіричних формул при обробці результатів вимірювань глибинної залежності дози, виконаних у радіаційно-технологічному центрі Інституту Ядерної Хімії і Технологій, Варшава, Польща.

КЛЮЧОВІ СЛОВА: енергія пучку електронів, дозиметричний клин, напівемпірична модель, метод Монте-Карло.

ОПРЕДЕЛЕНИЕ СТАНДАРТНЫХ ХАРАКТЕРИСТИК ГЛУБИННЫХ РАСПРЕДЕЛЕНИЙ ДОЗЫ НА ОСНОВЕ ПОЛУЭМПИРИЧЕСКОЙ МОДЕЛИ ПОГЛОЩЕНИЯ ЭНЕРГИИ ЭЛЕКТРОНОВ

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В работе проведено сравнение стандартных характеристик распределений поглощенной дозы электронов, таких как практический пробег R_p и глубина половинного уменьшения дозы R_{50}, рассчитанных в полуэмпирической модели (ПЭМ) и методом Монте-Карло (МК) с использованием детальной физической модели. Было показано, что ПЭМ поглощения энергии электронов позволяет с хорошей точностью (<2%) определять значения стандартных характеристик глубинных

распределений дозы электронов в алюминиевой мишени в диапазоне энергий электронов, который обеспечивает основной практический интерес для промышленных радиационных технологий. На основе ПЭМ поглощения энергии электронов был рассчитан систематический набор величин характеристик $R_p(E)$ и $R_{50}(E)$ в алюминиевой мишени в области релятивистских энергий от 1 МэВ до границы оценки точности полуэмпирической модели – 20 МэВ. Эти данные были аппроксимированы с использованием линейной и квадратичной функций, в результате были получены эмпирические формулы для зависимостей этих характеристик $R_p(E)$ и $R_{50}(E)$ от энергии электронов *E*. Проведена апробация эмпирических формул при обработке результатов измерений глубинной зависимости дозы, выполненных в радиационно-технологическом центре Института Ядерной Химии и Технологий, Варшава, Польша.

КЛЮЧЕВЫЕ СЛОВА: энергия пучка электронов, дозиметрический клин, полуэмпирическая модель, метод Монте-Карло

The expansion of the range of practical use of radiation technologies, makes it necessary to improve existing today and to develop new methods for determination and audit of parameters of the radiation-technological processes [1,2]. One opportunity to increase the accuracy and informativeness of methods is development of software for processing measurement results, carried out in the composition of these methods [2,3].

Note, that increasing of accuracy and informativeness of computational methods is based on usage of physical laws in algorithms of computations. Therefore, an actual task is to study the possibilities to use the approximate physical models, such as the empirical model for the development of improved (enhanced) algorithms of processing the measurement results [4,5].

It is required the new modern methods of electron energy determination through depth-dose distribution to ensure the practical realization of radiation-technological processes with electron beams. Traditionally, the standard characteristics for depth-dose distributions, such as the practical range R_p and half-value depth R_{50} determine during radiation treatment. These characteristics are used for determination and audit of the energy characteristics of electron beams.

In connection with said above, it is interesting the approach proposed in [4,6,7]: to use the software EMID [8] for approximation the measuring results of the depth-dose distributions. The software EMID realizes a semi-empirical model (SEM) for the depth-dose distribution of a monoenergetic electrons beam which is normally incident on a semi-infinite target. This semi-empirical model describes well the values of the depth–dose distributions in the targets and therefore for half-value depth R_{50}, we should expect good agreement, calculated by SEM with the measurements results. However, to calculate the values of practical range R_p in according with the definition of this value, it is necessary to calculate the point of maximum slope of depth-dose distribution and the value of the derivative at this point [2]. As a rule, the models built on the empirical relationships do not provide the correct description of the derivative from these relationships. Therefore, the evaluation of the accuracy of modeling the spatial characteristics of R_p and R_{50} dose distributions, on the base of the semiempirical model of electrons energy deposition is of interest for the development of new computational methods for determining the energy of the electrons in the radiation technologies.

In this study it was performed a comparison of values of R_p and R_{50} which were calculated in the semi-empirical model and the Monte Carlo method with the data given in the standard [1]. Because the depth-dose distributions which were calculated in the semi-empirical model and by Monte Carlo method are the sets of discrete data, it was performed estimation of uncertainty for obtained R_p values through the use of two computational methods based on traditional approximation of linear function data and approximation with use of fourth-degree polynomial [9]. For dependencies of spatial characteristics $R_p(E)$ and $R_{50}(E)$ of the electrons dose as functions of the electron energy *E*, the data sets and empirical formulas were obtained. On the base of received formulas, the method of determining the standard characteristics such as - practical range R_p and half-value depth R_{50} with use the two-parameter fitting of measurement results the depth-dose distributions, and of the empirical formulas, was tested.

The main objectives of the present paper are the following:

- To get a set of spatial characteristics such as the practical range R_p and the depth of the half dose reduction R_{50} and to obtain empirical formulas describing the spatial characteristics of $R_p(E)$ and $R_{50}(E)$ in an aluminum target as a function of electron energy *E*.
- On basis of the obtained empirical formulas, to estimate the errors of method for determining the standard characteristics R_p and R_{50} for the depth-dose distribution, on the base of two-parametric fitting semi-empirical model to the measurement results.

ESTIMATION OF ERRORS AT MODELLING OF THE STANDARD CHARACTERISTICS FOR DEPTH-DOSE DISTRIBUTIONS IN ALUMINUM TARGET ON BASE OF THE SEMIEMPIRICAL MODEL OF THE ELECTRONS ENERGY DEPOSITION

The values $R_p(E)$ and $R_{50}(E)$ were determined with use of two stages in calculating:

At the first stage: the depth-dose distributions of monoenergetic electrons with energy *E* in the semi-infinite aluminum target on the basis of semi-empirical model according to [8] and with use Monte Carlo method were calculated. The computing blocks "Analytics" and “Monte Carlo” in software ModeRTL [3] were used for calculations. As a result, the values of dose $D_e(x,E)$ were obtained into 50 basis space points, which uniformly covered the interval of depths *x*, from the surface of the target up to $R_0(E)$ -continuous slowing-down approximation range of electrons.

At the second stage: two computational methods based on approximations of discrete data with use linear functions and a fourth–degree polynomial [9] were used to determine the practical range of electrons $R_p(E)$. In accordance with the recommendations of standards, area of recession dose, where change the dose to between 0.2 and 0.8 of the maximum dose in the target, was to selected for the approximations of discrete data. In this area, the number of spatial points, at which carried out an approximation, was in the range 10 – 14 points.

Presented in the Table 1 $R_p(E)$ values were obtained on the basis of semi-empirical model with using approximations of data by linear functions (values in column R_p-Line) and polynoms of 4th degree (values in column R_p-Pol). Values in column R_p-MC were obtained on the basis of Monte Carlo method and calculated as average results obtained with use of the data approximation by linear functions and polynoms of 4th degree.

The accuracy estimation of the calculation results was based on comparison of the results which were obtained by approximation of discrete data, with use the linear function or polynom of 4th degree. Depths at which the dose is two times smaller than the maximum value – $R_{50}(E)$ was determined by the values of absorbed dose $D_e(x,E)$ energy deposition obtained in the first stage.

The maximum dose in the target is presumed equal to the maximum value in data set. The values $R_{50}(E)$ (data in column R_{50}-Mod) were determined by using linear interpolation of the dose values between the reference points.

On the basis of the data in Table 1 it was estimated the uncertainty of the results obtained on the basis of the semiempirical model of electrons energy deposition. Relative uncertainty is a few percent for the low-energy electrons (for 0.2 MeV is equal 2.8%) and reduced up to 1% with increasing electron energy up to 20 MeV. Note, that errors of the semiempirical model of electrons energy deposition is not more than 4% [8]. Uncertainty values for practical range R_p and half-value depth R_{50} obtained with using the various methods of approximation of the data was estimated by value of less than 2% for the data obtained on the basis of semi-empirical model and with use Monte Carlo method.

Table 1.

Values of the practical range R_p and half-value depth R_{50} for depth-dose distributions in aluminum target.

E, MeV	R_p-Line, cm	R_p-Pol.,cm	R_p-MC, cm	R_p-St,cm	R_{50}–Mod,cm	R_{50} –St, cm
0.2	0.0160	0.0158	0.0168	0.0161	0.0114	0.0116
0.5	0.0628	0.0622	0.0641	0.063	0.0448	0.0448
1	0.1564	0.1547	0.159	0.152	0.1115	0.111
2	0.3558	0.3516	0.360	0.356	0.2576	0.259
5	0.9748	0.9617	0.983	0.971	0.7370	0.741
10	2.028	2.007	2.021	2.00	1.5904	1.59
20	4.107	4.075	4.037	4.04	3.3152	3.28

The data in the Table 1 show, that the results for practical range R_p and half-value depth R_{50}, obtained on the basis of the semiempirical model of electrons energy deposition and by Monte Carlo method, are agreed with data from ASTM Standard E 1649-94. In the energy range that provides the main practical interest for radiation technologies, the relative uncertainty of the simulation do not exceed 2% and corresponds to the values of uncertainty of the results processing of measured data with use of aluminum wedge dosimetry. Note that there is a systematic overestimation of R_p values obtained on the base of the linear approximation of discrete data (column R_p-Line) with respect to the values obtained using a polynomial approximation (column R_p-Pol).

Based on the above estimates of the uncertainties values, we can conclude that used computational methods allow to accurately simulate the standard characteristics of depth-dose distributions in an aluminum target, such as the practical range R_p and half-value depth R_{50} on the base of the semiempirical model of electrons energy deposition.

DEPENDENCES OF THE SPATIAL CHARACTERISTICS $R_P(E)$ AND $R_{50}(E)$ OF ELECTRON RADIATION DOSE AS FUNCTIONS OF THE ELECTRON ENERGY *E*

For obtaining empirical formulas describing the dependence of $R_p(E)$ and $R_{50}(E)$, a series of calculations on the base of the semi-empirical model of electrons energy deposition was performed. Calculation procedures described in the previous section. Results calculation are presented in Table 2 and Figure 1.

R_p data were obtained using the method of linear approximation of values the depth-dose distributions. Values of the electrons energy, were selected in the field of relativistic energies – from 1 MeV to the border of the estimated accuracy of the semi-empirical model – 20 MeV.

The values of the spatial characteristics of $R_p(E)$ and $R_{50}(E)$ for electron radiation dose were approximated using linear and quadratic functions. Approximation polynomial 2nd degree have the form:

$$R_p(E) = 8\times10^{-6}\times E^2 + 0.2089\times E - 0.0641 \quad (1)$$
$$R_{50}(E) = 0.0004\times E^2 + 0.1628\times E - 0.0736$$

As follows from (1), the contribution of the quadratic term in this energy range is not great. Therefore, it is of interest linear approximation:

$$R_p(E) = 0.209\times E - 0.0647 \quad (2)$$
$$R_{50}(E) = 0.1704\times E - 0.1007$$

Table 2.

Values of practical range R_p and half-value depth R_{50} obtained on the base of the semi-empirical model of electrons energy deposition

E, MeV	R_p, cm.	R_{50}, cm.		*E*, MeV	R_p, cm.	R_{50}, cm.
1	0.156	0.112		9	1.81	1.42
2	0.356	0.258		10	2.03	1.59
3	0.561	0.412		11	2.23	1.76
4	0.767	0.574		12	2.44	1.96
5	0.975	0.737		14	2.87	2.29
6	1.18	0.91		16	3.29	2.65
7	1.40	1.075		18	3.70	2.98
8	1.60	1.25		20	4.11	3.32

Empirical dependencies (1) and (2) are shown in Figure 1 with continuous curves. As can be seen from the Figure 1, the difference from the values of the linear and quadratic approximations are small and simple empirical formula obtained fairly well describes the dependence of the spatial characteristics of $R_p(E)$ and $R_{50}(E)$ dose of electron radiation as function of the electron energy *E*. The formulas of approximation curves 1st and 2nd degree are presented in the Fig. 1.

The accuracy of empirical formulas will be estimated using the spatial characteristics of $R_p(E)$ and $R_{50}(E)$ dose of electron radiation as functions of the electron energy *E* in the methods of processing the results of measurements in the next section.

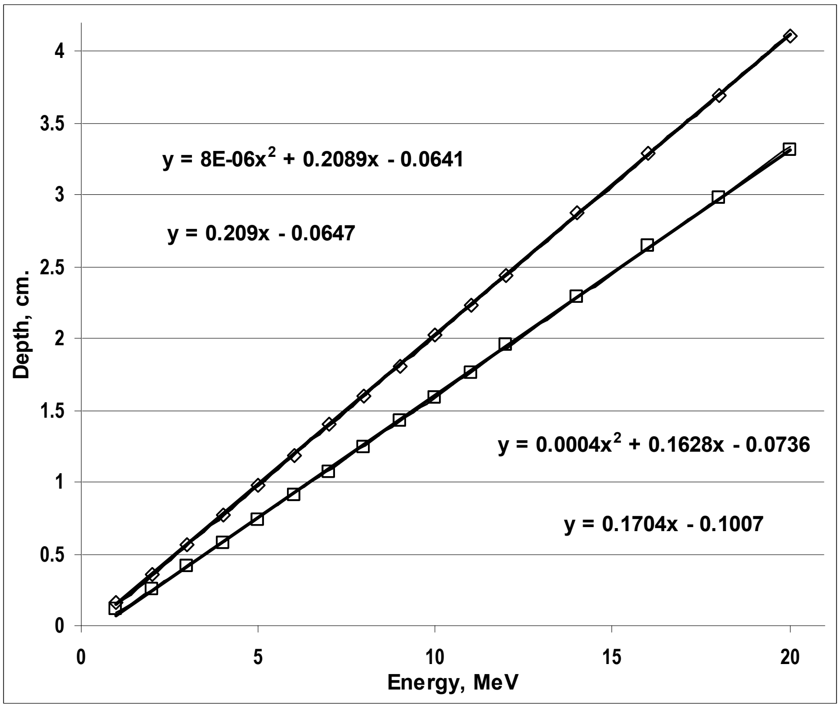

Fig. 1. Dependences of the spatial characteristics of $R_p(E)$ and $R_{50}(E)$for dose of electron radiation as function of the electron energy *E*. Points - data from Table 2, the rhombus - the values of $R_p(E)$, the squares - the value $R_{50}(E)$. Solid curves - linear and quadratic approximations of tabular data.

APPROBATION OF EMPIRICAL RELATIONSHIPS $R_P(E)$ AND $R_{50}(E)$ AT PROCESSING THE RESULTS OF MEASUREMENTS PERFORMED WITH A DOSIMETRIC WEDGE

Irradiation of 2 standard Al wedges with CTA dosimetric films was performed on the electron linear accelerator Elektronika 10/10 at INCT, Warsaw with electron beam energy of 10 MeV [10]. Al wedge with CTA 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 [11].

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 CTA 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.

CTA dosimetric films were calibrated against alanine dosimeter which is traceable to National Physical Laboratory, Teddington, Middlesex, UK [12].

Characteristics of dosimetric films are the following: CTA – Cellulose Triacetate film: density 1.32 g/cm^3, thickness 0.125 mm, width 8mm. The FDR001 spectrophotometer in automatic mode was used for reading the optical density for CTA strip films using a wavelength 280 nm.

Preliminary processing of measurement results was performed. The initial points of the depth-dose curves in CTA dosimetric films located in dosimetric wedges were determined. 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. 2.

As you can see at Fig. 2, experimental data for the depth-dose curves are not suitable for calculation with use the standard numerical methods, values "rate of dose reduction" (first derivative) and "the points of maximum rate of dose reduction" (second derivative) as is required by the standard for calculating the values of practical range R_p.

For processing the measurement results of the depth-dose curve obtained with dosimetric wedge it was used the method of parameter fitting of semi-empirical model [7].

Herewith, the parameters of semi-empirical model are the following: electron energy (E_0) and displacement of initial point (dX) on depth-dose curve.

$$Q^2 = \sum_{i=1}^{N} [D_e(x_i + dX, E_0) - D_i]^2 \,. \tag{3}$$

Here $D_e(x, E)$ - a dose of electrons with energy E on the distance x from surface target, N – the numbers of spatial points in one measurement, (D_i, x_i) - normalized measurement results for a set of dose values and spatial coordinates at the measuring points i = 1 .... N.

The method of coordinate descent was used for determination with prescribed accuracy the value of energy E_0 and displacement the initial point dX for the depth-dose curve. These characteristics ensure of minimum square deviation Q^2 between $D_e(x_i + dX, E_0)$ normalized calculated data and D_i measurement data.

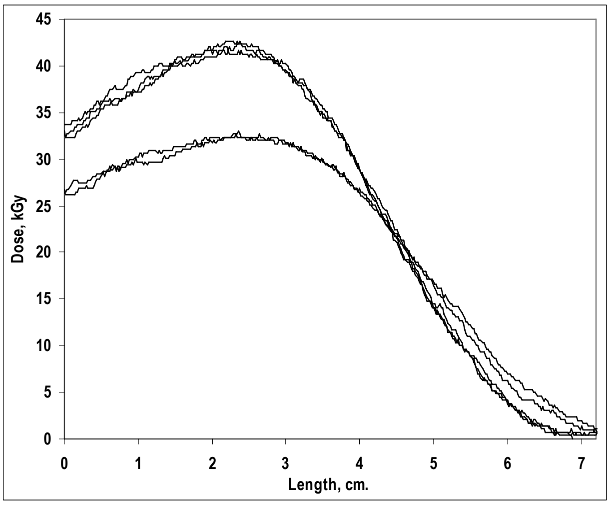

Fig. 2. The depth-dose curves of electrons in CTA dosimetric films located in the standard dosimetric wedges.

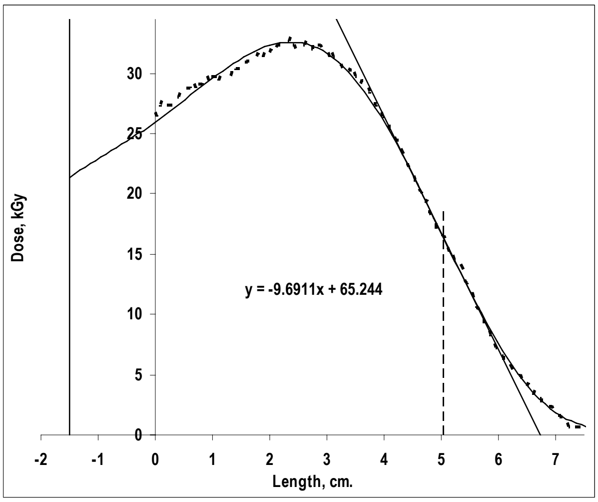

Fig. 3. Two-parameter fitting of measurement results. Points - results of measurement. The solid curve – calculation of the dose in the semi-empirical model with fitted model parameters.

The calculations results of EB characteristics with use of method PFSEM [7] and methods of polynomial approximations DELEN [6] are presented in the Table 3. Values in column R_p were calculated as average results obtained with use of the measurement data approximation by linear functions and polynoms of 4th degree.

Uncertainty assessment for values R_p was performed on the basis of a comparison of the results obtained using two computational methods for determining the tangent (derivative) on the measurement data. The results of uncertainty evaluation of quantity values R_p are shown in column Unc. Uncertainty assessment for values R_{50} was determined with taking into account the spatial resolution of measurements and compose value that do not exceeding 0.5% for all of the measurement results shown in Table 3.

It should be noted that the values of R_p obtained with using linear approximation of measurement results (column R_p – Line) with respect to the values obtained using a polynomial of 4-th degree (column R_p – Pol) systematically overestimated. A similar fact was found in the processing of the calculated depth-dose dependencies based on semi-empirical model (Table 1.)

A geometric interpretation of the displacement parameter *dX* in the method of two-parameter fitting (Fig. 3), and established fact, in the first section of this work, that using computational methods allow accurately simulate practical range R_p and half-value depth R_{50} allow us to write the following relations:

$$R_p = R_p(E_0) - dX \qquad (4)$$
$$R_{50} = R_{50}(E_0) - dX$$

where R_p, R_{50} - spatial parameters for measurement results of the depth-dose distribution, $R_p(E)$, $R_{50}(E)$ - empirical spatial parameters of the depth-dose distribution as function of electron energy *E* obtained on the base of the semiempirical model of electrons energy deposition, E_0, *dX* - the values of model parameters defined by PFSEM method.

Table 3.
The calculations results of electron beam characteristics with use of method PFSEM and methods of polynomial approximations (DELEN)

	PFSEM		DELEN				
Samples	E_0, MeV	*dX*, cm.	R_p-Line	R_p-Pol	R_p, cm.	Unc. %	R_{50}, cm.
R1_1	10.95	0.370	1.83	1.81	1.82	0.79	1.41
R1_2	11.39	0.423	1.89	1.88	1.88	0.53	1.42
R2_1	10.03	0.336	1.69	1.65	1.67	2.56	1.26
R2_2	9.96	0.308	1.72	1.68	1.70	2.09	1.28
R2_3	9.93	0.311	1.70	1.65	1.67	2.62	1.27

For measured depth-dose distributions by parameters calculated with use of PFSEM method (Table 3), there were determined also the spatial parameters R_p and R_{50} in according to relations (4) and the empirical formulas (2). The calculations results of values of R_p and R_{50} are shown in Table 4 in the columns Mod. For comparison, in columns Exp were transfer data from columns R_p and R_{50} of Table 3. The relative deviation of the results presented in columns Mod and Exp were placed in the column Error.

Table 4.
The values of R_P and R_{50} obtained with standard (DELEN) and PFSEM methods by using empirical formulas.

	R_p, cm.			R_{50}, cm.		
	Exp.	Mod.	Error, %	Exp.	Mod.	Error, %
R1_1	1.82	1.85	1.77	1.41	1.40	1.12
R1_2	1.88	1.89	0.62	1.42	1.42	0.09
R2_1	1.67	1.70	1.52	1.26	1.27	1.13
R2_2	1.70	1.71	0.42	1.28	1.29	0.48
R2-3	1.67	1.70	1.54	1.27	1.28	0.75

It should be note that for the electrons energy used in the experiments (column E_0 in Table 3), difference between obtained results with using linear empirical relationships (2) and empirical relationships (1) does not exceed 0.05% for the values of R_p (E) and 0.5% for the values of R_{50} (E).

Comparison of the data in the Table 4 shows that the values R_P in column Mod are systematically larger than the values in the column Exp and close to the values given in the Table 3 in the column R_p - Line. This is due to the fact that when determining the empirical relationships there were used data from the Table 2, which are obtained on the base of the linear approximation of calculation results for the depth-dose dependence. As can be seen from Table 4, the differences between the spatial characteristics of dose distributions, such as the practical range R_p and half-value depth R_{50}, calculated using the equations (2) and (4) derived from the traditional calculation methods coincide up to an estimated error of the measurement results.

Thereby, processing of measurement results with PFSEM method allows to obtain the data by which you can with high accuracy (<2%) determine the spatial characteristics of dose distributions, such as the practical range R_P and half-value depth R_{50}.

CONCLUSIONS

In this paper it was studied the possibility to use the semiempirical model of electrons energy deposition for determination of the practical range $R_p(E)$ and half-value depth $R_{50}(E)$ (standard characteristics) of depth-dose distributions in aluminum target. Selection of aluminum target for performing investigations is connected with great interest to the development of enhanced methods of radiation monitoring conducted with use of standard dosimetry aluminum wedges, which are distributed in dosimetry of radiation technological centers.

The investigation results indicate the possibility of increasing the accuracy and informativeness of the dosimetry monitoring, through the use of the new algorithm for processing the results of measurements performed with the use of aluminum dosimetric wedge. In practical dosimetry, together with dosimetric wedges for measuring of depth-dose distributions is used the stack (Stack Energy Measurement Device) consisting of a set of flat layers of suitable reference material interleaved with dosimeter films. In particular, water and polystyrene as suitable materials for the dosimetric stack, were discussed in [1]. Therefore, investigations of the possibilities of using the semiempirical model of electrons energy deposition for determination of the characteristics of depth-dose distributions in the materials, which are recommended in standards, are of interest.

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