Biological Dosimetry in Contaminated Areas: Semipalatinsk Nuclear Test Site, Techa River, Three Mile Island

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Cytogenetic examination of the Altai population exposed to ionizing radiations as a result of nuclear explosions on the Semipalatinsk nuclear test site

As a result of nuclear tests in the air on the Semipalatinsk nuclear test site in 1949-1962, a number of regions of the Altai Territory were exposed to the action of high doses of ionizing radiations capable of inducing serious genetic effects. According to the data of the Semipalatinsk nuclear test site [7], radioactive products from more than 50 explosions made in the air and on the earth for a period from 1949 till 1962 spread in the direction of the Altai Territory. A collective effective dose from the first nuclear explosion in 1949 made up 32000 man-Sv. A total dose for the Altai population from all subsequent explosions is estimated at 10000 man-Sv. Thus, the contribution from the explosion in 1949 constitutes about 80% of the total collective effective dose received by the Altai population as a result of nuclear tests on the Semipalatinsk test site [7].

A study of the genetic impacts from nuclear explosions for the Altai population was started after several decades had passed since the radiation exposure. In this section, we present the materials of a cytogenetic examination of people from 7 settlements of the Altai region (226 individuals) that suffered most greatly from the explosion in 1949 [15-17].

In 1992, blood samples were collected in the following settlements: Uglovskoye (average dose - about 0.1 Sv), Ozernoye-Kuznetsovo (about 0.1 Sv), Laptev Log (0.97 Sv) and Topolnoye (2.43 Sv). Later on, in 1993 and in 1994, cytogenetic examinations were continued in the villages Zelyonaya Dubrava (0.18 Sv), Belenkoye (1.87 Sv) and Naumovka (1.86 Sv). The village Tyumentsevo was chosen as a control (0.05 Sv). The social-economic and climatic-geographic conditions were analogous for all examined groups.

The results of these cytogenetic studies are presented in Table 1. In addition to chromatid aberrations (mainly single fragments), the spectrum of aberrations included chromosome aberrations: acentric fragments, centric rings, dicentric and even tricentric chromosomes. Atypical monocentric chromosomes resulting from translocations were also detected. In some exposed individuals cells with multiple chromosome aberrations were found.

In the populations of Zelyonaya Dubrava, Laptev Log, Naumovka, Belenkoye and Topolnoye the frequency of aberrant metaphases significantly exceeds the control level. In the same populations, a statistically significant excess over the control level by the frequency of chromatid aberrations was observed. No differences were found by the frequency of acentric fragments (non-associated with dicentrics and centric rings), except an increased frequency of acentric fragments in the inhabitants of the village Belenkoye ($p<0.05$).

Most informative in respect of biological dosimetry are dicentrics and centric ring chromosomes as recognized markers of radiation effects [1]. For all examined populations, except the village Ozernoye-Kuznetsovo, the average rate of cells with dicentrics and centric rings (C_{dr}) significantly exceeds the control level. The frequency of these chromosomes in the examined groups of people from the villages Uglovskoye, Naumovka, Laptev Log, Topolnoye, Belenkoye and Zelyonaya Dubrava exceeds the control level 12-fold, 9-fold, 6-fold, 6-fold, 4-fold and 3.5-fold, respectively.

The frequency of cells with dicentrics and centric rings in the inhabitants of several settlements of the Altai region depending on the values of effective doses presumably absorbed by them was studied. These doses were estimated on the basis of experimental measurements and with the help of mathematical simulation performed by the Central Physical-Technical Institute of the Ministry of Defence of the Russian Federation [9].

Statistical analysis of the results was performed on the basis of a linear dose-effect relationship. Approximating equation coefficients were determined by the method of maximum likelihood assuming Poisson distribution. The following linear regression equation was derived:

$$y = (0.8 \pm 0.2) \times 10^{-3} + (0.6 \pm 0.2) \times 10^{-3} \times Sv^{-1} D,$$

where y is the frequency of cells containing dicentrics and centric rings (C_{dr}), D - dose. The level of significance of the linear regression coefficient is $p<0.05$. The results of the study clearly demonstrate that despite a long post-exposure time (several decades) an increased number of cells with unstable chromosome aberrations, the level of which depends on the effective dose value, is observed in peripheral blood of the examined people. It can be inferred that the source of such cells carrying dicentrics and centric ring chromosomes are radiation-injured stem cells of the blood-forming tissue.

Among 40777 cells analyzed in the examined groups of the Altai population 10 cells were found to have multiple chromosome aberrations. The distribution of multiaberrant cells among these groups and their characteristics are shown in Table 2. One multiaberrant cell containing five acentric fragments was found in the peripheral blood of the examined persons from Tyumentsevo (control group). Multiaberrant blood cells, including dicentrics, tricentrics and centric rings, were discovered in the examined inhabitants from the settlements exposed to ionizing radiations. The frequency of multiaberrant cells in them is higher than in the control group.

The nature of such multiaberrant cells is not completely understood yet [2, 13]. Probably they are induced by chemical or biological mutagenic factors. One possible explanation of the nature of such cells is the action of densely-ionizing radiations, and first of all, of alpha-particles of various radionuclides, assuming their high concentration in the human body. Since ^{239}Pu, a source of alpha-particles, is a component of the mixture of products of the nuclear explosions that affected the Altai population, it can be inferred that the entry of plutonium into the human organism caused the appearance of multiaberrant cells. This hypothesis is confirmed by the data of A. M. Marenny et al. [10] who detected hot particles (a source of alpha-radiation) in the lungs and in the lymph nodes of ten patients from the radionuclide-contaminated regions of Altai who were operated from lung cancer.

Thus, within 43-45 years after the first nuclear explosion on the Semipalatinsk nuclear test site in 1949, the inhabitants of all examined settlements revealed an increased frequency of unstable chromosome aberrations, mainly dicentrics and centric rings. The frequency of cells with such chromosome aberrations was linearly related to effective doses presumably accumulated by the populations of the examined settlements. At present, it is hard to say anything about the initial level of dicentrics and centric rings immediately after the explosion since the dynamics of these chromosome aberrations for a period of several decades is unknown. This hinders the use of the presented data for the reconstruction of absorbed doses in the Altai population.

The results of a cytogenetic examination of the Altai population with the FISH method are presented in Table 3. The average levels of translocations for the populations of Laptev Log, Belenkoye and Topolnoye are 0.41 per 100 cells, 0.56 per 100 cells and 0.40 per 100 cells, respectively. These values significantly exceed our control level and therefore it is safe to assume the presence of radiation-induced changes in the cell chromosome apparatus in the examined persons. As noted above, about 80% of the external radiation dose falls on the explosion made in 1949; therefore people born before 1949 received the highest doses. In connection with this, the results of examination of this group of the population should be analyzed separately. For example, the group of examined persons from the village Laptev Log included those born before and after 1949. As seen in Table 4, the average level of stable translocations for 8 individuals born before 1949 is 0.58 per 100 cells and for 6 individuals born after 1949 it is 0.14 per 100 cells. In the first group, the frequency of stable translocations is more than 5 times higher than in the control, and in the second group the frequency of stable translocations does not differ from the control level. The data obtained are far from being sufficient to make any final conclusions, however even these results confirm the fact that the most affected part of the population are people born before 1949 and that they must be, in the first turn, in the focus of attention when undertaking medical and preventive measures.

The absorbed dose value estimated by the frequency of stable translocations for three villages, Laptev Log, Belenkoye and Topolnoye, is about 300 mGy. It should be mentioned that this value was obtained using the linear-quadratic dose-effect model for acute exposure [3]. The situation observed in the Altai region due to surface nuclear explosions is much more complicated in terms of dosimetry than that could be assessed with the use of this model. It is important to take into account the long-term chronic irradiation from external and internal radiation sources [9]. A true estimate of effective doses based on the frequency of stable aberrations can be obtained only given clear-cut data on the dynamics of irradiation of the population both during the nuclear test period and after it. A correction factor 3 is usually used for assessing chronic irradiation doses [20]. Hence it follows that in the case of the exposure that took place in the Altai region the linear-quadratic model yields underestimated dose values. In view of the above-stated, the average dose for the examined groups of the population calculated on the basis of cytogenetic analysis makes up about 1 Gy.

It is obvious that the values of absorbed doses for the part of the Altai population exposed to ionizing radiations from nuclear explosions on the Semipalatinsk nuclear test site will be corrected with accumulation of cytogenetic data obtained by the FISH method.

Cytogenetic examination of the population of Muslyumovo located on the banks of the radionuclide-contaminated Techa river

In 1949-1951, the plutonium-producing plant („Mayak“) in the Chelyabinsk region discharged radioactive waste products (a total of 2.76 10^6 Ci) into the open hydrosystem of the rivers Techa, Iset, Tobol [12]. 124000 people, including 28100 of those living on the Techa banks, were exposed to radiation. The doses of exposure were rather high - a collective dose made up about 6000 man-Sv. Nearly 7500 individuals evacuated from 20 settlements received, according to official data, average effective equivalent doses from 3.5 to 170 cSv [12]. The highest radiation doses were recorded for the evacuated population of the village Metlino (170 cSv, 1200 people). Among non-evacuated settlements, the most serious radiation situation remains in Muslyumovo (30 km from the Mayak plant). In 1949, the population of this settlement was 4000 people, and at present it is about 2500 people. The level of exposure here is critical - the average bone marrow dose is 0.25 Gy. In a subgroup of nearly 5% of the population the average bone marrow dose is 1 Gy [5]. The first medical examinations were organized within 2 years after the discharge of radioactive waste products into the Techa river only for the population of one settlement in the upper reaches of the river - Metlino. In other settlements the medical examination was started only after 3-6 years. The register of exposed people living along the river was initiated only in 1968. These facts in combination with a high migration of the exposed population has created a situation in which the assessment of remote radiation effects becomes rather difficult.

At the same time, even the first studies showed that the exposure of people in the upper reaches of the Techa river had led to the development of chronic radiation sickness (particularly in Metlino where this disease was diagnosed in 1956 in 64.7% of the adult population and in 63.15% of examined children) [8]. Chronic radiation sickness was revealed in a total of 935 people. An increase in the incidence of leukoses in the examined population was established. For a period of 33 years, 52 cases of hemoblastoses were recorded, including 37 leukosis patients among 17200 people examined since 1950, which is by 15 cases more than expected without irradiation.

Besides chronic radiation sickness, a decrease in immunologic reactivity, depression of hemopoiesis, an increase in cases of vegetovascular dystonia, hypertensive disease, pathologic pregnancy and labor, and increased infantile mortality were recorded in the inhabitants of the riverside settlements. As shown in the work by M. M. Kossenko and M. O. Degteva [8], the mortality from cancer increased in 1950-1982 as compared to a group of people living in non-contaminated areas with similar social-economic conditions.

Cytogenetic examinations of the population of Muslyumovo were performed in 1993-1994. The examination was carried out on a total of 116 persons. The data of the cytogenetic analysis were compared with the results of the control group (30 individuals, 7831 metaphases analyzed) formed of the inhabitants from a non-contaminated region of the Altai. In view of the tasks of the examination, all people were divided in several groups. The first group included all examined people. The second group united inhabitants of Muslyumovo born before 1949 (beginning of the contamination of the Techa river) and living there permanently. The third group was composed of people born from 1949 till 1956 (this time is characterized by the highest level of contamination of the Techa river). The fourth group consisted of people born after 1957, and the fifth group was formed of migrants, i.e. people who came to Muslyumovo at different times, including those evacuated from villages exposed to radioactive contamination.

Table 5 presents the results of cytogenetic examination by the conventional method (analysis of unstable chromosome aberrations). In all groups, the frequency of chromosome aberrations exceeded the control level. It is worth noticing that the value of this frequency was higher in the second and third groups. In all examined groups exchange aberrations (dicentrics and centric rings) were revealed, and their frequency significantly exceeded (5-10-fold) that in the control group. The highest frequency of dicentrics and centric rings, as well as cells containing such aberrations, was noted in the second and third groups. The frequency of acentric fragments did not differ significantly in the groups of examined people from Muslyumovo and in the control group. In all examined groups an excess over the control level by the frequency of chromatid aberrations was observed.

Cells with multiple chromosome aberrations were found in the examined persons from Muslyumovo (Table 2). On the whole, 6 multiaberrant cells were discovered among 32203 analyzed metaphases, including tricentric and tetracentric cells which are not practically found normally.

It can be assumed that the appearance of cells with multiple aberrations is the result of the action of alpha-radiation from plutonium and its fission products [2, 13, 14]. According to A.V. Trapeznikov et al. [18], the Techa river contains about 8 Gbq $^{239,240}Pu$. This estimate was made within the river section from 50 km to 240 km from the Mayak plant, i.e. up to the place of confluence with the Iset river.

Thus, the cytogenetic study carried out in Muslyumovo revealed an increased level of chromosome aberrations of the exchange type - dicentrics and centric rings - which are characteristic of ionizing radiation exposures. The highest level of such aberrations (9-10 times exceeding the control) was detected in the people born before 1949 or in the period of the most significant contamination of the Techa river with radionuclides. Cells with multiple chromosome aberrations detected in the blood of the examined inhabitants of Muslyumovo seem to be the result of exposure to densely-ionizing alpha-radiation from plutonium and its radioactive products.

Cytogenetic examination of the population from the neighbourhood of the Three Mile Island nuclear power plant in USA

In 1979, an accident occurred at the Three Mile Island (TMI) Nuclear power plant (unit [1]2) located within several miles from the capital of Pennsylvania, Harrisburg (USA). The extent and consequences of this accident have not been uniquely assessed yet. According to the official data stated in the NUREG report in 1980 [6], no impact from this accident on the population, flora and fauna is expected. At the same time, the discovery of radioactive iodine in the air, calculations of experts concerning the extent of possible discharges of radioactive inert gases, and several publications of scientists on radiation effects in trees and animals observed after the accident prompt the public and scientists to perform new studies for assessing the impacts from this nuclear incident [11].

In 1994-1995, cytogenetic examinations of the population living in the neighbourhood of the TMI nuclear power plant were carried out. The aim of this study was to analyze the level of unstable and stable chromosome aberrations in people assumed to be exposed to ionizing radiations due to the TMI accident. The basis for such assumption were the signs of radiation damages in people (skin reddening, peculiar metallic smack in the mouth, irritation of mucous membranes, vestigo, vomiting, diarrhea, etc.) at the time of the accident and also a number of diseases that occurred some time later.

The cytogenetic study was carried out in July-August, 1994, and in January-February, 1995. In selecting a group of patients, their possible diagnostic and therapeutic irradiation as well as a number of additional factors that might influence the results of cytogenetic analysis were taken into account. The results of the study are presented in Table 6. Given a relatively normal general level of chromosome aberrations, a significant increase in the frequency of cells containing chromosome aberrations, namely dicentrics, was recorded. In the group of examined people from the TMI region this rate exceeded 10-fold the control level (0.2 10-3 dicentrics per 1000 cells). Dicentrics were found in 20 persons, i.e. in 70% of cases. The rate of cells containing exchange aberrations (dicentrics) varied from 0.2 to 0.8% and exceeded the control level 10-40-fold, respectively. In one patient, a cell with a tricentric was discovered.

The obtained results suggest that the group of examined individuals from the TMI neighborhood presumably exposed to the action of ionizing radiations as a result of the accident at the nuclear power plant is characterized by an increased frequency of chromosome exchange aberrations - dicentrics.

In 6 persons from the examined group the rate of stable translocations was analyzed with the FISH method. Cells with translocations were found in peripheral blood of all examined people, and the level of these cells exceeded the control; in 3 persons these differences were statistically significant. Table 7 demonstrates the data on the frequency of translocations in the group of examined people from the TMI neighbourhood. It is seen that its value exceeds 5-fold the control level. Here the frequency of translocations per genome (F_G) and the results of traditional cytogenetic analysis (analysis of unstable aberrations) are also presented.

The induced ratio of stable and unstable aberrations at the time of exposure is assumed to be 1:1 [4, 19]. The prevalence of cells with translocations indicates that for a period of 15 years after the accident the level of cells with unstable chromosome aberrations decreased due to their elimination from the blood channel.

The frequency of cells with translocations in the peripheral blood of the examined individuals living in the neighbourhood of TMI is 0.49±0.06 per 100 cells. This value is close to the level of cells with translocations observed in the Altai population (see Table 3). This fact permits the comparison of these groups with respect to absorbed radiation doses. In view of a limited amount of data (the number of examined persons, the number of metaphases analyzed), an average absorbed dose was determined for the whole examined group of people. On the basis of the obtained cytogenetic data and using calibration dose-effect curves [3] a dose estimate of 0.30±0.10 Gy was obtained. This dose is consistent with the situation of acute radiation exposure. In the case of prolonged and chronic exposure, which is more real for the situation observed after the TMI accident, the dose assessment should involve the use of correction factors 2-3. Therefore, the estimated dose for the exposed group of people is 0.6-0.9 Gy.

Thus, the cytogenetic examination of people living in the vicinity of the TMI nuclear power plant and presumably exposed to radiation as a result of the accident that took place in 1979 revealed in them an increased level of stable and unstable chromosome aberrations. This finding undoubtedly indicates that the examined group of people was affected by ionizing radiation. The preliminary data on the frequency of translocations obtained with the FISH method made it possible to estimate an average absorbed dose for the given group of examined persons. This value is 0.6-0.9 taking into account the prolonged or chronic character of the exposure.

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Table 1
Frequency of unstable chromosome aberrations in blood lymphocytes of the Altai population $(M \pm SEM) \times 10^{-3}$

Group	No of persons	No of cells	Cells with aberrations	Total number of aberrations	$dic+R_c$	a c e	C_{dr}	Chromatid aberrations
Tyumentsevo (control)	30	7831	10.2 ± 1.1	10.7 ± 1.2	0.3 ± 0.2	5.7 ± 0.9	0.3 ± 0.2	4.7 ± 0.8
Ugly	15	1958	7.8 ± 2.0	16.8 ± 2.9	3.7 ± 1.4 *	9.2 ± 2.2	1.0 ± 0.7	3.1 ± 1.3
Ozernoye-Kuznetsovo	12	1523	12.0 ± 2.8	12.0 ± 2.8	0.7 ± 0.7	6.0 ± 1.9	0.7 ± 0.7	5.4 ± 1.9
Zelenaya Dubrava	24	2749	31.6 ± 3.4 *	32.0 ± 3.4 *	1.1 ± 0.6 *	8.1 ± 1.7	1.1 ± 0.6 *	22.1 ± 2.8 *
Laptev Log	84	22195	14.4 ± 0.8 *	16.5 ± 0.9 *	3.1 ± 0.4 *	5.3 ± 0.5	1.9 ± 0.3 *	7.6 ± 0.6 *
Naumovka	26	4275	16.8 ± 2.0 *	17.5 ± 1.9 *	2.6 ± 0.7 *	6.2 ± 1.3	2.6 ± 0.7 *	8.8 ± 1.4 *
Belenkoye	35	9069	13.6 ± 1.2 *	16.9 ± 1.4 *	1.3 ± 0.4 *	7.3 ± 0.9	1.2 ± 0.4 *	7.5 ± 0.9 *
Topolnoye	30	6530	20.4 ± 1.8 *	20.5 ± 1.8 *	1.7 ± 0.5 *	6.2 ± 1.0	1.7 ± 0.5 *	12.3 ± 1.4 *

Level of significance * $p<0.05$; SEM standard error of the mean;
dic dicentrics; R_c ring chromosomes; ace acentrics; C_{dr} cells containing $dic+R_c$

Table 3
Frequency of symmetrical translocations (FISH method) in blood lymphocytes in the Altai population

Group	No of persons	No of cells scored	No of translocations	$(F_P \pm SEM)\times10^{-2}$	$(F_G \pm SEM)\times10^{-2}$
Laptev Log	14	7026	29	0.41 ± 0.08 *	1.29 ± 0.11
Belenkoye	6	3213	18	0.56 ± 0.13 *	1.76 ± 0.19
Topolnoye	4	2762	11	0.40 ± 0.12 *	1.26 ± 0.17
Altai region (total)	24	13001	58	0.45 ± 0.06 *	1.42 ± 0.10
Control	12	13586	13	0.10 ± 0.03	0.32 ± 0.05

Level of significance * $p<0.05$; SEM standard error of the mean;
F_P translocations/100 cells; F_G genomic translocation frequency

Table 2
Frequency of multiple aberration per cell in blood lymphocytes of people from different radionuclide-contaminated areas

Group	Patients *	Age (Year of birth)	Sex	Description of multiple aberration
Muslyumovo (116 persons)	1	1949	f	tric-2; dic-3
	2	1975	m	tric-2
	3	1950	f	dic-8; ace-4
	4	1980	m	dic-2
	5	1915	f	tet-1; tric-1; dic-1
	6	1958	f	dic-2
Altai (178 persons)	1	1947	m	dic-2
	2	1945	m	ace-9; SF-1
	3	1930	m	tric-5;dic-5;Rc-1;t-2
	4	1941	m	dic-3; ace-1
	5	1956	m	dic-1; ace-2;
	6	1949	f	dic-2;tric-2; ace-11
	7	1935	m	tric-2;dic-2;t-1;ace-5
	8	1949	f	dic-2; ace-7
	9	1961	m	dic-2
	10	1946	m	dic-1; ace-2
Control (30 persons)	1	1962	f	ace-5

dic dicentric; tric tricentric; tet tetracentric; Rc centric ring;
ace acentric (double fragment); SF single fragment; t translocation;
* people with multiple aberrations

Table 4
Frequency of symmetrical translocations (FISH method) in blood lymphocytes of the Laptev Log (Altai region) population

Group	No. of persons	No. of cells scored	No. of translocations	(Fp±SEM)×10^{-2}	(F_G±SEM)×10^{-2}
I (born before 1949)	8	4271	25	0.58 ± 0.12 *	1.82 ± 0.17
II (born after 1949)	6	2755	4	0.14 ± 0.01	0.44 ± 0.10
Control	12	13586	13	0.10 ± 0.03	0.32 ± 0.05

Level of significance * p<0.05; SEM standard error of the mean

Table 5
Cytogenetic results obtained in a human population continually exposed to low doses of radiation in the South Urals, Chelyabinsk area, Muslyumovo

[(M ± SEM) x 10^{-3}]

Group	No of persons	No of cells	Cells with aberrations	Total number of aberrations	dic + Rc	a c e	Cdr	Chromatid aberrations
1	116	32203	14.4 ± 0.7 *	15.3 ± 0.7 *	2.2±0.3 *	5.4±0.4	1.4±0.2 *	7.6±0.5 *
2	23	6730	19.3 ± 1.7 *	19.4 ± 1.7 *	2.7±0.6 *	6.6±1.0	1.9±0.5 *	9.8±1.2 *
3	46	5730	15.8 ± 1.7 *	17.2 ± 1.7 *	3.2±0.7 *	7.6±1.1	2.1±0.6 *	6.3±1.1 *
4	49	14052	11.9 ± 0.9	12.4 ± 0.9	1.5±0.3 *	3.3±0.5	1.1±0.3 *	7.6±0.7 *
5	21	5691	13.3 ± 1.5	15.4 ± 1.6 *	2.2±0.6 *	6.7±1.1	0.9±0.4	6.4±1.1
Control	30	7831	10.2 ± 1.1	10.7 ± 1.2	0.3±0.2	5.7±0.8	0.3±0.2	4.7±0.8

Groups1: total; 2: born before 1949; 3: born in 1949-1956;
4: born in 1957-1988; 5: migrants
Level of significance * p<0.05;
M man number of aberrations per 1000 cells; SEM standard error of the mean

Table 6
Frequency of unstable chromosome aberrations in blood lymphocytes from persons living in the neighbourhood of TMI
[(M ± SEM) × 10^{-3}]

Groups	Number of persons	Number of cells scored	Total number of aberrations	Cdr	ace	Chromatid aberrations
Population	29	14854	14.0 ± 1.0 *	2.0 ± 0.4 *	4.0 ± 0.5	7.0 ± 1.0
Control	82	26849	10.9 ± 0.6	0.2 ± 0.1	3.9 ± 0.4	6.6 ± 0.5

Level of significance * $p<0.05$;
M number of aberrations per 1000 cells; SEM standard error of the mean;
Cdr cells containing dicentrics and/or centric rings

Table 7
Frequency of symmetrical translocations detected by FISH and results of conventional cytogenetic examination of persons living in the neighborhood of TMI.

Groups	FISH method				Conventional scoring		
	Cells scored	Trans-location	(Fp±SEM) ×10^{-2}	(FG±SEM) ×10^{-2}	Cells scored	Cdr	(Cdr ± SEM) ×10^{-2}
Population	3468	17	0.49± 0.12 *	1.55 ± 0.21	3024	14	0.46 ± 0.12
Control	13586	13	0.10 ± 0.03	0.32 ± 0.05	26849	5	0.02 ± 0.01

Fp translocations/100 cells; FG genomic translocation rate;
Level of significance * $p<0.05$;
SEM standard error of the mean; Cdr cells containing dicentric and/or centric rings