Retrospective estimation of individual accumulated doses for population of Bryansk region irradiated as a result of Chernobyl accident using tooth enamel EPR-spectroscopy technique

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The standardized procedure that has been developed in MRRC of RAMS for estimating individual accumulated dose based on EPR-spectroscopy of tooth enamel samples was applied in a large-scale dosimetric study. Measurements were made of over 2000 individual accumulated doses in residents of the south-west areas of Bryansk region contaminated as a result of Chernobyl accident (with ^{137}Cs soil contamination density between 5 and 30 Ci/km^2) and in control territories. Teeth extracted by medical indications were collected from dentist outpatients.

Doses were estimated using the calibration relationships resulted from exposure of enamel samples to γ-radiation from a collimated ^{137}Cs source. The statistical analysis of the measurement results has shown that dose distribution is adequately described by the log-normal function for the population of different territories. With allowance for a fixed error, the average doses range from 3 to 5 cGy for the uncontaminated areas and about 12 cGy for the contaminated ones. Residents having accumulated doses much higher the average ones are referred to a risk group and have to be followed up and subjected to dosimetric investigation.

It has been established that there is a clear correlation between the average individual accumulated doses measured by EPR and the level of radioactive contamination of the area. The linear regression coefficient has been found to be 0.24 ± 0.08 cGy (Ci/km^2). The dependence of individual doses on age is given by a linear regression with the slope of 0.14 ± 0.05 cGy/year. The indicated relationships are in agreement with results obtained with the models estimating retrospectively the accumulated doses.

Introduction

The Chernobyl accident has led to radioactive contamination of extensive areas in central Russia. Due to logistical reasons it was impossible to ensure individual dosimetric control of the population on a large scale. Originally, in the contaminated areas only collective radiation doses and doses averaged over a settlement were critically estimated (see for example [1]). Because of considerable heterogeneity in the contamination density and differences in life patterns it should be expected that individual doses will vary significantly and there will be noticeable deviations from average values even within population points. Therefore, estimation of individual doses using calculation methods based on the level of contamination is rather problematic. At the same time, it is essential to know individual accumulated doses when forming groups of enhanced risk for compulsory medical surveillance and rehabilitation.

Recent studies [2-4] have demonstrated that the method of electron paramagnetic resonance (EPR) of tooth enamel for evaluation of individual doses holds much promise. The essence of the method is as follows. Under exposure to ionizing radiation stable radiation induced paramagnetic centres are formed in enamel and they accumulate during the whole life of the tooth enamel. These centres can be registered by EPR-spectroscopy and based on their concentration and using calibration curves one can determine the accumulated dose.

We used EPR-spectroscopy of tooth enamel during examination of the population in south-west areas of the Bryansk region affected by radioactive contamination at the density of ^{137}Cs contamination of up to 40 Ci/km^2. For comparison, we surveyed the population of uncontaminated (control) areas in Borovsk and Zhukovo districts of the Kaluga region. Altogether, 2000 samples of enamel of teeth extracted in dentist clinics on medical grounds were analysed.

The method under discussion is currently being actively developed and improved. Sources of systematic errors (relationship of radiation spectrum and radiation sensitivity of enamel, influence of solar light, features of spectra analysis) are being identified and way to eliminate them are sought [5, 6].

With EPR-spectroscopy of tooth enamel different methodological approaches can be used for sample preparation, measurements of spectra and their mathematical processing and interpretation of results for determination of individual doses [7]. Each of these methods has its peculiarities which ultimately show themselves as a systematic error in the dose estimate.

We used a methodological approach which was standardised in the experimental nuclear medicine laboratory of MRRC of RAMS to analyse all collected tooth samples. The special feature of this method is that there is no additional irradiation of the samples and they can be subject to repeated analysis, as the method is perfected and new factors to be taken into account are identified. The systematic errors of the method make an equal contribution to all doses that are determined and can be allowed for in data analysis as EPR-dosimetry continues to be developed.

The resulting accumulated doses should be considered as specific tooth enamel. Using these dose measures to estimate whole-body doses, account should be taken of features of formation of radiation-induced paramagnetic centres in enamel.

The doses determined by tooth enamel are stored in a computer database together with data on a patient; the tooth samples are also preserved. As the method is updated the results obtained with the standardized methodology will be refined. Some data and results of statistical analysis were published earlier [8, 9]. This paper presents results of a statistical analysis of available data which allows the evaluation of the contribution of different factors to formation of individual doses measured by EPR-spectroscopy of tooth enamel and some refined data and results of their analysis.

Methods and materials

The methodology used for sample preparation and dose measurements is described in detail in [10]. Here we will discuss it only briefly. The enamel samples were produced by removing dentine from a crown of tooth using hard-alloy dental drills and were ground to pieces of 1-2 mm. The analysis sample weight was 50-150 mg. The EPR-spectra were recorded at room temperature with ESP-300E (Bruker, Germany) spectrometer using a standard rectangular resonator in X-range with microwave power of 10 mW. The time of recording of each spectrum with 16-time accumulation was 45 min.

The background signal from the organic component of enamel was subtracted with a built-in computer using basic software. For modelling the subtracted background signal we used a spectrum of enamel of childrens' teeth selected by the criterion of " minimum signal" . The shape of the modelled signal was fitted to the signal from organic components by changing its amplitude, field shift and width using software with operator control. The subtraction resulted in the radiation-induced signal whose intensity was determined by amplitude of low-field component.

Accumulated dose was evaluated by the signal intensity normalized to a sample weight using the universal calibration coefficient. This coefficient was taken to be the value of the average slope of calibration dependencies measured for several tens of enamel samples exposed to a direct collimated beam of γ-

radiation of ^{60}Co and ^{137}Cs under electron equilibrium (the samples were placed between plates of tissue equivalent material of 1 g/cm^2). For both types of sources the same values of the calibration coefficient were derived.

Results and discussion

The frequency distribution of individual doses evaluated by tooth enamel without account taken of the tooth number (incisor, premolar, and molar tooth) for separate areas and major population points were described by a lognormal function. The average dose for adults of the control areas is 10-12 cGy (standard deviation of 7-8 cGy). In the areas contaminated after the Chernobyl accident the average doses for some population points was 15-20 cGy (standard deviation of 8-12 cGy) and depended on ^{137}Cs contamination density. Histograms of dose distribution for some areas of the Bryansk region have been presented in an earlier work [9].

The observed wide spread in the dose values can be attributed to several reasons:

1. A major contribution is made by the experimental error.

2. The observed spread in doses is due to different ages of the patients and hence different accumulated doses due to the natural radiation background. The dependence of individual doses measured by EPR method on patient age for the population of the control area (Borovsk area of Kaluga region) and the population of the contaminated Gordeevka district of Bryansk region is shown in Figure 1.

Each point in Figure 1 is given as an average over five measurements of doses in patients similar in age. There is a clear trend of an increase in doses with age. The slope of the line derived from data analysis by linear regression is 0.14±0.05 cGy/ year for both areas. The intersection point of the regression line and ordinate axis is 5.2±3.0 cGy for the control area and 9.3±2.3 cGy for the contaminated area. The difference between these two values is explained by additional irradiation during 8 years after the Chernobyl accident due to the soil contamination The regression line slope is explained by annual dose corresponding to natural background γ-radiation with exposure dose rate of 18±6 μR/hour.

3. Additional input to the spread of doses can be attributed to heterogeneity of the contamination. This explains the difference in variance in dose distribution for the population of the control and contaminated areas. The trend has been towards an increase in the average doses measured in residents of different population points with an increase in contamination level. Dependence of average dose for some population points on ^{137}Cs soil contamination level is shown in Figure 2. The figure indicates doses only for those population points in which more than 30 measurements have been made.

The data shown in Figure 2 can be approximated with a linear regression relationship with a slope 0.24±0.08 cGy/(Ci/km^2) and the intersection point with the ordinate axis of 11.3±2.0 cGy. The value of the slope with an allowance for the adjustment coefficient for scattered radiation (K_{av} ≈ 1.5) [5] is 0.16±0.05 cGy/(Ci/km^2) and close to the value of 0.126 cSv/(Ci/km^2) derived by calculations with allowance for 8 years of external γ-radiation exposure of the rural population in the contaminated areas (Balonov M.I. et al see the present issue of the Bulletin, Table 4). Part of the dose corresponding to the intersection point is due to natural radiation background and the other part seems to be associated with the systematic error and should be taken into account as a correction factor after estimation.

Thus, the statistical analysis of dose measurements leads us to conclude that the determination of doses with EPR-spectroscopy of tooth enamel permits registration of accumulated dose which is contributed by natural radiation background and radioactive contamination of the area.

The spread of experimental data due to absolute error can be partly caused by the fact that some signals in the EPR spectra of enamel lie in the region of the radiation induced signal. These signals may be of different origin, namely due to uncontrollable paramagnetic impurities, X-ray exposure during medical examination etc. Moreover, we have demonstrated that paramagnetic centres giving the same signal as a radiation induced one are formed in enamel under the action of the ultraviolet component of solar light [6].

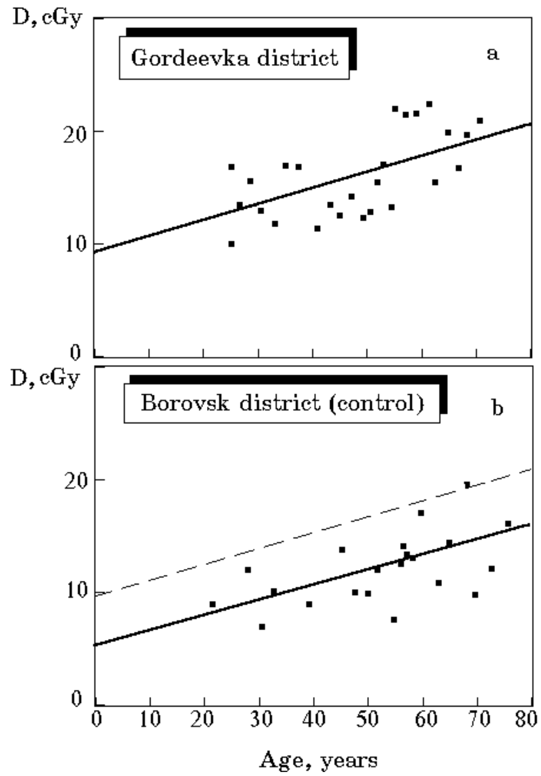

Fig. 1. Dependencies of individual accumulated doses measured by EPR-spectroscopy of tooth enamel on patient age for the population of the contaminated area of Gordeev district, Bryansk region (a) and the control area of the of Borovsk district Kaluga region (b). Each point is an average of five measurements.

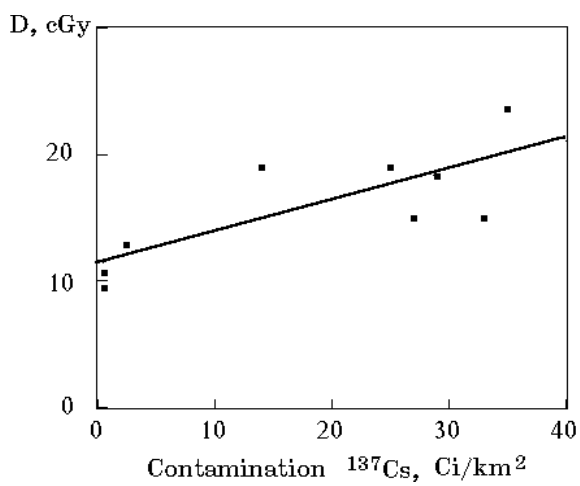

Fig. 2. Dependence of accumulated external dose averaged over the populated points measured by EPR-spectroscopy of tooth enamel on average density of ^{137}Cs soil contamination.

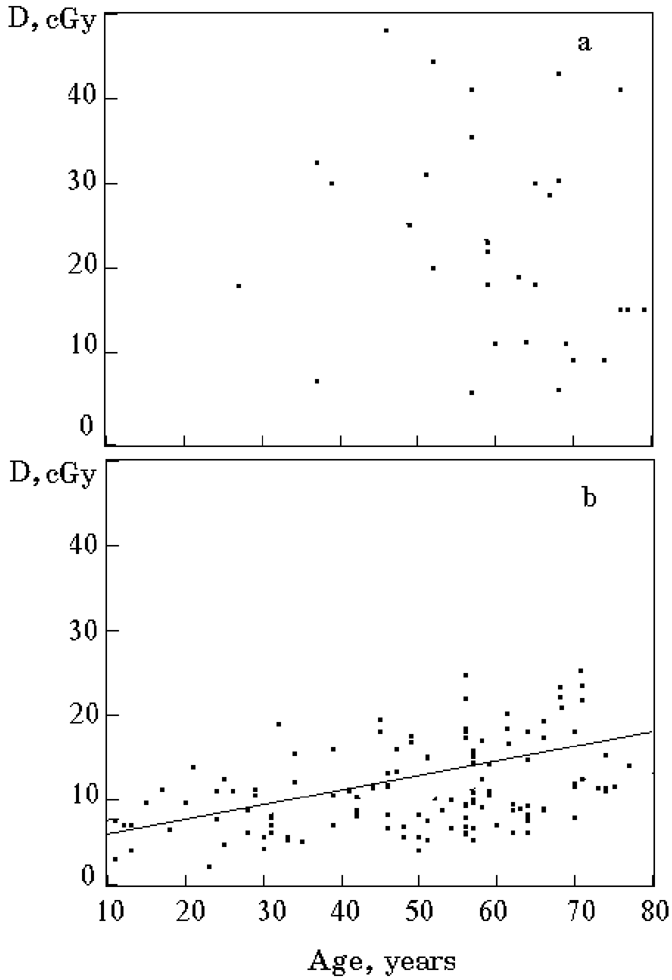

Fig. 3. Dependence of individual dose on patient age measured by EPR-spectroscopy of enamel of 1-3 anterior (a) and 4-8 posterior teeth (b).

Figure 3 shows separately age dependencies of doses measured by enamel from anterior (incisor, canine teeth 1-3) and posterior teeth (premolar, molar teeth 4-8) in the population of the control area.

As can be seen from Figure 3 the spread of doses measured by teeth with numbers 4-8 are much lower those for teeth 1-3. This difference in the spread of the values is explained by the fact that the front teeth are more exposed to direct solar light.

In the ENM laboratory of MRRC RAMS work is now under way to study the effect of solar light on formation of paramagnetic centres in enamel and ways are explored for treating enamel to reduce the induced light signal. However, as long as such methods are not available, posterior teeth extracted for medical reasons should be used for dose evaluation.

The statistical analysis of results of dose determination by enamel of the 4-8-th teeth for the control areas shown in Figure 3b suggests that the linear regression slope is 0.14±0.03 cGy/year, the standard deviation from the regression line being 4.0 cGy. This deviation value can be considered as an upper estimate of the random error of the method, assuming that all patients living in this area were exposed to natural background radiation of equal strength under similar conditions.

Because of the detected influence of solar light on formation of radiation-induced signal of tooth enamel we have excluded from the analysis part of the data on the contaminated areas of Bryansk region derived by dose measurement of front teeth 1-3. As was to be expected, this caused the variance in individual dose values to decrease and mean values to decrease too. The frequency distribution of refined values of individual doses for the areas and major population points were described by the lognormal function - see Figure 4.

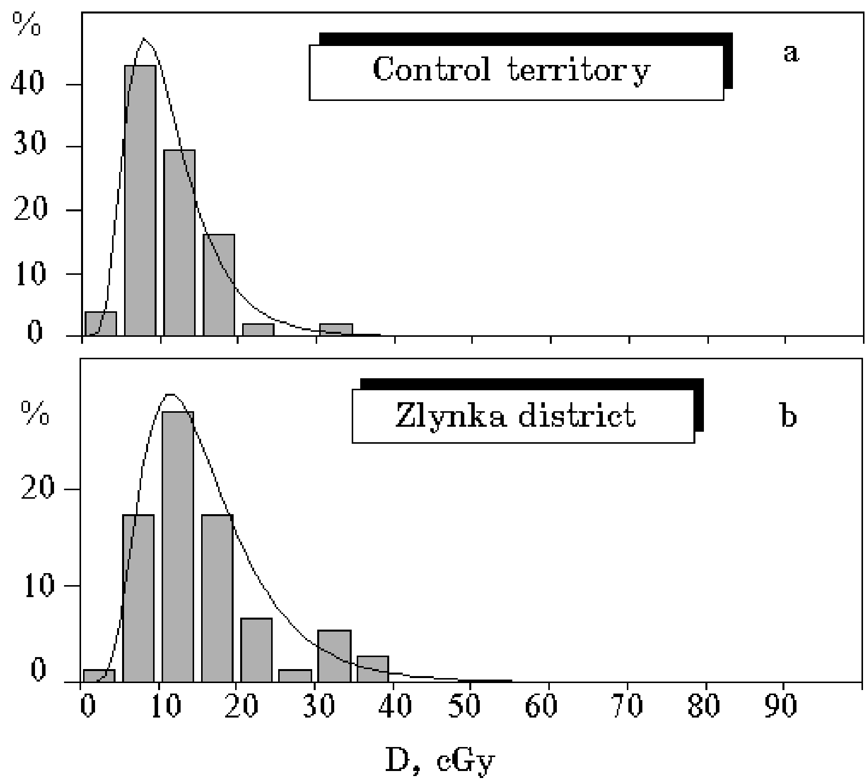

Fig. 4. Histogrammes of frequency distribution of accumulated dose measured with enamel of 4-8 posterior teeth for the population of Borovsk district of Kaluga region (a) and Zlynka district of Bryansk region (b). Borovsk district: number of measurements - 105; average accumulated dose - 11.1 cGy; standard deviation - 5.0 cGy; Zlynka district: number of measurements - 75; average accumulated dose - 14.8 cGy; standard deviation - 8.5 cGy.

The derived characteristics of the frequency distribution of individual doses measured by the EPR-method can be compared with parameters of doses measured during individual dosimetric monitoring in the contaminated areas [11], which were characterised by a lognormal function of distribution of daily mean doses measured during two months with the variance of 40% of the mean value.

Figure 5 shows dependencies of refined (measured by 4-8 posterior teeth) individual doses on age for residents of some populated points in the Bryansk region and results of data processing with the linear regression method. In particular, each point in Figure 5e is presented as a mean over five sequential values. The age value of 10 years to which the regression line was extrapolated approximately corresponds to the age when permanent 4-8 posterior teeth are formed. The linear regression slope in Figure 5 seems to be due to the influence of γ-radiation of natural sources and for different population points it lies in the range from 0.1 to 0.25 cGy/year with the mean value of 0.14±0.05 cGy/year. It may be assumed that individual dose values are much higher than the mean value derived from measurements in population on the control areas are attributed to the effect of the radioactive contamination of the area. We call your attention to relatively low individual doses in residents of settlement Mirny of Gordeevka district, Bryansk region in spite of considerable ^{137}Cs contamination of the area.

Figure 6 presents a dependence of individual doses measured by 4-8 posterior teeth on ^{137}Cs contamination level. Each point is given as a mean value over 10 sequential values. The linear regression slope is 0.22±0.05 cGy/(Ci/km^2); the value of the dose at zero ^{137}Cs contamination level is 7.4±0.7 cGy.

The value of the extrapolated dose at zero ^{137}Cs soil contamination density which is different from zero may probably be explained by the radiation dose accumulated from the natural background (by estimation, about 4 cGy with average age of teeth of 30 years) and a systematic error of the used dose evaluation method. The systematic error can arise because of discrepancy in the shape of signal used for modelling the native background signal in subtraction and the shape of the true native signal characteristic of a specific enamel sample. Such a discrepancy leads to additional contribution to the radiation induced signal and should be taken into account as a method correction factor. It can be estimated by extrapolation of the regression line, built by doses in the control areas as a function of age, to the age when formation of permanent teeth is, on the average, finishes. For the posterior teeth 4-8 the mean age can be taken to be 10 years. Based on these estimates with age dependence of Figure 3 b the correction value is 7.0±0.5 cGy, though this value should be specified more accurately and can be even an individual value for population living in a specific area. The above correction emerges because of the difference in the shape of EPR signal for enamel of non-irradiated children’s teeth used for modelling the background signal and the (averaged) shape of the background signal for adults.

The results of the evaluation of mean radiation dose with allowance for the systematic error for districts and selected major population points (in which at least several measurements are available) are shown in Table 1.

Figure 7 presents a dependence of refined mean dose for selected population points on ^{137}Cs contamination density.

This figure shows mean the dose after subtraction of a mean dose due to γ-radiation of natural origin which was taken to be 4.0 cGy.

The spread of measured values is also contributed by the differences in the individual radiation sensitivity of enamel, for which standard deviation is about 20% of the mean value. This contribution is camouflaged by other error sources and is not predominant in the region of low doses (below 15 cGy), but is quite significant in the region of higher values. That is why it is necessary to measure individual radiation sensitivity of enamel using additional irradiation to determine more accurately radiation doses in people showing increased intensity of radiation-induced signal of enamel. Work is now under way to make such corrections in the derived dose values and its results will be published in the near future.

When interpreting the obtained data and to determine them more accurately and pass to effective doses, the correction associated with dependence of radiation sensitivity of enamel on energy of radiation should be taken into account. Our experimental studies and theoretical estimates [5] suggest that with the scattered irradiation of ^{137}Cs the value of the correction factor allowing for overestimation of dose in measurements by tooth enamel can be as high as 2.4 and depends on mean energy of scattered γ-irradiation. The variety of exposure conditions in the contaminated areas can lead to an additional spread in measured individual doses, unless the indicated correction is taken into account.

It may be worth pointing out that an important factor contributing to the differences in estimated individual doses are social-economic features and behaviour of individual people in the area contaminated after the Chernobyl accident.

D, cGy

D, cGy

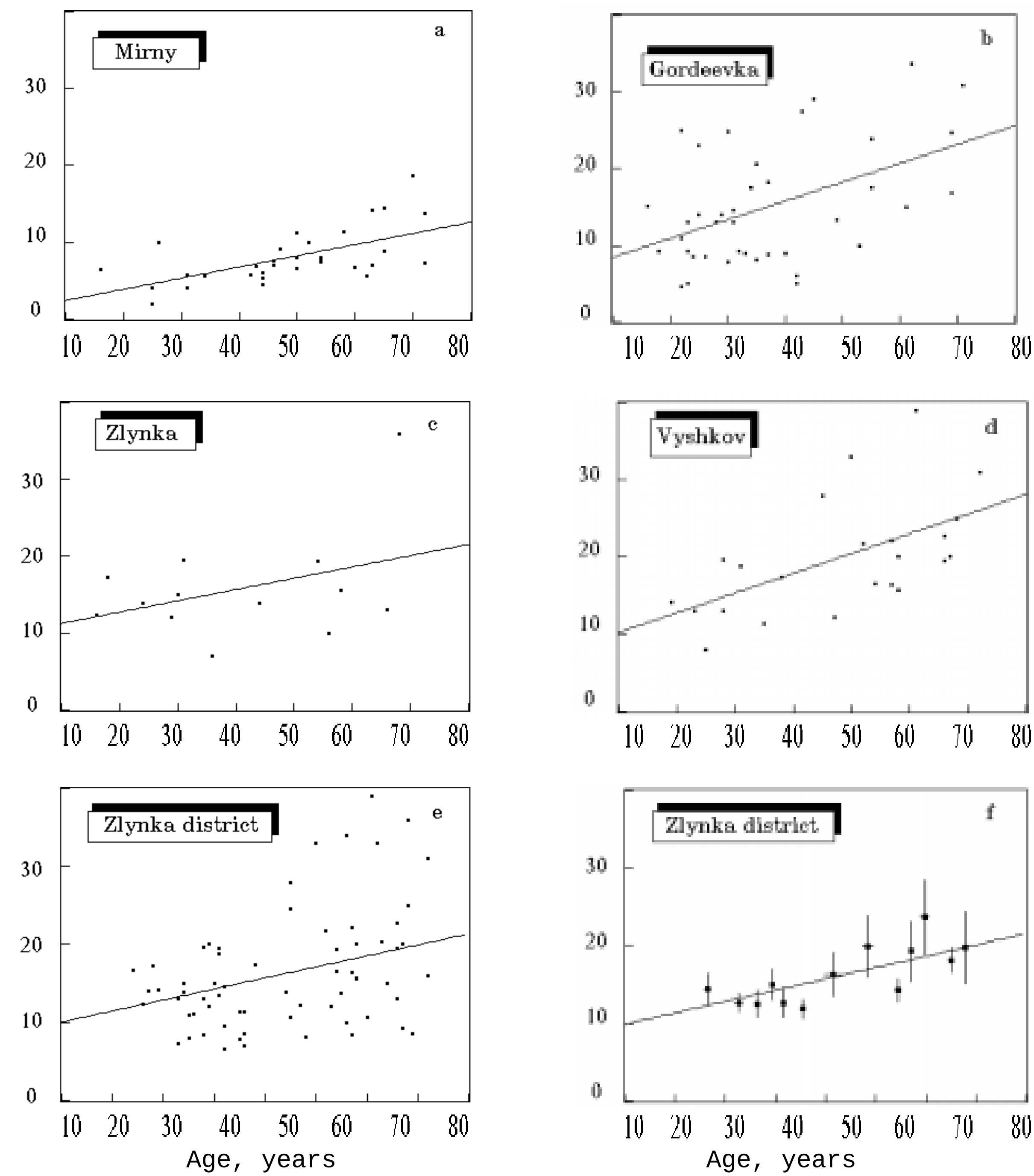

Fig. 5. Dependence of individual external accumulation doses on age measured by EPR-spectroscopy of 4-8 posterior teeth in residents of two contaminated areas of Bryansk region.

"a" - settl. Mirny, Gordeevka district, ^{137}Cs soil contamination density ranges from 9.6 to 85.2 Ci/km^2, the average being 29.8 Ci/km^2; "b" - settl. Gordeevka, ^{137}Cs contamination ranges from 5.3 to 40.4 Ci/km^2, the average being 20.4 Ci/km^2; "c" - settl. Zlynka, ^{137}Cs contamination ranges from 10.8 to 70.2 Ci/km^2, the average being 26.4 Ci/km^2; "d" - c. Vyshkov, Zlynka district, ^{137}Cs contamination ranges from 9.1 to 45.0 Ci/km^2, the average being 26.8 Ci/km^2.

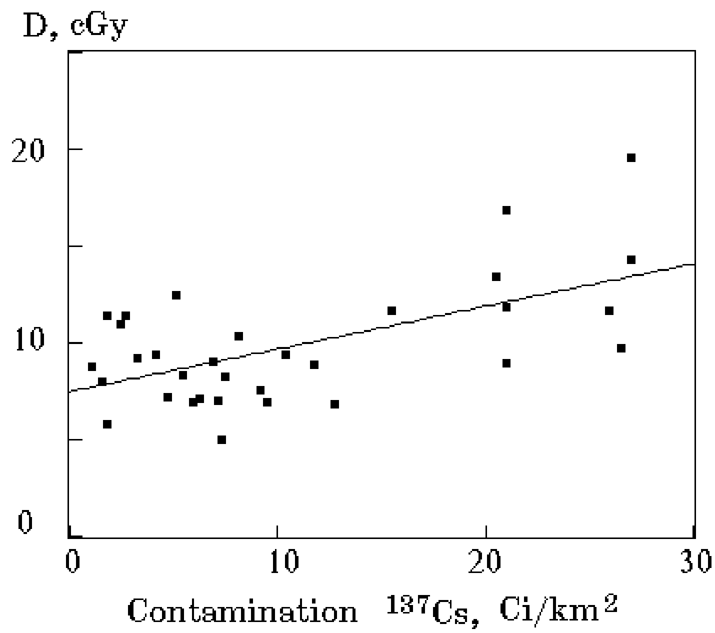

Fig. 6. Dependence of individual accumulated dose averaged over 10 consecutive values, measured by EPR-spectroscopy of 4-8 posterior teeth on ^{137}Cs contamination level in the areas dwelled by the patients.

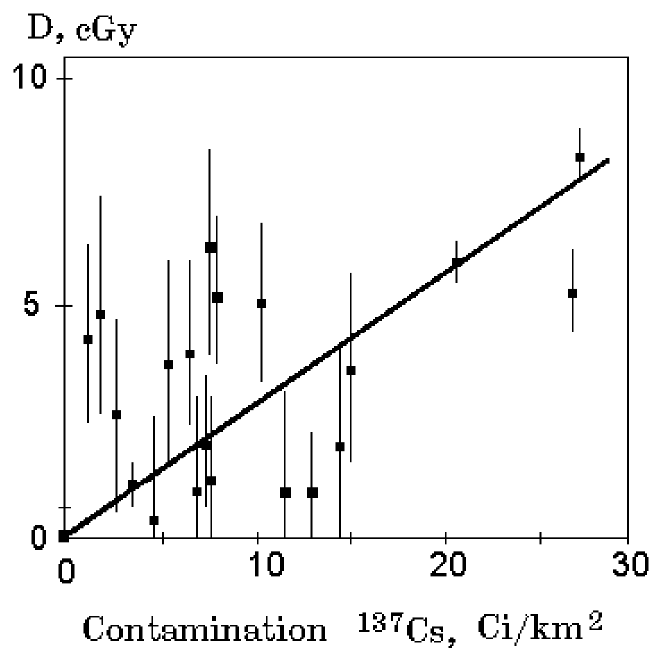

Fig. 7. Dependence of accumulated dose averaged over populated points on average ^{137}Cs soil contamination density. The doses values have been corrected for a systematic bias of the methodology and average dose accumulated due to the natural radiation background.

Table 1

Refined results (for premolar and molar teeth and subtraction of the systematic correction of 7.0 cGy) of determination of individual accumulated doses by EPR- spectroscopy of teeth enamel in adults

N - number of samples; ***D*** - average accumulated external dose;
S_D - error in average value; ***d*** - standard deviation;
σ_{137} - averaged ^{137}Cs soil contamination density [1].

Administrative district: populated points	***N***	***D***, cGy	S_D, cGy	***d***, cGy	σ_{137}, Ci/km^2
Gordeevka district:	225	6.8	0.5	7.3	
Mirny	50	2.1	0.7	5.1	30.2
Gordeevka	41	8.6	1.3	8.2	20.7
Tvorishino	15	8.9	2.0	6.7	10.3
Kozhany	13	3.0	1.3	4.5	37.7
Strugova Buda	10	5.4	3.2	7.1	8.0
Petrova Buda	9	4.8	2.0	5.6	14.5
Smyalch	7	7.3	2.8	7.0	15.1
Yamnoe	7	10.7	1.4	3.5	7.6
Maloudebnoe	6	5.4	3.2	7.1	18.5
Klintsy district:	264	6.3	1.0	6.0	
Klintsy	150	6.0	1.5	6.0	3.6
Smotrova Buda	16	7.4	2.0	7.8	5.4
Smolevichi	16	7.4	2.0	7.8	2.7
Gulevka	11	4.9	2.0	5.9	7.0
Olkhovka	10	2.5	6.0	3.8	9.5
Korzhevka	9	5.4	6.6	6.1	1.8
Kivai	6	5.1	2.5	6.6	7.8
Lopatni	6	0.1	2.0	5.0	7.2
Velikaya Topal	5	3.8	6.1	6.0	7.7
Pavlichi	5	8.9	1.5	6.2	1.2
Turosna	5	5.1	1.5	3.4	7.1
Zlynka district:	104	8.7	1.0	8.0	
Zlynka	32	8.8	2.1	6.9	26.8
Vyshkov	26	11.5	1.5	7.3	27.1
Dobreevka	4	5.6	2.3	4.7	26.0
Spiridonova Buda	8	5.0	2.2	3.9	11.6
Lysye	6	4.9	1.8	4.2	13.0
Shcherbinichi	5	0.9	1.0	1.9	11.3
Kozhany	4	0.2	1.2	2.5	1.5
Karpilovka	3	2.2	1.3	2.0	11.3
Denisyukovichi	3	2.0	1.8	2.7	15.2
Krasnya Gora district	26	3.3	1.0	5.2	
Klimovo district:	34	4.0	0.7	3.9	
Klimovo	11	5.8	1.5	4.7	7.4
Lakomaya Buda	4	2.8	3.0	6.0	9.9
Borovsk district	84	4.0	0.5	5.1	< 0.1
Zhukovo district	31	4.0	0.8	4.8	< 0.1

Conclusion

Based on experimental and theoretical estimates and statistical analysis of results of measurements of more than 2000 individual doses by EPR-spectroscopy of tooth enamel using a methodology standardized in ENM laboratory of MRRC RAMS we have identified the contributions to formation of individual dose from natural radioactive background and radiation due to the radioactive contamination of the area.

Sources of random and systematic errors have been analysed and methods have been proposed to correct results of measurements of individual doses by EPR-spectroscopy of tooth enamel.

Regularities in formation of individual doses as a function of patient age and ^{137}Cs contamination density have been traced.

The results of measurements of individual doses by the EPR-method are used for forming groups of increased risk among the persons under special medical surveillance.

In conclusion it should be noted that the average doses of external exposure of the population obtained with EPR spectroscopy of tooth enamel are in good agreement with results based on other methods of direct and retrospective dosimetry [12, 13].

The authors express their gratitude to V.A.Pitkevich for useful discussion of the results presented in the paper.

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