Application of the medical linear accelerator ELEKTA AXESSE in the study of sorption properties of impurities and absorption coefficients of medium and heavy chemical elements

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Abstract. In this article, the authors propose a new technique for measuring linear attenuation coefficients on the medical linear accelerator Elekta Axesse. Linear attenuation coefficients were obtained for four samples at different concentrations of substances at a gamma-ray energy of 6 MeV. A unified ionization chamber was used as a detector to register the transmitted gamma-ray beam through the samples under study. Linear absorption coefficients were obtained for elements B, C, O, S, Fe, Ba taking into account their concentration, as well as taking into account the different mass inclusion of paraffin in the samples under study, which is acyclic hydrocarbons CₙH₂ₙ₊₂. The measurement results showed that taking into account certain components in impurities leads to relatively small, but quite noticeable differences in the determination of the total absorption coefficients. This is especially important to take into account for determining the concentration of light elements in samples. To determine the content of medium and heavy chemical elements, taking into account the content of light elements can be neglected. The use of a 6 MeV gamma-ray beam made it possible to reduce the errors in determining the absorption coefficients, since their dependence on energy in the region of applicable gamma-ray energies is not so great in comparison with the low-energy region, in which the shell effects for heavy elements will introduce significant contribution.

1. Introduction
Since the beginning of the development of nuclear physics, radioactive radiation has been used in its various fields: medical physics [1, 2], dosimetry and radiation protection [3, 4], industry and technology [5, 6], radiation biophysics [7, 8]. The development of modern biophysics requires the creation of more and more perfect models of the intracellular interaction of living matter - organelles, membranes, nuclei, DNA and RNA. When solving the problems of nuclear medicine, in particular, the problems of radiation damage to the cell and, in particular, the cell nucleus, which contains the entire apparatus of heredity, it is relevant to involve a certain arsenal of means and methods of nuclear physics. In particular, the exact values of the ranges of alpha particles and the coefficients of linear absorption of gamma quanta are required, for practically all elements of the Mendeleev table.
same information is important for other applications as well. Due to the absence of electric charge in gamma rays, the study of the mechanisms of attenuation of gamma radiation in matter is an urgent task [9-11] and one of the most important aspects of the use of gamma rays in nuclear medicine [12, 13].

The most important quantities characterizing the penetration and diffusion of gamma rays in extended media are its attenuation coefficients [14]. Accurate data on these values are required for the use of gamma radiation in many fields, such as nuclear medicine, tomography, oncology, and radiation biophysics. The measurements and calculations of attenuation coefficients using different methods and materials have been performed by different groups [15-18]. The theoretical values of the mass attenuation coefficients can be found in [19].

The purpose of this study was to measure the linear absorption coefficients of gamma quanta in samples containing light chemical elements and impurities of medium-heavy and heavy elements. The difference between this work and research carried out by other scientific groups [15-18] is the direct measurement of the absorption coefficients in the interaction of 6 MeV gamma quanta with matter at the medical linear accelerator Elekta. It is specially designed for external beam radiation therapy and has a small energy spread. At a given energy of gamma quanta, it is necessary to take into account the contribution of only two mechanisms: the Compton effect and the creation of electron-positron pairs in the nuclear field. This makes it possible to reduce the errors in determining the absorption coefficients, since their dependence on the energy of gamma quanta is not as great as, for example, in comparison with the low-energy region, in which the shell effects for heavy elements will make a significant contribution. Thus, the obtained values can be used for a more accurate assessment of the dose in the field and outside the radiation field and for assessing the risk of tissue damage when interacting with gamma radiation, due to the fact that the development of nuclear physical methods used in medicine actualizes research in the area of predicting the received radiation doses of patients during diagnostics and therapy with nuclear medical equipment [20-22].

2. Material and methods

To study the coefficients of linear absorption of gamma quanta in the studied chemical elements, an electron accelerator Elekta Axesse was used as a source of gamma quanta [23]. The energy of gamma quanta in the beam was 6 MeV. The operating principle of the Elekta Axesse electron accelerator installation is described in detail in [23]. To study the linear absorption coefficients in the studied chemical elements, we used samples made at Cairo University (Egypt) and preliminarily analyzed in [24]. Geometrically, the samples are cylinders 100 mm in diameter and 10 mm in height. Each sample consisted of 20 identical cylinders.

Linear absorption coefficients were obtained for elements B, C, O, S, Fe, Ba, taking into account their concentration, as well as taking into account the different mass inclusion of paraffin in the samples under study, which is C_{n}H_{2n+2}.

Measurements of the absorbed dose of the beam of gamma quanta were carried out by the following method (Figure 1): the detector (1), which was placed on a movable table, moved with an increase in the thickness of the sample under study (2) by the corresponding value equal to 1 cm. Thus, in the method used, the thickness of the air gap (h) between the sample and the source remained constant and was equal to 100 cm. A unified ionization chamber with an active measurement area of 24.4 cm × 24.4 cm is used as a recording system. It contains 1020 sensors in a 32 × 32 grid. Dose Rate Dependence ±1.0% [23]. Detection of the shape of the beam of gamma quanta passed through the sample under study and its intensity was carried out using standard software, which is supplied with this linear accelerator [23].
3. Results and discussion
As a result of measurements, data were obtained and the dependences of the absorption dose on the thickness of the samples were plotted (Figure 2).

For comparison with experimental data, the linear absorption coefficients of gamma quanta for impurities in the form of chemical elements B, C, O, S, Fe, Ba were calculated taking into account their concentration. The main effects of the interaction of 6 MeV gamma quanta with matter arise due to the contribution of two main mechanisms, the Compton effect and the creation of electron-positron pairs in the nuclear field [25]. The use of a 6 MeV gamma ray beam made it possible to reduce the errors in determining the absorption coefficients, since their dependence on the gamma ray energy is not so great, for example, in comparison with the low-energy region, in which the shell effects for heavy elements will make a significant contribution. The attenuation of a narrow beam of monochromatic gamma radiation when passing through a layer of a medium with thickness \( x \) and density \( \rho \), containing elements with atomic numbers \( Z_1, Z_2, \ldots, Z_n \), occurs according to the law

\[
I = I_0 e^{-\rho x \sum \mu c_i},
\]

where \( I_i \) – beam intensity before and after attenuation; \( c_i \) – concentration of a chemical element in a mixture with an atomic number \( Z_i \); \( \mu = \mu(Z_i, E) \) – mass attenuation coefficient for a given element.
From the composition of impurities and their mass fraction in the samples, $c_i$ and $\mu_i$, were calculated, as well as the total absorption coefficient for each corresponding sample. The results of the theoretical coefficients are presented in Table 1.

| $Z$ | Symbol | $\mu_i$, g/cm$^2$ | Sample 1, $c_i$ | Sample 2, $c_i$ | Sample 3, $c_i$ | Sample 4, $c_i$ |
|-----|--------|----------------|-----------------|-----------------|----------------|----------------|
| 5   | B      | 0.138238       | 0.097525        | 0.097525        | 0.097525        | 0.097525        |
| 6   | C      | 0.1017         | 0.029258        | 0.029258        | 0.029258        | 0.029258        |
| 8   | O      | 0.0555         | 0.034975        | 0.035279        | 0.069949        | 0.070557        |
| 16  | S      | 0.012355       | 0               | 0.017639        | 0               | 0.035279        |
| 26  | Fe     | 0.003809       | 0.091808        | 0               | 0.183617        | 0               |
| 56  | Ba     | 0.000528       | 0               | 0.0755186       | 0               | 0.151037        |
|     | Paraffin Wax | C$_n$H$_{2n+2}$ | 0.010885       | 0.206022        | 0.206022        | 0.103011        |
|     | With Paraffin Wax | $\sum_i \mu_i c_i$ & - | 0.020693 | 0.020618 | 0.0220115 | 0.021861 |
|     | Without Paraffin Wax | $\sum_i \mu_i c_i$ & - | 0.018748 | 0.0186730 | 0.0210388 | 0.020889 |

Taking into account the experimental correction, the results of the experimental and theoretical (taken from [25]) absorption coefficients for the test samples are shown in Table 2 and Figure 3.

| $\mu$, 1/cm | $\rho$, g/cm$^3$ | With Paraffin Wax, $\mu$, 1/cm | Without Paraffin Wax, $\mu$, 1/cm |
|-------------|-----------------|---------------------------------|-----------------------------------|
| Sample 1    | 0.0479          | 1.19                            | 0.05038                           | 0.048065                         |
| Sample 2    | 0.048           | 1.19                            | 0.050291                          | 0.047976                         |
| Sample 3    | 0.0551          | 1.43                            | 0.057231                          | 0.05584                          |
| Sample 4    | 0.0554          | 1.43                            | 0.057017                          | 0.055626                         |

From the obtained values of the absorption coefficients, it can be seen that the contribution of the linear absorption coefficient in paraffin is not large due to the content of light elements in its composition.
Thus, the obtained total attenuation coefficients of samples containing light chemical elements and impurities of medium-heavy and heavy elements will make it possible to obtain more accurate dose data for the destruction of oncological formations of potential patients of medical cancer centers of the Republic of Kazakhstan.

Below is the calculation of the absorbed dose using the obtained total attenuation coefficients for these samples. To calculate the dose, the following expressions were used

\[ D = \frac{\Delta I(h) \cdot E_\gamma \cdot t}{m}, \]

where \( \Delta I \) – the loss of the intensity of the beam of gamma quanta passed through one sample of thickness \( h \); \( E_\gamma \) – gamma ray beam energy; \( t \) – beam exposure; \( m \) – mass of sample. Formula (1) will be rewritten in (2) as follows

\[ D = I_0 \cdot \left( 1 - e^{-\rho \sum \mu(c)} \right) \cdot E_\gamma \cdot t \cdot \frac{1}{m}, \]

where \( I_0 \) – beam intensity on the surface of the entire sample area. Taking into account the calibration data of the linear accelerator, the beam intensity and exposure time can be replaced by the correction factor \( C = 1.2 \text{ J} \). Thus, the calculation of the dose by the formula

\[ D = C \cdot \left( 1 - e^{-\rho \sum \mu(c)} \right) \cdot \frac{1}{m}. \]

The results of the calculated doses received by the samples are shown in Table 3. The calculated doses are in good agreement with the experimental values when they are irradiated with gamma quanta on the linear accelerator of the samples under study.
Table 3. Absorbed doses for test samples.

| Sample   | $\rho$, g/cm$^3$ | m, kg | Dose $D$, cGy |
|----------|------------------|-------|---------------|
| Sample 1 | 1.19             | 0.0934| 63.12         |
| Sample 2 | 1.19             | 0.0934| 63.02         |
| Sample 3 | 1.43             | 0.1123| 59.44         |
| Sample 4 | 1.43             | 0.1123| 59.22         |

4. Conclusion
1. Experimental linear attenuation coefficients were obtained for four samples with different concentrations of substances.
2. Taking into account certain components in impurities leads to relatively small, but quite noticeable differences in the determination of the total absorption coefficients. This is especially important to take into account for determining the concentration of light elements in samples by this method. To determine the content of medium and heavy chemical elements, taking into account the content of light elements can be neglected. Thus, for example, for a substance with the composition $Z=(1, 8, 12, 13, 14, 16, 20, 26, 56)$, the mass absorption coefficient is $0.03162$ cm$^2$/g [26], while our results show a value from $0.03874$ to $0.04025$ cm$^2$/g for a substance with $Z=(1, 5, 6, 8, 12, 16, 26, 56)$. This is most likely due to the fact that the test samples contain chemical elements with $Z = (5, 6)$ and are absent with $Z = (13, 14, 20)$, which make an insignificant difference in the mass absorption coefficient. This is apparently due to the fact that their concentrations are low in the samples.
3. The use of a 6 MeV gamma-ray beam made it possible to reduce the errors in determining the absorption coefficients, since their dependence on energy in the region of applicable gamma-ray energies is not so great in comparison with the low-energy region, in which the shell effects for heavy elements will introduce significant contribution.

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