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The assessment of the annual effective dose due to ingestion of radionuclides from drinking water consumption: calculation methods

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Abstract
In the present paper the different ways of assessing the annual effective dose due to ingestion of radionuclides by drinking water consumption were examined and exemplified. On a set of 10 samples the gross alpha activity, the gross beta activity, the concentration of ^{210}Po, ^{210}Pb, ^{238}U, ^{232}Th and, ^{226}Ra were measured. The highest annual effective dose values assessed by relying on the investigated sample set were found by using the rationale according to which all the gross alpha and beta activity is due to the alpha and beta radionuclide, with the highest effective dose coefficient, namely ^{210}Po and ^{210}Pb/^{228}Ra, respectively.

Keywords Annual effective dose · Effective dose coefficient · Natural radionuclides

Introduction

The main processes contributing to the internal exposure of the human body to ionizing radiation are represented by air inhalation and by water and food ingestion.

The natural radionuclides present in the atmosphere, contributing to the exposure of the human body to ionizing radiation by inhalation, are in fact radioactive decay products resulting from cosmic radiation, gaseous emissions from the soil, emissions from the soil surface matter or from building materials. Radon and its decay products have the most important contribution to the effective dose due to indoor exposure of the population to ionizing radiation by inhalation [1].

Occasionally, artificial radionuclides may be released into the atmosphere, in which case they contribute to internal exposure by inhalation and not only.

UNSCEAR estimates the contribution of natural sources to the population's effective dose at 2.4 mSv year^{-1}, this dose comprising the amount of 0.29 due to food and water consumption [2]. The presence of natural radionuclides in water and food is due to the radioactive decay products from the three natural radioactive series existing on Earth (Uranium-238, Uranium-235, Thorium-232 series) and Potassium-40. It is estimated that thorium, with the highest natural isotopic abundance corresponding to the ^{232}Th isotope, is three times more abundant than uranium in the Earth's crust, which is found in the largest proportion in the form of the ^{238}U isotope [3]. The specific activity of the isotope ^{238}U ($T_{1/2} = 4.46 \times 10^9$ years, $\Lambda_{specific} = 12.432 \times 10^3$ Bq g^{-1}) is three orders of magnitude greater than the specific activity of the ^{232}Th isotope ($T_{1/2} = 1.4 \times 10^{10}$ years, $\Lambda_{specific} = 4.1 \times 10^3$ Bq g^{-1}), therefore, in the Earth's crust, the uranium activity concentration is higher than the thorium activity concentration.

The Uranium-238 and Thorium-232 series isotope content analysis in the human body requires tissue measurements

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[1]. In the case of ^{40}K, regardless of its intake, its concentration in the body is kept under control by hemostatic balance. This biological mechanism does not apply to the radionuclide penetration from the three natural radioactive series whose parents are ^{238}U, ^{232}Th, ^{235}U. Determining the concentration of radionuclides in water and food is a much more useful alternative in assessing the effective dose due to internal exposure of the body to ionizing radiation by drinking water and food consumption. The assessment of the effective dose due to water and food consumption in the world population varies according to geographic specificity, seasonal cultural and food habits, in the range 0.2–0.8 mSv year^{-1} [1]. There are many studies to assess the annual effective dose due to ingestion of radionuclides by food consumption [4–23], and by water consumption [24–57], which use different calculation methods of this physical magnitude.

Calculation methods

The quantification of the ionizing radiation effects on the human body due to the consumption of drinking water is performed by calculating the physical magnitude called the annual effective dose—expressed in Sv year^{-1}, defined in Council Directive 2013/51/EURATOM as *the committed effective dose for 1 year of ingestion resulting from all the radionuclides whose presence has been detected in a supply of water intended for human consumption, of natural and artificial origin, but excluding tritium, potassium-40, radon and short-lived radon decay products*.

The European legislation [58] transposed into Romanian legislation [59] recommends that this value parameter should not exceed 0.1 mSv year^{-1}.

The European and Romanian legislation [58–60] states that, if the formula below is complied with, then the total effective reference dose (called indicative dose- ID) is less than the value parameter 0.1 mSv year^{-1} and no additional investigations are required:

$$\sum_{i=1}^{n} \frac{C_{i(\text{det.})}}{C_{i(\text{der.})}} \leq 1 \tag{1}$$

where $C_{i(\text{det.})}$—measured concentration of the radionuclide i, $C_{i(\text{der.})}$—the derived concentration of the radionuclide i, i.e., the concentration of the radionuclide i, which determines a dose of 0.1 mSv year^{-1} at an intake of 730 L, by using the effective dose coefficients (CF)

$$C_{i(\text{der.})}\left(\text{Bq L}^{-1}\right) = \frac{10^{-4}\left(\text{Sv year}^{-1}\right)}{\text{CF}\left(\text{Sv Bq}^{-1}\right) \times 730(\text{L})} \tag{2}$$

n—the number of detected radionuclides.

The effective dose coefficients (CF) used are tabulated as *The committed effective dose per unit intake for each radionuclide type* [61–64]. For the most important radionuclides, these tabulated values were exemplified, given in different sources: Table 1. Currently the values given in IAEA, 2014, Table III.2D. [63] are used.

The assessment of the annual effective dose using the measured concentrations of the investigated radionuclides

The specific concentration of natural radionuclides in drinking water, multiplied by the annual intake rate and the effective dose coefficient, for each radionuclide type and age

Table 1 The committed dose equivalent per unit intake (Sv Bq^{-1}) (D_{ef}), the fractional absorption in the gastrointestinal tract (f) for age < 1a, and age > 1a, [61–63] and the derived concentration ($C_{der.}$), calculated according to Eq. (2)

Nuclide	Half-life $T_{1/2}$	D_{ef} [61] (Sv Bq^{-1})	D_{ef} [62, 63] (Sv Bq^{-1})			$C_{der.}$ (guidance level) (Bq L^{-1})
			D_{ef}	f		
				< 1a	> 1a	
^{227}Ac	22 years	3.85×10^{-6}	1.1×10^{-6}	0.005	5×10^{-4}	0.124
^{228}Ac	6.13 h	5.85×10^{-10}	4.3×10^{-10}	0.005	5×10^{-4}	318.573
^{238}U	4.47×10^{9} years	6.88×10^{-8}	4.5×10^{-8}	0.040	0.02	3.044
^{235}U	7.04×10^{8} years	7.19×10^{-4}	4.7×10^{-8}	0.040	0.02	2.915
^{234}U	2.4×10^{5} years	7.66×10^{-8}	4.9×10^{-8}	0.040	0.02	2.796
^{224}Ra	3.66 days	9.89×10^{-8}	6.5×10^{-8}	0.6	0.2	2.107
^{226}Ra	1.6×10^{3} years	3.58×10^{-7}	$2{,}8\times10^{-7}$	0.6	0.2	0.489
^{228}Ra	5.75 years	3.88×1010^{-7}	6.9×1010^{-7}	0.6	0.2	0.198
^{228}Th	1.91 years	1.03×10^{-4}	7.2×10^{-8}	0.005	5×10^{-4}	1.902
^{232}Th	1.4×10^{10} years	7.38×10^{-7}	2.3×10^{-7}	0.005	5×10^{-4}	0.595
^{230}Th	7.7×10^{4} years	1.48×10^{-7}	2.1×10^{-7}	0.005	5×10^{-4}	0.652
^{210}Pb	22.3 years	5.14×10^{-7}	6.9×10^{-7}	0.6	0.2	0.198
^{210}Po	138 days	5.14×10^{-7}	1.2×10^{-6}	1.0	0.5	0.114

category, serve to determine the annual effective dose due to ingestion of radionuclides by drinking water consumption.

Using the measured concentrations of radionuclides in water, the effective dose coefficients, the fractional absorption in the gastrointestinal tract [62, 63], and the annual water consumption rate [60], the annual effective dose due to radionuclide ingestion through drinking water consumption (D_{ef}) according to the following formula is calculated [24–44]:

$$D_{ef} = \sum \left(C_X \times f \times \mathrm{CF} \times R\right) \left(\mathrm{Sv\ year^{-1}}\right) \quad (3)$$

where C_X—is the measured concentration of radionuclide X (example: $X = {}^{210}$Po, ^{210}Pb, ^{238}U, ^{232}Th, ^{40}K, ^{226}Ra) (Bq L^{-1}), R—is the annual consumption rate of drinking water (L $year^{-1}$), assumed to be 730 L $year^{-1}$ for adults; 350 L $year^{-1}$ for children, 250 L $year^{-1}$ for lactation age, [60]; or R—is the annual consumption rate of drinking water and beverages (L $year^{-1}$) assumed to be 150 L $year^{-1}$ for infants, 350 L $year^{-1}$ for children, and 500 L $year^{-1}$ for adults [65]. F—is the fractional absorption in the gastrointestinal tract. Often the factor of fractional absorption in the gastrointestinal tract is neglected. CF—is the effective dose coefficient (the committed effective dose per unit intake for each radionuclide type and age category (Sv Bq^{-1}) [63].

The assessment of the annual effective dose using the assumed concentrations based on the gross alpha and the gross beta activities

Another way of estimating the annual effective dose due to the intake of radionuclides from drinking water is based on the gross alpha and the gross beta activities [45–50].

This method of calculation is based on the following rationale: the specific activities of natural radionuclides from drinking water are due to the specific activities of decay products from the three natural radioactive series, whose parents (series heads) are ^{238}U, ^{232}Th, ^{235}U. The committed effective dose per unit intake for adults, for the most important radionuclides, increases in the following order:

$$^{238}\mathrm{U} < ^{235}\mathrm{U} < ^{234}\mathrm{U} < ^{232}\mathrm{Th} < ^{224}\mathrm{Ra} < ^{226}\mathrm{Ra} < ^{210}\mathrm{Pb} < ^{228}\mathrm{Ra} < ^{210}\mathrm{Po} \quad (4)$$

Considering this series, in order to calculate the annual effective dose due to drinking water intake, was take into account the worst prediction in which were assume that the gross alpha and beta activities are derived from the ^{210}Po and ^{228}Ra radionuclides, these having the highest effective dose coefficients.

Based on this rationale, the following calculation formula is used for assessing of the annual effective dose due to radionuclide intake from drinking water:

$$D_{ef} = \sum \left[\left(\Lambda_\alpha \times \mathrm{CF}_{210\mathrm{Po}}\right) + \left(\Lambda_\beta \times \mathrm{CF}_{228\mathrm{Ra}}\right)\right] \times R \left(\mathrm{Sv\ year^{-1}}\right) \quad (5)$$

where Λ_α—is the gross alpha activity (Bq L^{-1}), Λ_β—is the gross beta activity (Bq L^{-1}), R—is the annual consumption rate of drinking water (L $year^{-1}$) assumed to be 730 L $year^{-1}$ for adults [60], CF_{210Po}, CF_{228Ra}—is the effective dose coefficient for ^{210}Po and ^{228}Ra, respectively (Sv Bq^{-1}).

This calculation method does not take into account the following very important aspect, which was reported in WHO, 2017 [60]: the gross beta activity measured in a sample includes a contribution from the presence of the primary radionuclide ^{40}K, which occurs naturally with K stable in a stable ratio: the specific activity of ^{40}K is 27.6 Bq g^{-1} of K stable. Unlike other radionuclides, ^{40}K introduced into the body it does not accumulate due to the hemostatic balance [65]. Moreover, K is an essential element for the good functioning of the human body. Therefore, the ^{40}K contribution should be subtracted from the gross beta activity, thus remaining the so-called residual beta activity and only this should be assumed for the ^{228}Ra radionuclide. In the light of these considerations, in the annual effective dose calculation formula (2), Λ_β should represent the residual beta activity in order to avoid dose overestimation.

The assessment of the annual effective dose using the gross alpha activity

Following the procedure of Fernandez et al. [66], according to which more than 50% of the annual effective dose is due to the contribution of the radium, some authors [51–54] estimate the annual effective dose due to the ingestion of radionuclides through drinking water consumption by using the following formula [67]:

$$D_{ef} = \Lambda \times \mathrm{CF} \times 730 \times 2 \left(\mathrm{Sv\ year^{-1}}\right) \quad (6)$$

where Λ—is the gross alpha activity (Bq L^{-1}), CF—the effective dose coefficient, corresponding to the isotope ^{226}Ra, (Sv Bq^{-1}), 730 L—is the annual consumption rate of drinking water (adults) [60].

The value of 3.58 10^{-7} Sv Bq^{-1} for members of the public committed effective dose per unit intake via ingestion corresponding to the ^{226}Ra isotope, given by the USA-EPA, 1998, Table 2.2, [61] should be updated to the value of 2.8 10^{-7} Sv Bq^{-1} given by the IAEA, 2014, Table III. 2D [63].

The assessment of the annual effective dose by associating the gross alpha activity and the gross beta activity with the alpha emitters (ex ^{210}Po, ^{226}Ra, ^{232}Th, ^{238}U), and with the beta emitters, respectively (^{228}Ra, ^{210}Pb)

Some authors [37, 45, 55–57] do not assess the total effective reference dose, but the assumed contribution of each radionuclide:

$$D_{\text{ef}} = A_x \times R \times \text{CF}\left(\text{Sv year}^{-1}\right) \quad (7)$$

where Λ—is the gross alpha or gross beta activity (Bq L^{-1}), CF—is the effective dose coefficient (Sv Bq^{-1}). *R*—is the annual consumption rate of drinking water.

Without direct data on the concentrations of the assumed radionuclides, only the gross alpha and beta activity is used. In this type of rationale, the annual effective dose generated by each individual radionuclide is assessed.

The application of the calculation methods: experimental

In order to apply the calculation methods described above, a set of 10 drinking water samples was taken into consideration, on which the following measurements were performed: gross alpha activity, gross beta activity [57] and the concentration of ^{210}Po, ^{210}Pb, ^{238}U, ^{232}Th, ^{226}Ra. The physicochemical and radiological parameters of dinking water depend on the water source used. In the studied area one of the water sources used is the Danube river, characterized in many scientific works [68–76].

The gross alpha and the gross beta activity was determined in accordance with ISO 9696 and ISO 9697, respectively [77, 78]. The ^{210}Po, ^{210}Pb measurements were performed by the spontaneous deposition onto Ni disc and the gross alpha activity measurement [79, 80]. The U-natural and Th-natural measurements were performed through radiochemical separation on a Dowex ion exchange resin followed by Arsenazo III complexation and spectrophotometric measurement [81]. Based on the natural isotopic abundance of ^{238}U (99.27%) and ^{232}Th (100%) from U-natural and Th-natural, respectively, the specific activities of ^{238}U and ^{232}Th were calculated. The measurement of the ^{226}Ra concentration was performed by storing the samples for 30 days, which were required in order to reach the ^{226}Ra/^{222}Rn equilibrium, and then measuring it by using the Sarad RTM instrument.

The methods for determining the gross alpha activity, gross beta activity, the concentration of ^{210}Po, ^{210}Pb, ^{226}Ra were described in detail on [34, 57]. The measurements were performing in the Ionizing Radiations Laboratory from Galati—the accredited laboratory (Tables 2, 3).

The methods described above for estimating the annual effective dose due to ingestion of radionuclides by drinking water were used.

Due to the fact that the effective dose coefficients, FC for ^{210}Pb and for ^{228}Ra are equal, the annual effective doses for both radionuclides are equal.

It may be noticed that, for all the investigated samples, relation (1) is complied with. The domain of the annual effective dose value variation in a range (one string) of investigated samples, calculated through the same method, is not relevant. Is relevant the variation of the annual effective dose value in the same sample, calculated through the various previously described methods.

For all the investigated samples it may be noticed that the values of the annual effective doses due to the ingestion of radionuclides through drinking water consumption, assessed by the measurement of radionuclide concentration method, Eq. 3, in this case ^{210}Po, ^{210}Pb, ^{226}Ra, ^{238}U, ^{232}Th, are lower as compared to the effective dose values, calculated by assuming the gross alpha and beta activities

Table 2 The gross alpha and beta activity [57] the activities specific to the following radionuclides: ^{210}Po, ^{210}Pb, ^{238}U, ^{232}Th, ^{226}Ra, from drinking water (the samples taken from Galați 2014)

Sample code	Λ^*_α mBq L^{-1}	Λ^*_β	Λ_{210Po}	Λ_{210Pb}	Λ_{238U}	Λ_{232Th}	Λ_{226Ra}
DW1	6.0 ± 1.8	25.0 ± 6.2	2.8 ± 0.7	3.1 ± 0.8	36.0 ± 4.8	41.0 ± 4.5	30 ± 9
DW2	18.5 ± 5.5	25.0 ± 6.2	1.8 ± 0.5	4.2 ± 1.1	3.0 ± 0.3	10.0 ± 1.1	18 ± 5
DW3	6.0 ± 1.8	25.0 ± 6.2	2.9 ± 0.7	3.6 ± 0.9	31.0 ± 3.4	38.0 ± 4.2	30 ± 9
DW4	6.0 ± 1.8	62.4 ± 16.6	1.6 ± 0.4	5.2 ± 1.3	3.0 ± 0.3	11.4 ± 1.3	20 ± 6
DW5	43.3 ± 13.0	96.5 ± 24.1	11.4 ± 2.9	14.7 ± 3.7	18.5 ± 2.0	24.5 ± 2.7	18 ± 5
DW6	22.8 ± 6.8	25.0 ± 6.2	12.5 ± 3.1	14.2 ± 3.6	21.4 ± 2.4	31.4 ± 3.5	27 ± 8
DW7	22.0 ± 6.6	88.9 ± 22.2	2.3 ± 0.6	6.4 ± 1.6	14.5 ± 1.6	21.7 ± 2.4	14 ± 4
DW8	7.7 ± 2.3	25.0 ± 6.2	11.5 ± 2.9	14.9 ± 3.7	18.3 ± 2.0	21.6 ± 2.4	18 ± 5
DW110	12.1 ± 3.6	25.0 ± 6.2	1.8 ± 0.5	4.4 ± 1.1	6.2 ± 0.7	14.2 ± 1.6	23 ± 7
DW130	6.0 ± 1.80	25.0 ± 6.2	7.2 ± 1.8	10.5 ± 2.6	7.5 ± 0.8	18.4 ± 2.0	8 ± 2

Λ^*_α, Λ^*_β data published [57]

Table 3 The evaluation of the annual effective dose due to the radionuclide ingestion by drinking water—samples taken from Galați during the year 2014, using the Eqs. (3), (5), (6), (7)

Sample code	$\sum_{i=1}^{n} \frac{C^*_{i(\text{det.})}}{C_{i(\text{der.})}}$	D_{ef} (μSv year^{-1}), calculated by relying on					
		$C^a_{i(\text{det.})}$	$C^b_{(\text{assum. 210Po})}$ and $C^b_{(\text{assum. 228Ra})}$	Λ_α	$C^b_{(\text{assum. 210Po})}$	$C^b_{(\text{assum.226Ra})}$	$C^b_{(\text{assum. 228Ra})}$ or $C^b_{(\text{assum. 210Pb})}$
	Equation (1)	Equation (3)	Equation (5)	Equation (6)	Equation (7)		
DW1	0.23	9.78 ± 1.97	17.85 ± 4.72	2.45 ± 0.74	5.26 ± 1.58	1.23 ± 0.37	12.59 ± 3.15
DW2	0.22	5.36 ± 1.11	28.80 ± 8.01	7.56 ± 2.27	16.21 ± 4.86	3.78 + 1.13	12.59 ± 3.15
DW3	0.23	9.70 ± 1.95	17.85 ± 4.72	2.45 ± 0.74	5.26 ± 1.58	1.23 ± 0.37	12.59 ± 3.15
DW4	0.22	5.59 ± 1.24	36.68 ± 9.43	2.45 ± 0.74	5.26 ± 1.58	1.23 ± 0.37	31.42 ± 7.85
DW5	0.22	14.28 ± 1.17	86.59 ± 2.54	17.72 ± 5.31	37.96 + 11.39	8.86 ± 2.66	48.62 ± 12.16
DW6	0.23	17.18 ± 1.78	32.56 ± 9.14	9.32 ± 2.80	19.97 ± 5.99	4.66 ± 1.40	12.59 ± 3.15
DW7	0.21	5.36 ± .91	64.02 ± 16.97	8.99 ± 2.70	19.26 + 5.78	4.49 ± 1.35	44.76 ± 11.19
DW8	0.22	14.36 ± 1.17	19.33 ± 5.17	3.15 ± 0.94	6.74 ± 2.02	1.57 ± 0.47	12.59 ± 3.15
D110	0.22	6.49 ± 1.43	23.18 ± 6.32	4.94 ± 1.48	10.58 ± 3.17	2.47 ± 0.74	12.59 ± 3.15
DW130	0.21	8.19 ± 0.52	17.85 ± 4.72	2.45 ± 0.74	5.26 ± 1.58	1.23 ± 0.37	12.59 ± 3.15

$C^a_{i(\text{det.})}$—measured concentrations of the following radionuclides: ^{210}Po, ^{210}Pb, ^{226}Ra, ^{238}U, ^{232}Th, $C^b_{(\text{assum. 210Po})}$—assumed concentration for the specific activity of ^{210}Po, as derived from the entire measured gross alpha activity, $C^b_{(\text{assum. 228Ra})}$—assumed concentration for the specific activity of ^{228}Ra, as derived from the entire measured gross beta activity, $C^b_{(\text{assum. 226Ra})}$—assumed concentration for the specific activity of ^{226}Ra, as derived from the entire measured gross alpha activity, $C^b_{(\text{assum. 210Pb})}$—assumed concentration for the specific activity of ^{210}Pb, as derived from the entire measured gross beta activity

Table 4 The Pearson correlation between the alpha radioactivity parameters in the analysed water samples

(mBq L^{-1})	Λ_α	$\Lambda_{210\text{Po}}$	$\Lambda_{238\text{U}}$	$\Lambda_{232\text{Th}}$	$\Lambda_{226\text{Ra}}$
Λ_α	1				
$\Lambda_{210\text{Po}}$	**0.44**	1			
$\Lambda_{238\text{U}}$	−0.04	0.21	1		
$\Lambda_{232\text{Th}}$	−0.05	0.21	**0.98**	1	
$\Lambda_{226\text{Ra}}$	−0.15	−0.11	**0.67**	**0.66**	1

as specific concentrations of ^{210}Po and ^{228}Ra radionuclides, Eq. 5, as expected.

This can be explained as follows: in the present study and in general, the measurement of the gross alpha activity [77, 78] was performed using the usual method of residue measurement according to which, obtaining the desired residue, which could be measured from a gross alpha activity point of view, is done at a temperature of up to 350 °C, at which ^{210}Po is already volatilized. Therefore, the measured gross alpha activity does not represent an exact measure of the specific activity of ^{210}Po, as one may notice a weak correlation between these two radioactivity parameters assessed by means of the Pearson correlation shown in Table 4. There is not a correlation between the gross alpha activity and the concentration of alpha emitter radionuclides, for these reasons: when this method is used, the different radioisotopes with the different energy are present in standard and samples, the pretreatment might lead to release the radioisotopes from the sample, the very low concentration of isotopes requires their preconcentration and purification to become detectable by radiochemical separation.

It is noteworthy that, for the investigated samples, a very good correlation was found between $\Lambda_{232\text{Th}}$ and $\Lambda_{238\text{U}}$, between $\Lambda_{226\text{Ra}}$ and $\Lambda_{238\text{U}}$, between $\Lambda_{226\text{Ra}}$ and $\Lambda_{232\text{Th}}$.

The values of the annual effective dose (D_{ef}) due to the ingestion of the ^{210}Po radionuclide by drinking water consumption, for the investigated samples, based on the specific *measured* activity of ^{210}Po ($\Lambda_{210\text{Po}}$) are lower than the values of the annual effective dose assessed on the basis of the specific *assumed* activity of ^{210}Po ($C_{(\text{assum.210Po})}$), except in the case of the samples DW8, DW110.

In the case of relation (5), this leads to higher D_{ef} values as compared to relation (3). Moreover, it may be noticed that, in the case of this study, relation (5) leads to the highest values for the annual effective dose. This calculation method is based on the maximum associated risk for estimating the annual effective dose due to the ingestion of natural radionuclides by drinking water consumption.

The D_{ef} values calculated with relation (3) are lower than the annual effective dose values calculated by assuming the measured beta activity as specific activity of ^{228}Ra/^{210}Pb, except for samples DW6 and DW8. In this case, too, it can be said that the measurement of the gross beta activity is not an exact measure of the specific activity of beta radionuclides, in this case ^{228}Ra/^{210}Pb, for which radiochemical separations are necessary.

The D_{ef} calculated based on the measured concentration of ^{238}U has the same order of magnitude as that calculated based on the assumed concentration as derived from the measured gross alpha activity. The same happens when using the measured and the assumed concentration of ^{226}Ra. However, this is not the case with the ^{232}Th radionuclide, in which case the D_{ef} calculated on the basis of the assumed concentration of ^{232}Th is derived from the measured gross alpha activity.

The D_{ef} calculated from a single radionuclide based on the measured concentrations and on the assumed concentrations differ very little in the case of ^{238}U and very much in the case of ^{232}Th.

Conclusions

In the present study, the calculation methods of the annual effective dose due to the ingestion of natural radionuclides through drinking water consumption were analysed, exemplified and discussed. This was done on the basis of the *measured* radioactivity parameters, on the one hand, and on the basis of the *assumed* radioactivity parameters, on the other hand, using the calculation rationale found in the domain-specific literature. The advantages and disadvantages of the calculation methods are are shown in the Table 5.

Two algorithms of assessment of the annual effective dose due to radionuclide intake through of drinking water consumption were identified: based on the *measured* radionuclide concentrations and on the basis of the *assumed* radionuclide concentrations. There are major differences between the two algorithms.

The use of relation (3) in order to calculate the annual effective dose leads to an appreciation characterized by high accuracy of the result. The annual effective dose, calculated in this way, should be accompanied by the specification of the radionuclides whose measured concentration was used. It is worth mentioning here that it is advisable to determine the concentrations of radionuclides with the highest effective dose coefficient. Also, when using this calculation method, one should take into account the recommendations of the EU Directive—according to which the contribution of *tritium, of potasium-40, of radon and of short-life products resulting from the decay of radon* mustn't be used.

The use of relation (5) in which the entire gross alpha and beta activity is attributed to the ^{210}Po radionuclide and the ^{210}Pb/^{228}Ra radionuclide, respectively, leads to an overassessment of the annual effective dose. This calculation method covers the maximum risk due to radiation effects and is taken into account only when gross alpha or beta activity measurements are available and when there isn't any data on radionuclide concentrations.

Table 5 The advantages and disadvantages of calculation methods

The methods	The advantages	The disadvantages
2.1. The assessment of the annual effective dose using the *measured* concentrations of the investigated radionuclides (Eq. 3)	The accuracy of the result is high Provides informations about the contribution of the determined radionuclides to the annual effective dose	High response time Radiochemical (reagent-time-consuming) determinations of radionuclides with the highest effective dose coefficients is required
2.2. The assessment of the annual effective dose using the *assumed* concentrations based on the gross alpha and beta activities (Eq. 5)	Fast response time Covers the maximum risk due to radiation effects Only radiometric determinations are required: alpha and beta global activity	The accuracy of the result is low The ^{40}K contribution from global beta activity is not subtracted
2.3. The assessment of the annual effective dose using the gross alpha activity (Eq. 6)	Fast response time Only one type of determination is required: global alpha activity	The accuracy of the result is low Not provide information on the contribution of radionuclides to the dose
2.4. The assessment of the annual effective dose by associating the gross alpha activity and the gross beta activity with the alpha emitters (ex ^{210}Po, ^{226}Ra, ^{232}Th, ^{238}U), and with the beta emitters, respectively (^{228}Ra, ^{210}Pb) (Eq. 7)	Fast response time Only radiometric determinations are required: alpha and beta global activity	The accuracy of the result is low The ^{40}K contribution from global beta activity is not subtracted

Relation (6) generally leads to lower D_{ef} values than relation (5), but closer to the values determined based on relation (3). Relationship (6) represents a rapid method of D_{ef} assessment, generating a minimal risk of over assessment, often used only when the gross alpha and beta activities for the investigated water samples are available and a quick response is required.

Relationship (7) uses assumed alpha-emitting radionuclide concentrations as derived from the measured gross alpha activity and assumed beta-emitting radionuclide concentrations as derived from the measured gross beta activity. This calculation method is useful when it is desirable to assess D_{ef} on radionuclide type and cannot be compared to the other calculation methods (relations 3, 5, 6) that include the contribution of several radionuclides whose concentration is either measured or assumed.

Depending on the laboratory (both from a technical and from a specialized human resource point of view), on the available data, on the response time available, on the aim pursued, the most adequate method of D_{ef} assessment is selected, each of the above-mentioned methods providing valuable information on quantifying the exposure of the population to ionizing radiation through drinking water consumption.

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References

1. United Nations Scientific Committee on the Effects of Atomic Radiation (2000) Annex B: exposures from natural radiation sources
2. World Health Organisation (2008) Guidelines for drinking water quality, 3 edn. Geneva
3. Nuccetelli C, Risica S (2008) Thorium series radionuclides in the environment: measurement, dose assessment and regulation. Appl Radiat Isot 66:1657–1660
4. Darko G, Faanu A, Akoto O, Acheampong A, Goode EJ, Gyamfi O (2015) Distribution of natural and artificial radioactivity in soils, water and tuber crops. Environ Monit Assess 187:339. https://doi.org/10.1007/s10661-015-4580-9
5. Alzubaidi G, Hamid F B S, Abdul Rahman I (2016) Assessment of natural radioactivity levels and radiation hazards in agricultural and virgin soil in the state of Kedah, North of Malaysia. Sci World J. Article ID 6178103 https://doi.org/10.1155/2016/6178103
6. Jibiri NN, Isinkaye MO, Bello IA, Olaniyi PG (2016) Dose assessments from the measured radioactivity in soil, rock, clay, sediment and food crop samples of an elevated radiation area in south-western Nigeria. Environ Earth Sci 75:107. https://doi.org/10.1007/s12665-015-4819-3
7. Alharshan GA, Aloraini DA, Al-Ghamdi H, Almuqrin AH, El-Azony KM, Alsalamah AS (2017) Measuring the radioactivity concentration of ^{40}K and ^{137}Cs and calculating the annual internal doses from ingesting liquid and powdered milk. Radiochemistry 59(1):98–103. https://doi.org/10.1134/S1066362217010131
8. Pintilie V, Ene A, Georgescu LP, Moraru DI, Pintilie A (2018) Determination of gross alpha, gross beta, and natural radionuclides (^{210}Po, ^{210}Pb, ^{238}U, ^{232}Th and ^{40}K) activity concentrations in bread and their contribution to the effective dose. Rom J Phys 63(1–2):801
9. Jemii E, Alharbi T (2018) Measurements of natural radioactivity in infant formula and radiological risk assessment. J Radioanal Nucl Chem 315(2):157–161. https://doi.org/10.1007/s10967-017-5646-7
10. Nguyen VT, Vu NB, Huynh NPT (2018) Gross alpha and beta radioactivity in food crops and surface soil from Ho Chi Minh City, Vietnam. J Radioanal Nucl Chem 315(1):65–73. https://doi.org/10.1007/s10967-017-5631-1
11. Pintilie V, Ene A, Georgescu LP, Pintilie AG, Moraru DI, Iticescu C (2018) Gross alpha, gross beta and radionuclides (^{210}Po, ^{210}Pb, ^{238}U, ^{232}Th, ^{226}Ra and ^{40}K) exposure assessment due to meat consumption. J Radioanal Nucl Chem 318(2):991–1000. https://doi.org/10.1007/s10967-018-6156-y
12. Yadav P, Garg VK, Singh B, Pulhani V, Mor S (2018) Transfer factors and effective dose evaluation due to natural radioactivity in staple food grains from the vicinity of proposed nuclear power plant. Exposure Health 10(1):27–39. https://doi.org/10.1007/s12403-017-0243-0
13. Boryło A, Romańczyk G, Wieczorek J, Strumińska-Parulska D, Kaczor M (2019) Radioactivity of honey from northern Poland. J Radioanal Nucl Chem 319:289–296. https://doi.org/10.1007/s10967-018-6343-x
14. Aswood MS, Abojassim AA, Al Musawi MSA (2019) Natural radioactivity measurements of frozen red meat samples consumed in Iraq. Radiat Detect Technol Methods 3:57. https://doi.org/10.1007/s41605-019-0136-9
15. Yii MW (2019) Measurement of activity concentrations in powdered milk and estimation of the corresponding annual effective dose. J Radioanal Nucl Chem 320(1):193–199. https://doi.org/10.1007/s10967-019-06460-6
16. Kandić I, Kandić A, Čeliković I, Gavrilović M, Janaćković P (2020) Activity concentrations of ^{137}Cs, ^{40}K, and ^{210}Pb radionuclides in selected medicinal herbs from Central Serbia and their effective dose due to ingestion. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2019.134554
17. Lopes JM, Garcêz RWD, Silva LB, Silva RC, Domingues AM, Silva AX, Dam RSF (2020) Committed effective dose due to

consumption of fruits and vegetables peels: analysis on cancer risk increase. Radiat Phys Chem 167:108243. https://doi.org/10.1016/j.radphyschem.2019.03.047
18. Szymańska K, Strumińska-Parulska D, Falandysz J (2020) Uranium (^{234}U, ^{238}U) and thorium (^{230}Th, ^{232}Th) in mushrooms of genus Leccinum and Leccinellum and the potential effective ionizing radiation dose assessment for human. Chemosphere. https://doi.org/10.1016/j.chemosphere.2020.126242
19. Van Duong H (2020) Assessment of the annual committed effective dose due to the ^{210}Po ingestion from selected sea-food species in Vietnam. Chemosphere 252:126519. https://doi.org/10.1016/j.chemosphere.2020.126519
20. Strumińska-Parulska D, Falandysz J, Wang Y (2020) Radiotoxic ^{210}Po and ^{210}Pb in uncooked and cooked Boletaceae mushrooms from Yunnan (China) including intake rates and effective exposure doses. J Environ Radioact. https://doi.org/10.1016/j.jenvrad.2020.106236
21. Kim SH, Lee SH, Lee HM, Hong GH (2020) Distribution of ^{239,240}Pu in marine products from the seas around the Korean Peninsula after the Fukushima nuclear power plant accident. J Environ Radioact 217:106191. https://doi.org/10.1016/j.jenvrad.2020.106191
22. Guy S, Gaw S, Pearson AJ, Golovko O, Lechermann M (2020) Spatial variability in Polonium-210 and Lead-210 activity concentration in New Zealand shellfish and dose assessment. J Environ Radioact 211:106043. https://doi.org/10.1016/j.jenvrad.2019.106043
23. Hansen V, Mosbech A, Søgaard-Hansen J, Rigét FF, Merkel FR, Linnebjerg JF, Asmund G (2020) ^{210}Po and ^{210}Pb activity concentrations in Greenlandic seabirds and dose assessment. Sci Total Environ 712:136548. https://doi.org/10.1016/j.scitotenv.2020.136548
24. Jia G, Torri G, Ocone R, Di Lullo A, De Angelis A, Boschetto R (2008) Determination of thorium isotopes in mineral and environmental water and soil samples by α-spectrometry and the fate of thorium in water. Appl Radiat Isot 66(10):1478–1487. https://doi.org/10.1016/j.apradiso.2008.03.015
25. Rajashekara KM, Narayana Y, Narasimha SA, Shetty P, Prakash V (2011) Effective doses due to intake of radiotoxic radionuclides ^{226}Ra, ^{210}Po and ^{210}Pb through drinking water of coastal Karnataka. J Radioanal Nucl Chem 290:137–140. https://doi.org/10.1007/s10967-011-1159-y
26. Rožmarić M, Rogić M, Benedik Štrok M (2012) Natural radionuclides in bottled drinking waters produced in Croatia and their contribution to radiation dose. Sci Total Environ 437:53–60. https://doi.org/10.1016/j.scitotenv.2012.07.018
27. Walsh M, Wallner G, Jennings P (2014) Radioactivity in drinking water supplies in Western Australia. J Environ Radioact 130:56–62. https://doi.org/10.1016/j.jenvrad.2013.12.016
28. Malakootian M, Khashi Z, Iranmanesh F, Rahimi M (2014) Radon concentration in drinking water in villages nearby Rafsanjan fault and evaluation the annual effective dose. J Radioanal Nucl Chem 302(3):1167–1176. https://doi.org/10.1007/s10967-014-3345-1
29. Althoyaib SS, El-Taher A (2015) Natural radioactivity measurements in groundwater from Al-Jawa, Saudi Arabia. J Radioanal Nucl Chem 304(2):547–552. https://doi.org/10.1007/s10967-014-3874-7
30. Altıkulac A, Turhan S, Gumus H (2015) The natural and artificial radionuclides in drinking water samples and consequent population doses. J Radiat Res Appl Sci 8(4):578–582. https://doi.org/10.1016/j.jrras.2015.06.007
31. Srinivasa E, Rangaswamy DR, Sannappa J (2015) Determination of radon activity concentration in drinking water and evaluation of the annual effective dose in Hassan district, Karnataka state, India. J Radioanal Nucl Chem 305(2):665–673. https://doi.org/10.1007/s10967-015-4034-4
32. Malakootian M, Darabi Fard Z, Rahimi M (2015) Determination of radon concentration in drinking water resources of villages nearby Lalehzar fault and evaluation the annual effective dose. J Radioanal Nucl Chem 304(2):805–815. https://doi.org/10.1007/s10967-014-3845-z
33. Benedik L, Rovan L, Klemenčič H, Gantar I, Prosen H (2015) Natural radioactivity in tap waters from the private wells in the surroundings of the former Žirovski Vrh uranium mine and the age-dependent dose assessment. Environ Sci Pollut Res 22(16):12062–12072. https://doi.org/10.1007/s11356-015-4481-z
34. Pintilie V, Georgescu LP, Moraru L, Ene A, Iticescu C (2016) Natural radioactivity in drinking water from Galati and Vrancea areas, Romania. Radiat Appl 1(3):165–170. https://doi.org/10.21175/RadJ.2016.03.031
35. Abdurabu WA, Saleh MA, Ramli AT, Heryansyah A (2016) Occurrence of natural radioactivity and corresponding health risk in groundwater with an elevated radiation background in Juban District, Yemen. Environ Earth Sci 75(20):1–12. https://doi.org/10.1007/s12665-016-6142-z
36. Sharma S, Duggal V, Srivastava AK, Mehra R (2017) Assessment of radiation dose from exposure to radon in drinking water from western Haryana, India. Int J Environ Res 11(2):141–147. https://doi.org/10.1007/s41742-017-0015-5
37. Alharbi T, Adel A, Baloch MA, Alsagabi SF, Alssalim YA, Alslamah AS, Alkhomashi N (2018) Natural radioactivity measurements and age-dependent dose assessment in groundwater from Al-Zulfi, Al-Qassim and Al-Majmaah regions, Saudi Arabia. J Radioanal Nucl Chem 318(2):935–945. https://doi.org/10.1007/s10967-018-6053-4
38. Darko G, Faanu A, Akoto O, Acheampong A, Goode EJ, Gyamfi O (2015) Distribution of natural and artificial radioactivity in soils, water and tuber crops. Environ Monit Assess 187(6):339. https://doi.org/10.1007/s10661-015-4580-9
39. Alomari AH, Saleh MA, Hashim S, Alsayaheen A, Abdeldin I (2019) Activity concentrations of ^{226}Ra, ^{228}Ra, ^{222}Rn and their health impact in the groundwater of Jordan. J Radioanal Nucl Chem 322(2):305–318. https://doi.org/10.1007/s10967-019-06686-4
40. Fathabadi N, Salehi AA, Nadda K, Kardan MR, Yunesian M, Nodehi RN, Deevband MR, Shooshtari MG (2019) Public ingestion exposure to ^{226}Ra in Ramsar, Iran. J Environ Radioact 198:11–17. https://doi.org/10.1016/j.jenvrad.2018.11.016
41. Ho PL, Minh VT, Hung LD, Trung DQ, Van Chinh D, Thanh TT, Van Tao C (2019) Assessment of annual effective dose from radium isotopes in groundwater samples in households along the lower Mekong River. J Radioanal Nucl Chem 322(2):503–511. https://doi.org/10.1007/s10967-019-06699-z
42. Silva CR, Machado DV, da Silva-Filho EV (2019) Determination of the natural radioactivity in the mineral water distributed in the Salutaris Park, Paraíba do Sul, Brazil. Environ Earth Sci 78(22):1–9. https://doi.org/10.1007/s12665-019-8661-x
43. Madruga MJ, Gomes AR, Abrantes J, Santos M, Andrade E, Mourato A, Reis M (2020) Internal effective dose assessment for the public based on the environmental radioactivity data in Portugal. Radiat Phys Chem 168:108558. https://doi.org/10.1016/j.radphyschem.2019.108558
44. Semerjian L, Alrajaby H, Naaz N, Kasfah R, Dalah Z, Waheed E, Metwally WA (2020) Age-dependent effective ingestion dose estimations and lifetime risk assessment for selected radionuclides (^{40}K and ^{3}H) in bottled waters marketed in United Arab Emirates.

Chemosphere 249:126114. https://doi.org/10.1016/j.chemosphere.2020.126114
45. Gorur FK, Camgoz H (2014) Natural radioactivity in various water samples and radiation dose estimations in Bolu province, Turkey. Chemosphere 112:134–140. https://doi.org/10.1016/j.chemosphere.2014.02.074
46. Ogundare FO, Adekoya OI (2015) Gross alpha and beta radioactivity in surface soil and drinkable water around a steel processing facility. J Radiat Res Appl Sci 8(3):1–7. https://doi.org/10.1016/j.jrras.2015.02.009
47. Pintilie V, Georgescu LP, Ene A, Moraru L (2016b) Monitoring of gross alpha and beta activity in drinking water from Galati during 2013–2014. Annals of "Dunarea de Jos"University of Galati, FASCICLE II, YEAR VIII (XXXIX), No. 1, Mathematics, Physics, Theoretical Mechanics, ISSN 2067-2071. http://www.phys.ugal.ro/Annals_Fascicle_2/Year2016/SummaryII.htm
48. Korkmaz ME, Agar O, Şahin M (2016) Gross α and β activity concentrations in various water from Karaman, Turkey. Environ Earth Sci 75(1):1–9. https://doi.org/10.1007/s12665-015-4909-2
49. Yi P, Gong M, Zhang W, Hou XL, Aldahan A, Yang J, Chen P (2018) Evaluation of gross-α and gross-β activities in groundwater of the Haihe River Plain, China. J Radioanal Nucl Chem 317(1):193–201. https://doi.org/10.1007/s10967-018-5901-6
50. Yang Q, Wang L, Du H, Ge L, Lin X, Zhao X, Zhou X-J (2019) Investigation of radioactive level of drinking water sources in the Upper Yangtze River of Chongqing city. J Radioanal Nucl Chem 321(1):141–149. https://doi.org/10.1007/s10967-019-06551-4
51. Turhan S, Özçtak E, Taşkn H, Varinlioğlu A (2013) Determination of natural radioactivity by gross alpha and beta measurements in ground water samples. Water Res 47(9):3103–3108. https://doi.org/10.1016/j.watres.2013.03.030
52. Kobya Y, Taşkın H, Yeşilkanat MC, Çevik U, Karahan G, Çakır B (2015) Radioactivity survey and risk assessment study for drinking water in the Artvin Province, Turkey. Water Air Soil Pollut 226:49. https://doi.org/10.1007/s11270-015-2344-3
53. Saleh MA, Ramli AT, Hamzah K, Alajerami Y, Mhareb MHA, Aliyu AS, Hanifah NZHBA (2015) Natural environmental radioactivity and the corresponding health risk in Johor Bahru District, Johor, Malaysia. J Radioanal Nucl Chem 303(3):1753–1761. https://doi.org/10.1007/s10967-014-3631-y
54. Abbasi A, Mirekhtiary F (2017) Gross alpha and beta exposure assessment due to intake of drinking water in Guilan, Iran. J Radioanal Nucl Chem. https://doi.org/10.1007/s10967-017-5493-6
55. Akbulut S, Taskın H (2015) Determination of natural radioactivity by gross α and β measurements in tap waters in Rize province. J Radioanal Nucl Chem 303(1):413–420. https://doi.org/10.1007/s10967-014-3441-2
56. Faanu A, Adukpo OK, Tettey-Larbi L, Lawluvi H, Kpeglo DO, Darko EO, Agyeman L (2016) Natural radioactivity levels in soils, rocks and water at a mining concession of Perseus gold mine and surrounding towns in Central Region of Ghana. SpringerPlus 5(1):1–16. https://doi.org/10.1186/s40064-016-1716-5
57. Pintilie V, Ene A, Georgescu L P, Moraru L, Iticescu C (2016) Measurements of gross alpha and gross beta activity in drinking water from Galati region, Romania. Rom Rep Phys 68(3):1208–1220. ISSN 1221-1451 43 822, On-line ISSN 1841-8759. http://www.rrp.infim.ro/2016_68_3/A28.pdf
58. Council Directive 2013/51/Euratom, laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption
59. Law 301/2015 by establishing health protection requirements regarding the radioactive substances in drinking water (2015) Monitorul Official, 2015
60. WHO (2017) Guidelines for drinking-water quality: fourth edition incorporating the first addendum. ISBN 978-92-4-154995-0
61. EPA Federal Guide report No. 11 (1988) Limiting values of the radionuclide intake and air concentration and dose conversion factors for inhalation, submersion and ingestion, EPA 520/1-88-020. Washington, USA
62. ICRP (2012) Compendium of dose coefficients based on ICRP Publication 60 ICRP Publication 119. Ann. ICRP 41(Suppl.)
63. IAEA (2014) Safety Standards for protecting people and the environment. Radiation Protection and Safety of Radiation Sources: International Basic Safety Standard: General Safety Requirements Part 3, Vienna
64. Directive 96/29/Euratom (1996) laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation
65. United Nations Scientific Committee on the Effects of Atomic Radiation (2008) (UNSCEAR), Report to the General Assembly, with scientific annexes Annex B: Exposures of the public and workers from various sources of radiation
66. Fernandez JF, Lozano JC, Gomez JMG (1992) Natural radionuclides in ground water in western Spain. Radiat Prot Dosimetry 45:227–279. https://doi.org/10.1093/rpd/45.1-4.227
67. Sajo-Bohus L, Gomez J, Capote T, Greaves ED, Herrera O, Salazar V, Smith A (1997) Gross alpha radioactivity of drinking water in Venezuela. J Environ Radioact 35(3):305–312
68. Iticescu C, Georgescu LP, Murariu G, Topa C, Timofti M, Pintilie V, Arseni M (2019) Lower Danube water quality quantified through WQI and multivariate analysis. Water 11(6):1305. https://doi.org/10.3390/w11061305
69. Apetrei C, Iticescu C, Georgescu LP (2019) Multisensory system used for the analysis of the water in the lower area of River Danube. Nanomaterials 9–6:891. https://doi.org/10.3390/nano9060891
70. Arseni M, Rosu A, Iticescu C, Georgescu PL, Timofti M, Pintilie V, Calmuc M, Roman O (2018) A review of bathymetric measurements from august 2018 campaign on the lower course of Danube river, Annals of "Dunarea de Jos "University of Galati, FASCICLE II, YEAR X (XLI) 2018, No. 2, Mathematics, Physics, Theoretical Mechanics, ISSN 2067-2071
71. Banescu A, Georgescu LP, Iticescu C, Rusu E (2018) Analysis of river level and of the volume flow on the danube close to the city of Tulcea, based on in situ measurements. J Mar Technol Environ 1:7–13. ISSN (Online): 1884-6116. https://cmu-edu.eu/jmte/
72. Popa P, Murariu G, Timofti M, Georgescu LP (2018) Multivariate statistical analyses of water quality of Danube river at Galati, Romania. Environ Eng Manag J 17:491–509
73. Timofti M, Iticescu C, Arseni M, Calmuc M, Calmuc V-A, Georgescu LP (2019) Preliminary analysis on the River Danube water quality by using different kinds of methods. Int J Biosci Biochem Bioinform 9(1):65–72. https://doi.org/10.17706/ijbbb.2019.9.1.65-7
74. Iticescu C, Murariu G, Georgescu PL, Burada A, Topa CM (2016) Seasonal variation of the physico-chemical parameters and Water Quality Index (WQI) of Danube water in the transborder Lower Danube area. Revista de Chimie (Bucharest) 67(9):1843–1849
75. Iticescu C, Georgescu PL, Topa CM, Murariu G (2014) Monitoring Danube water quality near Galati City. J Environ Prot Ecol 15(1):30–38
76. Iticescu C, Georgescu LP, Topa MC (2013) Assessing the Danube water quality index in the city of Galati, Romania. Carpathian J Earth Environ Sci 8:155–164
77. ISO 9696:2018 Water quality—gross alpha activity—test method using thick source

78. ISO 9697:2019 Water quality—gross beta activity—test method using thick source
79. Water. The analysis of Po-210 concentration in water. STAS 12444-86
80. The methodological book Radiation Hygiene, Ministry of Health (1981)
81. STAS 12130-82 Water. Determination of the Uranium-natural and Thorium-natural