

Assessment of Occupational Exposure and Individual Radio-Sensitivity in People Subjected to Ionizing Radiation

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Abstract—The estimation of accumulated radiation doses in people professionally exposed to ionizing radiation was performed using methods of biological (chromosomal aberrations frequency in lymphocytes) and physical (radionuclides analysis in urine, whole-body radiation meter, individual thermoluminescent dosimeters) dosimetry. A group of 84 "A" category employees after their work in the territory of former Semipalatinsk test site (Kazakhstan) was investigated. The dose rate in some funnels exceeds 40 $\mu\text{Sv/h}$. After radionuclides determination in urine using radiochemical and WBC methods, it was shown that the total effective dose of personnel internal exposure did not exceed 0.2 mSv/year, while an acceptable dose limit for staff is 20 mSv/year. The range of external radiation doses measured with individual thermo-luminescent dosimeters was 0.3-1.406 μSv . The cytogenetic examination showed that chromosomal aberrations frequency in staff was $4.27 \pm 0.22\%$, which is significantly higher than at the people from non-polluting settlement Tausugur ($0.87 \pm 0.1\%$) ($p \leq 0.01$) and citizens of Almaty ($1.6 \pm 0.12\%$) ($p \leq 0.01$). Chromosomal type aberrations accounted for $2.32 \pm 0.16\%$, $0.27 \pm 0.06\%$ of which were dicentric and centric rings. The cytogenetic analysis of different types group radiosensitivity among «professionals» (age, sex, ethnic group, epidemiological data) revealed no significant differences between the compared values. Using various techniques by frequency of dicentric and centric rings, the average cumulative radiation dose for group was calculated, and that was 0.084-0.143 Gy. To perform comparative individual dosimetry using physical and biological methods of dose assessment, calibration curves (including own ones) and regression equations based on general frequency of chromosomal aberrations obtained after irradiation of blood samples by gamma-radiation with the dose rate of 0.1 Gy/min were used. Herewith, on the assumption of individual variation of chromosomal aberrations frequency (1–10%), the accumulated dose of radiation varied 0–0.3 Gy. The main problem in the interpretation of individual dosimetry results is reduced to different reaction of the objects to irradiation - radiosensitivity, which dictates the need of quantitative definition of this individual reaction and its consideration in the calculation of the received radiation dose. The entire examined contingent was assigned to a group based on the received dose and detected cytogenetic aberrations. Radiosensitive individuals, at the lowest received dose in a year, showed the highest frequency of chromosomal aberrations (5.72%). In opposite, radioresistant individuals showed the lowest frequency of chromosomal aberrations (2.8%). The cohort correlation according to the criterion of radio-sensitivity in our research was distributed as

follows: radio-sensitive (26.2%) — medium radio-sensitivity (57.1%), radioresistant (16.7%). Herewith, the dispersion for radioresistant individuals is 2.3; for the group with medium radio-sensitivity — 3.3; and for radio-sensitive group — 9. These data indicate the highest variation of characteristic (reactions to radiation effect) in the group of radio-sensitive individuals. People with medium radio-sensitivity show significant long-term correlation (0.66 ; $n=48$, $\beta \geq 0.999$) between the values of doses defined according to the results of cytogenetic analysis and dose of external radiation obtained with the help of thermoluminescent dosimeters. Mathematical models based on the type of violation of the radiation dose according to the professionals radiosensitivity level were offered.

Keywords—Biodosimetry, chromosomal aberrations, ionizing radiation, radiosensitivity.

I. INTRODUCTION

THE issues of controlling the intake of radioactive substances in the human body and their content in the body were and remain to be the most significant in the problem of radiation protection. This is due to the fact that radioactive substances are able to accumulate in the body, to be redistributed in tissues, reaching levels in certain organs that may be unsafe for health.

The main method of biodosimetry is the analysis of cytogenetic lesions in cultured human cells. When irradiating cells of the same donor *in vitro*, a strict dependence of the frequency of aberrations to the dose of radiation is observed. This gave grounds for using this criterion for the purpose of biodosimetry. However, the *in vivo* studies were found to be different from those of *in vitro*, and the results of biodosimetry often do not coincide with the doses documented by the dosimeters. At the same time, radiobiologists tend to believe that information obtained by biological methods is more reliable, and they conclude that the dose loads are incorrectly calculated, forgetting about the genetic differences of individuals. It is known that individuals of not only the same species, but even of the same population, can significantly differ in the degree of radiosensitivity. Most of the individuals are characterized by intermediate values of the trait, and only a small part of them have extreme values [1].

With chronic irradiation, such population processes as, for example, elimination of lesions during physiological renewal of cellular composition are added, cells with disabilities predominantly eliminated. At the same time, multidirectional processes can occur in populations. On the one hand, adaptation takes place - the selection and multiplication of

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cells with a more resistant genotype, which leads to a decrease in the radiosensitivity of the population. On the other hand, there may be genetic instability, leading to an increase in the frequency of genetic disorders in the following generations. Thus, even with the use of special calibration curves, we cannot be saved from serious errors in determining individual dose loads. In addition, the formation of nonspecific resistance of populations is a general pattern, manifested with long-term effects of a wide variety of environmental and anthropogenic factors. This phenomenon must be taken into account when assessing the genetic effects of environmental pollution or professional influence.

When assessing the average and collective doses received by populations exposed to radiation (for example, the population living on radionuclide-contaminated territories), it can be assumed that the influence of all these factors is averaged, so the use of existing methods of biodosimetry in this case may be completely correct. However, when determining individual doses by these methods, significant errors may arise. Because genetic predisposition is crucial and may even be more important than dose [2]. This dictates the need to develop better methods for assessing the genetic effects of ionizing radiation in humans, taking into account its individual characteristics, as well as carrying out complex studies taking into account genetic, physical and radiochemical methods of dosimetry. Therefore, for individual assessment of the dose load on the human body with chronic exposure to low-intensity γ -radiation, the task of establishing quantitative characteristics of the degree of radiosensitivity, adaptation and functioning of the reparative system becomes important. That can significantly reduce uncertainty in determining the effect of radiation doses and will allow taking into account their complex influence on the frequency of induced cytogenetic disorders [3] and the use of new technologies [4].

II. MATERIALS AND METHODS

A. Object of Study

In the work presented, people who professionally contact with sources of ionizing radiation (84 people) were examined. The surveyed completed questionnaires contain information on data, nationality, family composition, place of residence, social status, occupational characteristics, nutrition, bad habits, medical history, date of sampling of biomaterial, signature of informed consent. The average age of the examinees is 38.4 (20-60 years). The control group consisted of 42 people (mean age 39.9 (20-60 years) living in the ecologically clean settlement of Tausugur, Almaty region. The comparison group consisted of Almaty residents, Kazakhstan (megapolis) - 28 people.

We studied the content of radionuclides (^3H , ^{40}K , ^{90}Sr , ^{137}Cs , ^{241}Am , $^{239+240}\text{Pu}$) in biological samples (urine) by radiochemical method, the concentration of the incorporated ^{137}Cs and ^{241}Am radionuclides in the human body using a human radiation spectrometer (HRS), the frequency of

chromosomal aberrations and radiosensitivity by additional *in vitro* irradiation of their blood lymphocytes.

B. Estimation of Doses Using Physical Dosimetry Methods

The determination of radionuclide activity in the human body and assessment of doses by physical dosimetry methods were carried out by the Institute of Radiation Safety and Ecology (IRSE) of the NNC RK (Kurchatov, Kazakhstan), the results of which were provided to us within the framework of joint research (Contract No. 44/2014 of May 21, 2014).

Determination of radionuclide content in urine was performed by radiochemical method. As the studied biosubstrate, the urine of the subjects was used. The ^3H was measured on a TriCarb-2900 beta spectrometer in accordance with the procedure [5]. With the help of gamma spectrometric analysis on three gamma spectrometers of the Canberra firm: broadband detectors BE5030 and BE3830, as well as a coaxial detector GX2020 (measurement time 24 hours), the content of ^{137}Cs and ^{241}Am in urine was determined in accordance with the certified method. The activity of $^{239+240}\text{Pu}$ was determined on Alpha Analyst alpha spectrometer. The ^{90}Sr activity was determined by liquid scintillation spectrometry on a Tri-Carb-2900 beta spectrometer. For an assessment of doses of internal radiation by results of the content of radionuclide in urine methods recommended IAEA and MKRZ and the software of MONDAL3 recommended by IAEA are used [6], [7].

Determination of activity of radionuclides ^{137}Cs and ^{241}Am in the human body was performed using a human radiation counter (HRC). The research material was the whole human body. According to the international classification of human radiation counters, the HRC constructed in IRSE belongs to type C - the geometry of a flat couch, the detector is located above the examinee. As a detecting element of the HRC complex, the BE3830 and BE5030 semiconductor detectors were used from ultra-pure germanium produced by CANBERRA. The estimation of the effective dose of internal irradiation from ^{137}Cs and ^{241}Am is based on calculating the energy release of alpha-beta-gamma radiation in soft tissues, with the subsequent transition to an effective dose [6], [8].

Estimation of external doses of the received irradiation was carried out using individual thermoluminescent dosimeters ДТЛ-02 on the basis of LiF activated by Mg and Ti (Kazakhstan).

C. Cultivation of Human Lymphocytes and Preparation

Peripheral blood was taken from the ulnar vein into the heparinized plastic test tubes. To 0.5 ml of blood, there were added: 4.5 ml of a culture medium consisting of 80% RPMI-1640 medium with glutamine (2 mM) (Thermo Fisher Scientific, USA), 20% fetal bovine serum (Thermo Fisher Scientific, USA), penicillin 100 U/ml, streptomycin 100 U/ml (Santo, Kazakhstan). The lymphocyte division was stimulated by the addition of 2% PHA (Thermo Fisher Scientific, USA). Cells were incubated at 37 °C for 48 hours. To accumulate metaphase plates in the culture medium 2 hours before fixation, colchicine (RANECO, Russian) was introduced at a final concentration of 0.8 $\mu\text{g/ml}$. Then, the cells were

hypotonized with 0.075 M KCl (Sigma-Aldrich, USA) for 15 minutes at 37 °C, fixed with a mixture of methyl alcohol/glacial acetic acid (3/1) (Sigma-Aldrich, USA) and stained with a 4% Giemsa solution (Fluka Analytical, USA) within 5 minutes [9], [10].

Cytogenetic analysis was performed using a Zeiss Axioscop-40 microscope with an increase of 16x100 (oil). VideoTest-Karyo 3.1 software was used to obtain the image (Russian).

In the analysis of metaphase plates, we defined number of cells with aberrations, and also number and type of aberrations on 100 analyzed metaphases. From each individual, from 200 to 400 metaphase cells were analyzed. The obtained data were processed by statistical methods.

D. Radiation Treatment (γ -Radiation)

To study the radiosensitivity of "professionals", whole blood was irradiated with γ -quanta on the "Teragam" remote beam therapy device with cobalt charge (^{60}Co) (Institute of Oncology and Radiology, Almaty, Kazakhstan) with a nominal energy of 1.5 MeV accelerated electrons with a dose rate 0.1 Gy/min.

III. RESULTS

A. Estimation of Doses Using Physical Dosimetry Methods

The results of the current section were carried out by the Institute of Radiation Safety and Ecology (Kurchatov, Kazakhstan), commissioned by the Institute of General Genetics and Cytology (Almaty, Kazakhstan) (Contract No. 44/2014 of May 21, 2014) and paid for in the framework of joint research on "Retrospective Assessment of doses in people exposed to radiation due to their professional activities"

As a result of professional activity on the IRSE territory, personnel is affected by chronic radiation due to inhalation intake of technogenic radionuclide together with inhaled air, and also their peroral receipt owing to inadvertent swallowing the firm particles containing in a production dust.

For carrying out an assessment of concentration incorporated, as a result of professional activity of radionuclide, measurements of group of staff of the institute belonging to category of the personnel of group "A", after carrying out field works by them in the field camp located on a platform "Skilled field" were executed. This platform is characterized by the highest superficial pollution by artificial radionuclide (^3H , ^{137}Cs , ^{90}Sr , $^{239+240}\text{Pu}$ and ^{241}Am) in the territory Semipalatinsk nuclear test site (SNTS). In spite of the fact that employees when working use means of individual protection, they are in group of the increased risk [11].

The platform "A skilled field" represents a large-scale complex of the constructions intended for carrying out tests and registration of parameters of nuclear explosion in the conditions of natural experiment. In venues of land tests, there are funnels with thrown soil and fragments of the melted soil containing products of nuclear explosions. Dose power on the naval of some funnels exceeds 40 $\mu\text{Sv/h}$. In tests of the soils

selected near funnels, technogenic radionuclide ^{137}Cs , ^{241}Am , ^{60}Co , ^{152}Eu , ^{154}Eu , ^{90}Sr , $^{239+240}\text{Pu}$ were found. Specific activity of radionuclide in a soil and vegetable cover in venues of nuclear tests on a platform "A skilled field" reaches the following sizes: ^{60}Co , ^{154}Eu , ^{155}Eu – $\text{nx}10^2$ of Bq/kg, ^{137}Cs – $\text{nx}10^5$ of Bq/kg, ^{241}Am – $\text{nx}10^5$ of Bq/kg, ^{90}Sr – $\text{nx}10^6$ of Bq/kg, $^{239+240}\text{Pu}$ – $\text{nx}10^7$ of Bq/kg [5].

Typical methods of individual monitoring of intake of radionuclide in an organism are: the account of radiation of an organism as a whole, the gamma radiation consisting in detecting which is let out by incorporated radionuclide, by means of HRS and determination of the content of radionuclides ^{40}K , ^3H , ^{137}Cs , ^{241}Am , ^{90}Sr , $^{239+240}\text{Pu}$ in the urine [11].

Researches of the content of radionuclide in an organism of surveyed persons with application of an indirect method - definition of the content of radionuclide ^3H , ^{137}Cs , ^{241}Am , ^{90}Sr and $^{239+240}\text{Pu}$ in urine are conducted. According to the received results, it follows that the contents ^3H , ^{137}Cs , ^{241}Am , $^{239+240}\text{Pu}$ and ^{90}Sr are in tests of urine of the personnel below limits of detection of measuring equipment. The contents ^{40}K in tests of urine of the personnel are in limits of 12 - 152 Bq/l (natural volume activity ^{40}K in urine makes, on the average, 56 – 74 Bq/l) [8]. As all results on specific activities ^3H , ^{137}Cs , ^{241}Am , $^{239+240}\text{Pu}$ and ^{90}Sr in urine, are below detection limits, for an assessment of expected dose loadings, the minimum limits of detection are taken. Calculation of an expected effective dose of internal radiation was made for a peroral and inhalation way of intake of these radionuclides to an organism. The assessment of doses of internal radiation by results of research of radionuclide in urine was made: $^3\text{H} < 3.6 \cdot 10^{-7}$; $^{137}\text{Cs} < 1.3 \cdot 10^{-6}$; $^{241}\text{Am} < 1.7 \cdot 10^{-2}$; $^{239+240}\text{Pu} < 4.2 \cdot 10^{-3}$; $^{90}\text{Sr} < 1.0 \cdot 10^{-6}$ mSv/year [11].

Further determination of activity of radionuclide in a human body is carried out with the use of HRS. The Spectrometry of radiation of the person belongs to direct methods of definition of radionuclide in a body of the person and allows to find existence in an organism as natural radionuclide (^{226}Ra , ^{232}Th , $^{210,212}\text{Pb}$, $^{212,214}\text{Bi}$, ^{40}K , $^{235,238}\text{U}$), and radionuclide of a technogenic origin (^{60}Co , $^{134,137}\text{Cs}$, ^{241}Am). By results scale - spectrometer measurements of activities ^{241}Am and ^{137}Cs , the received values in all cases lie below a detection limit, thus the limit of detection is made for ^{137}Cs - from 0.03 Bq/kg to < 0.14 Bq/kg, for ^{241}Am - from 0.11 Bq/kg to < 0.3 Bq/kg. With use of the top limits of detection on ^{137}Cs and ^{241}Am , the assessment of expected dose loadings of radionuclide of the surveyed personnel which is carrying out professional activity on was carried out SNTS. By results of a conservative assessment, the expected effective dose of internal radiation of the personnel from ^{137}Cs does not exceed $2.7 \cdot 10^{-4}$ mSv/year, from ^{241}Am – 0.2 mSv/year [11].

Determination of the radionuclide content in the urine by the radiochemical method and the SMA method showed that the range of internal radiation doses was from 0.004 to 1.465 mSv at admissible limit of a dose for the personnel - 20 mSv in a year on the average for any consecutive five years, but no more than 50 mSv in a year [8], [11]. Range of doses of the

external radiation, measured by means of thermoluminescent dosimeters, was made from 0.3 to 1.406 mSv.

B. Cytogenetic Analysis of People who Are Professionally in Contact with Ionizing Radiation

The frequency of chromosome aberrations was studied in people professionally exposed to ionizing radiation with registered radiation doses using thermoluminescent dosimeters for the last year at the time of collection of peripheral blood samples.

Cytogenetic examination of people showed that the frequency of chromosomal abnormalities in the staff was $4.27 \pm 0.22\%$, which is significantly higher than in people from ecologically pure, Tausugur ($0.87 \pm 0.1\%$) ($p \leq 0.01$) and residents of Almaty (megapolis) ($1.6 \pm 0.12\%$) ($p \leq 0.01$). Individual fluctuations in the frequency of chromosomal aberrations were 1-9%. The spectrum of recorded aberrations was represented by chromosomal aberrations (double discontinuities and fragments, dicentric rings and translocations) and chromatid types (single discontinuities and fragments). Aberrations of the chromosome type amounted to $2.32 \pm 0.16\%$, $0.27 \pm 0.06\%$ of that were dicentrics and centric rings.

Comparative analysis of the types of aberrations with control data (Tausugur) showed that, if the frequency of chromatid-type aberrations in professionals is 2.87 times higher than the control level, then the frequency of chromosomal aberrations exceeds it by 12 times, which indicates the main influence of radiation factors nature.

Analysis of cytogenetic data of "professionals" in terms of group radiosensitivity of various types (age, gender, ethnicity, epidemiological data) did not reveal any significant differences between the compared indicators.

There are several main methods for retrospective assessment of external exposure doses. According to the frequency of dicentrics and centric rings, the mean group accumulated radiation dose was calculated (using various methods), which amounted to 0.143 Gy [12], 0.123 Gy [13], 0.084 Gy [14].

Individual assessment of doses based on the results of cytogenetic analysis was carried out using various calibration curves [15]-[17] (including intrinsic, obtained with γ -irradiation with a ^{60}Co radiation source at a dose rate of 0.1 Gy/min) and regression equations based on the total frequency of chromosomal aberrations. Based on the individual variation in the frequency of chromosomal aberrations (1-9%), the accumulated dose of irradiation also varies from 0 to 0.3 Gy.

The main problem in interpreting the results of individual dosimetry is a different response of objects to irradiation [18]-[20] which dictates the need for a quantitative determination of this individual reaction and its consideration in calculating the dose of the received irradiation.

The entire contingent of the subjects was divided into groups based on the dose received and the cytogenetic disorders detected in them. As can be seen from the presented data in Table I, in the radiosensitive individuals with the lowest dose received, the highest frequency of chromosomal

abnormalities was detected in a year and, on the contrary, in the stable individuals, the largest dose caused the least amount of chromosomal aberrations. The ratio of the cohort of the subjects according to the radiosensitivity criterion was distributed in our study as follows: radiosensitive (26.2%) - medium radiosensitivity (57.1%) - radio-resistant (16.7%), which corresponds to the literature data [16] and is close to the theoretically expectation. In this case, the dispersion for radio-stable individuals is 2.3, for a group with an average radiosensitivity of 3.3, and for radiosensitive individuals, it is 9. These data indicate the greatest variation in the sign (reaction to the radiation effect) in the group of radiosensitive individuals. The high variability in the frequency of chromosomal aberrations in the surveyed people showed the heterogeneity of the population by the radiosensitivity criterion, dependent not only on the dose received, but also on the level of radiosensitivity.

TABLE I
DISTRIBUTION OF THE SURVEYED PERSONNEL ACCORDING TO THE
RADIOSENSITIVITY CRITERION

Gradation of radiosensitivity	Stable	Medium	Sensitive
Number of people	22	48	14
Total aberrations (%)	5.72	4.0	2.8
Chromosomotype (%)	4.26	2.13	1.39
Dicentrics and rings (%)	0.41	0.25	0.14
The average dose of γ -irradiation, mSv	0.31	0.68	1.62

Radiosensitivity of the examined professionals was also studied by additional irradiation *in vitro* of lymphocytes from their peripheral blood with 0.5 and 2 Gy of gamma radiation at the G_0 stage of the cell cycle. Summary of the statistics is shown in Table II.

Radiosensitivity was assessed by the degree of increase in chromosomal aberrations (CA) after *in vitro* irradiation of «professional» lymphocytes frequency CA (vCA_{prof}), in comparison with the analogous data on induction of radiosensitivity in peripheral blood lymphocytes of healthy donors (vCA_{health}) (18 people) under the same irradiation regimens. The ratio of the frequency of chromosomal abnormalities detected in "professionals" to the average frequency of chromosomal abnormalities in healthy donors when their blood was irradiated with a similar dose of γ -radiation is conventionally designated as "radiosensitivity coefficient" ($RC = vCA_{\text{prof}} / \Sigma vCA_{\text{health}}$). The radiosensitivity of "professionals" when using a dose of 0.5 Gy, based on the number of cells carrying CA on average in the group, was slightly lower than 9.79-1.04%, than in healthy donors 12.0-4.4%, (Table II) ($p \leq 0.05$), which indicates the adaptation of the surveyed contingent to the ionizing effect. In human cells, according to their individual, genetic characteristics, different radiosensitivity is observed, and the RC varies from 0.33 to 2.

Irradiation of blood samples of "professionals" with a dose of 2 Gy of gamma radiation revealed that there is an increase in the frequency of chromosome aberrations, compared to the group of unirradiated healthy donors (Table II). The coefficient of radiosensitivity ranged from 0.43 to 2.55. The

obtained data indicate that, in the surveyed group of "professionals" chronically exposed to small doses of radiation in 95% of cases, adaptation or a standard response to doses of medium magnitude is formed, but exposure to large doses of

radiation in 30% of the subjects causes radiosensitization. The distribution of the "radiosensitivity coefficients" upon irradiation of lymphocytes examined by different doses of gamma radiation is shown in Fig. 1.

TABLE II
UNITS FOR MAGNETIC PROPERTIES

Cipher	Professionals 0.5 Gy (38)	Control 0.5Gy (18)	Professionals 1Gy (38)	Control 1Gy (18)
Cells with aberrations (%)	8.91±0.33	11.0±0.52	27.82±0.44	26.0±0.43
Total aberrations (%)	9.79±0.34*	12.0±0.54	34.25±0.47*	31.0±0.46
Chromosome type (%)				
Total	8.2±0.32	7.0±0.42	32.45±0.45*	28.0±0.44
Dicentrics	0.82±0.10	1.5±0.20	7.54±0.26	7.0±0.25
Rings	2.17±0.17	1.0±0.17	5.81±0.23	5.0±0.34
Translocations	0.44±0.08	0.5±0.12	1.77±0.13	2.0±0.17
Breaks, fragments, exchanges	4.75±0.34	4.0±0.33	16.87±0.37	14.0±0.34
Chromatic type (%)	1.6±0.14	6.0±0.39	1.8±0.13	3.0±0.17

* $p \leq 0.01$

From the presented diagram, it can be seen that, at the doses from *in vitro* irradiation, the curves have approximately the same shape, and in each variant, there are peaks of the most radiosensitive individuals and the dips of the most radioresistant ones. In both groups, individuals with an average radiosensitivity are 55-60%.

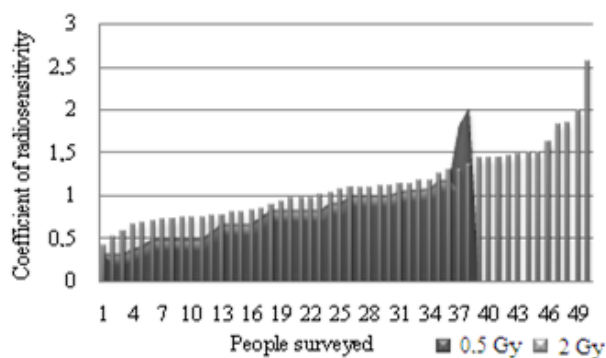


Fig. 1 Distribution of the radiosensitivity coefficients upon irradiation of lymphocytes examined by different doses of γ -radiation

Since, with doses of 0.5 Gy and 2 Gy, blood samples of the same people (32 people) were irradiated, a comparative analysis of the "radiosensitivity coefficients" obtained by irradiating these doses of gamma radiation was carried out. A high reliable positive correlation was found between these parameters ($+0.868$, $n=32$, $p \leq 0.01$), which indicates a practically corresponding reaction of people to irradiation with doses of 0.5 and 2 Gy and the possibility of using either of them to determine the radiosensitivity of specific individuals. For example, two people exhibiting maximum radiosensitivity values when exposed to 0.5 Gy also exhibited maximum values of this index when exposed to 2Gy, and on the contrary, other individuals also showed maximum adaptability to both doses.

Based on the assessment of doses using CA and data on radiation doses received by personnel over the past year, recorded using thermoluminescent dosimeters, a comparative

correlation analysis of the results was carried out. An analysis of the entire subset of the data between the dose values determined by the results of the cytogenetic analysis and the effective dose of external irradiation obtained in the last year showed no correlation between these variables for a sample of 84 people. However, if we split the reaction of people on radiation (as was demonstrated above) by three signs of gradation (radiostable, medium radiosensitive, radiosensitive), then in this case, one can see some relationship. In people with medium radiosensitivity, a significant positive correlation ($+0.66$, $n=48$, $\beta \geq 0.999$) is observed between the dose values determined by the results of cytogenetic analysis and the dose of external irradiation obtained with the help of thermoluminescent dosimeters.

We also tried to relate the coefficients of individual radiosensitivity (RC) obtained by irradiation of human lymphocytes with doses of 0.5 Gy and 2 Gy with spontaneous frequency of CA, excluding individuals with a spread in the RC less than 0.8 and more than 1.25 units. With this assumption, the correlation between RC at a dose of 0.5 Gy and the total frequency of CA is 0.642, $n = 21$, $p \leq 0.01$, and between it and chromosomal type aberrations, 0.595 $n = 21$, $p \leq 0.01$.

An analysis of the entire spectrum of cytogenetic data and data on individual radiosensitivity indicates that, when individual doses are assessed using CA, it is necessary to take into account individual radiosensitivity with the help of certain correction factors. This approach of dividing the surveyed people on the basis of radiosensitivity to a greater extent allows us to hope for a well-founded regression analysis and to reveal a stronger relationship between the frequency of disorders in lymphocytes and the dose of irradiation than without taking into account the gradation characteristic. In this regard, attempts of mathematical modeling for calculating radiation doses taking into account the radiation sensitivity of people are made. This approach allowed us to introduce dummy variables for regression analysis, such as the gradation of the radiosensitivity feature. For example, to determine the

dependence of the type of violations on the received dose of radiation for one year, taking into account the level of sensitivity for personnel in contact with ionizing radiation, the regression model was originally constructed using the formula:

$$Y = A + \alpha \times K_1 D + \beta \times K_2 D + \gamma \times K_3 D, \quad (1)$$

where D is the value of the dose received for the year (mSv), and K_1 , K_2 , K_3 are the coefficients of the radiosensitivity level gradation signs that take the value "1", with the corresponding gradation flag for the variable Y, or "0" in its absence. Due to the fact that the coefficients of gradation signs take the values "1" or "0", their simultaneous triple or pairwise acceptance of the value "1" is excluded due to non-overlapping ranges on the basis of gradation (observations on the number of violations), then the model (1) can be reduced to the form:

$$Y = A + K \times D + \alpha \times D \quad (2)$$

TABLE III
MODEL OF THE DEPENDENCE OF THE TYPE OF VIOLATIONS ON THE IRRADIATION DOSE TAKING INTO ACCOUNT THE SENSITIVITY LEVEL OF PROFESSIONAL WORKERS

Gradation of radiosensitivity	Linear model ($Y = A + K \times D + \alpha \times D$)					
	A±SE	K ± SE	α±SE	Df	R ²	p
Total aberrations (%)						
Stable		-1.8±0.20				
Medium	2.05±0.93	0.00	2.72±0.35	123	0.88	0.00
Sensitive		9.6±0.73				
Aberrations chromosomal type (%)						
Stable		-1.4±0.18				
Medium	1.01±0.91	0.00	1.64±0.38	123	0.88	0.00
Sensitive		8.4±0.72				
Dicentric + rings						
Stable		-0.9±0.15				
Medium	-0.56±0.41	0.00	1.34±0.36	123	0.82	0.00
Sensitive		1.5±0.18				

Linear and quadratic coefficients are approximately the same for all types of aberrations. The coefficient K in all cases, except for chromosome-type aberrations (where K = 0 for the mid-mode-stable group), increases from radio-resistant to radiosensitive.

As a result of the regression analysis, models for the calculation of radiation doses not only in the frequency of the dicentric and rings but also in the frequency of the entire spectrum of aberrations and CA have been obtained, taking into account the mean group radiosensitivity level of people (radiosensitive, average radiosensitivity, radio-resistant). Radiosensitivity can be determined on the basis of spontaneous cytogenetic disorders level and thermoluminescent dosimeters data, or with additional irradiation of their lymphocytes with a certain dose of radiation. Thus, the model obtained by us can be used to calculate doses in the case of uncontrolled irradiation of people with the prolonged nature of the radiation exposure, taking into account the level of radiosensitivity.

III. CONCLUSION

The accumulated radiation doses in people professionally exposed to ionizing radiation by biological and physical dosimetry have been estimated. Based on the results of determination of radionuclide content in the urine by the radiochemical method and the HRS method, it was revealed that the total effective dose of internal exposure of personnel does not exceed 0.2 mSv/year, with an allowable dose limit for personnel of 20 mSv/per year. The range of external radiation doses measured with the help of individual thermoluminescent dosimeters was from 0.3 to 1.406 mSv. Cytogenetic examination of humans revealed a significant increase in the frequency of CA compared with the control. The mean group cumulative dose of radiation calculated from the frequency of dicentric and centric rings was 0.143-0.044 Gy. Individual accumulated radiation doses vary from 0 to 0.3 Gy. Analysis of cytogenetic data in terms of group radiosensitivity of "professionals" of various types (age, gender, ethnicity, epidemiological data) did not reveal significant differences between the compared indicators. The radiosensitivity of the examined contingent was assessed on the basis of the spontaneous level of cytogenetic disorders and data of thermoluminescent dosimeters, or with additional *in vitro* irradiation of their lymphocytes with a certain dose of γ -radiation. It was shown that high variability in the frequency of chromosome aberrations in the examined people testifies the heterogeneity of the population by the radiosensitivity criterion, dependent not only on the dose received, but also on the level of radiosensitivity. In the people with an average radiosensitivity, a significant positive correlation is observed between the dose values determined by the results of the cytogenetic analysis and the dose of external irradiation obtained with the help of thermoluminescent dosimeters. As a result of the regression analysis, mathematical models of the dependence of the type of violations on the radiation dose are proposed taking into account the level of radiosensitivity of professional workers that can be used to calculate doses in the case of uncontrolled exposure of people with prolonged radiation exposure.

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