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THE DISTANCE EFFECT ON THE INDIVIDUAL EXPOSURES EVALUATED FROM THE SOVIET NUCLEAR BOMB TEST AT TOTSKOYE TEST SITE IN 1954

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Abstract — The first results of an EPR dose reconstruction with tooth enamel from eyewitnesses of the nuclear test at Totskoye, Southern Urals, Russia, are presented. This test was performed on 14 September 1954, when a nuclear device was detonated at a height of 350 m. The declared power of the explosion was 40 kt. Ten radiation doses have been reconstructed in the framework of the present study. Six of them were found to be higher than 0.4 Gy. The investigations performed have demonstrated a potential ability of EPR retrospective dosimetry to provide additional independent dose estimation for a population exposed as a result of the Totskoye nuclear test. The doses reconstructed for donors who were closer to the site during the nuclear test turned out to be considerably higher (up to factor of 10) than those for the donors who were further from the explosion site. Therefore, a crucially important factor to be borne in mind in collecting samples is the distance between the donor and the explosion site at the time of the explosion.

INTRODUCTION

There were a number of radiation accidents in the former Soviet Union whose consequences have been investigated in detail and are well known to the public. Among these are the Chernobyl catastrophe in 1986 and the immense radioactive contamination of the Techa river during the early operation (1948–1957) of the Mayak nuclear facility (see, for example, Refs 1–4). Western scientists have investigated circumstances and consequences of the A bombardment of Hiroshima and Nagasaki in great detail (see, for example, Refs 4–6). However, publications devoted to environmental and dosimetric studies of the consequences of the military nuclear tests are very rare.

The nuclear explosion at the Totskoye test site, Southern Urals (Figure 1), falls into the category of the 'not so well known' or even forgotten radiation incidents. On 14 September 1954 a nuclear device was detonated at a height of 350 m above the Totskoye test site in the Orenburg oblast of the Southern Urals in Russia (an oblast is an administrative unit of Russia similar to a province or state). The Totskoye test site is 15–20 km northeast from the town of the same name (Figure 1). The declared power of the explosion was 40 kt, and the design of the device was similar to that tested in Semipalatinsk in 1951. Some information about the specific design of this nuclear device can be found in the literature[7,8]. The aim of this test was to determine how well the army could operate during nuclear warfare.

Similarly to the Hiroshima and Nagasaki detonations, significant doses to people resulted from the Totskoye explosion both directly from the blast and indirectly through fallout. The peculiarity of the Totskoye event is that the portions of the population affected in these two ways are clearly distinguishable. A strong westerly wind during the time of the Totskoye blast (20 $m.s^{-1}$) focused the fallout along a narrow path, thus increasing exposure to the villages downwind. The estimated length of this radioactive trace is 210 km[9]. Its presumed axis is direct from the test site to the village of Yashkino (Figure 1) and further to the village of Pushkinskii (the other name of this village is Starobogdanovka). Dose reconstruction studies of the Totskoye population can provide additional data for assessing the health effects of direct exposures similar to those experienced in Japan (which is also of importance for the American and the Soviet nuclear veterans).

Recent epidemiological data have cast serious doubts on the reliability of the government's official radioactive dose estimations. Considerably higher cancer rates have been found in the Totskoye and Sorochinskii raions of Orenburg oblast as compared with average rates for that oblast (a raion is an administrative unit of Russia subordinate to oblast, similar to a county)[10]. Thus, from 1985 to 1993, the observed excess of malignant tumours for the adult population in these two regions was 225% for lungs, 260% for thyroid, and 670% for the lymphatic and blood systems[10].

A method that can be used for reassessing the radiation doses to the permanent residents of the villages is electron paramagnetic resonance (EPR) dosimetry with tooth enamel. Another name for EPR is electron spin resonance, or ESR. This method is based on quantitative EPR measurements of tooth enamel radicals generated

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during exposure of the teeth by ionising radiation. The radiogenic radicals used are very stable (~10^9 y)[11], largely because tooth enamel is a highly mineralised tissue (≈97% of hydroxyapatite[12]). Also, there is no mineral turnover in tooth enamel during human life. EPR dosimetry with tooth enamel has already been successfully applied to dose reconstruction for the atomic bomb survivors of Hiroshima and Nagasaki[5,6], victims of the Chernobyl accident[5,4,13], Russian nuclear workers[2] and residents of Techa River, Southern Urals, Russia[3].

MATERIALS AND METHODS

As a result of the Totskoye nuclear test, 45,000 soldiers and approximately 60,000 civil residents of roughly 20 villages were exposed to direct radiation from the blast, or delayed radiation from fallout[9]. Three small villages were demolished due to either blast effects or contamination from the fallout radiation. The population of these villages was evacuated before the test. According to local inhabitants, many people were on the roofs of their houses during the blast in order to observe the explosion. The official estimate of the doses received by the exposed population (military + civilians) is 0.08 to 0.7 Sv. These estimations were obtained as a result of the study of the residual radiation contamination performed in 1995–1996[14]. To our knowledge, no information was published on the external and internal dose components of this estimation.

As a preliminary study of the feasibility of EPR dose reconstruction in the area of the Totskoye test site (Figure 1) 10 teeth of nine permanent residents were studied. These residents were at various distances to the east from the test site during the detonation. An Eastern direction for the sample collection was selected because of the strong westerly wind that occurred during the nuclear test. All teeth were extracted in the course of routine dental care in 1997. Nine samples were obtained from a Totskoye local dentist. The donors of these teeth spent the main part of their lives in the same village where they were born. One sample (No 3) has been obtained via Dr Snigiryova (Russian Scientific Centre of Roentgenology and Radiology of the Ministry of Health Russian Federation, Moscow) who observed some residents of Orenburg oblast. Since 1984, the donor of sample No 3 has been residing in Moscow. There were no dental X ray investigations of the collected teeth. Table 1 provides information on the investigated samples regarding the age of their donor, his/her location of residence in 1954, and the tooth position. Figure 1 gives

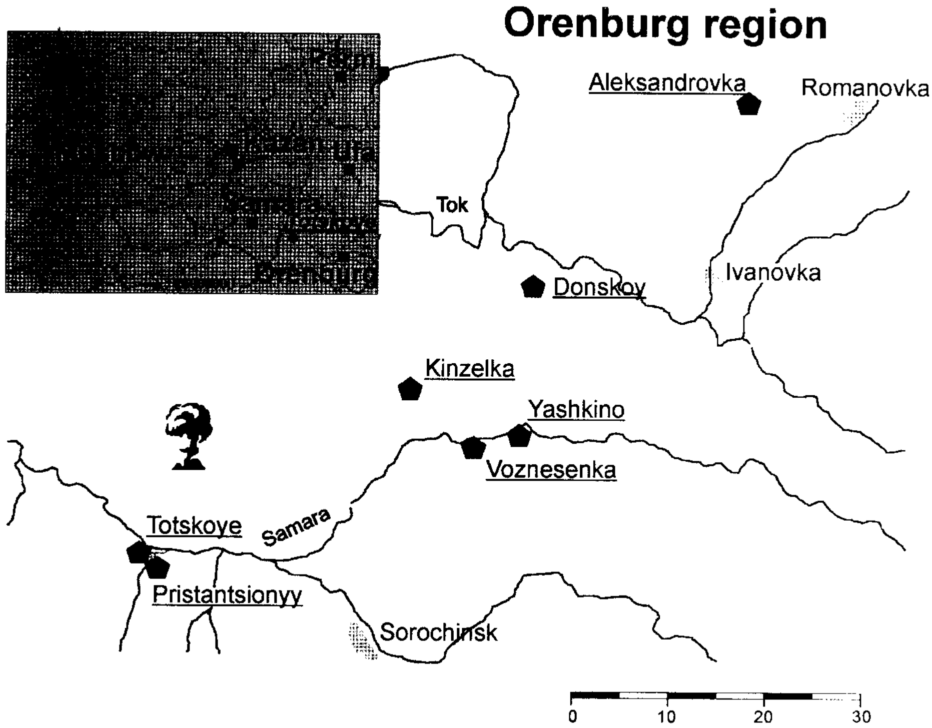

Figure 1. Geographic locations of the Totskoye test site (logo with the mushroom-like cloud) and places of residence of tooth donors (pentagons). In the insert: location of Totskoye test site on the map of the European part of Russia. Maps were created on the basis of Microsoft Encarta.

the geographic location of the villages where the tooth donors lived during the explosion (and still live at present, excluding No 3).

In order to decrease the amount of the organic component and to soften dentin, ultrasonic treatment with a 30% NaOH aqueous solution was applied to tooth enamel samples[2,13,15]. The procedure of sample preparation for EPR measurements was similar to that described elsewhere[2,16] and consisted of the following steps:

(1) Cutting off the root from the crown.
(2) Crushing the crown into 3–4 pieces with an agate mortar and pestle.
(3) First ultrasonic treatment with a 30% NaOH aqueous solution for 60 min to soften dentin.
(4) Washing sample with distilled water 5–10 times by adding water, shaking and decanting.
(5) Removing soft dentin and parts of tooth enamel coloured due to a disease with a dental drill.
(6) Second ultrasonic treatment with a fresh 30% NaOH solution for 120 min.
(7) Final washing of the samples with distilled water 5 times for 30 min each in an ultrasonic bath with fresh water replacement each time.
(8) Overnight drying in a desiccator.
(9) Final sample crushing in a mortar with a pestle followed by sample sieving to grain sizes of 0.3–0.6 mm.

Unfortunately, all collected front teeth (positions 2–3) were seriously damaged by caries (Table 1). Therefore, it was not possible to carry out EPR measurements separately for lingual and buccal parts of the tooth enamel, as was done by Nakamura *et al* in 1998[6]. Such separate measurements would be desirable because of a potential contribution to the EPR signal from sunlight, which can result in some dose overestimation in the buccal part of tooth enamel[17,18].

EPR spectra of tooth enamel samples were recorded at room temperature with the ERS-231 spectrometer (produced in the former GDR) operating in the X band. For mathematical treatment of spectra (accumulation, mass normalisation, baseline correction, spectrum subtractions, etc.) this spectrometer was connected with an IBM/PC. The sample mass for EPR measurements was usually about 100 mg. Some of the teeth were severely damaged by caries; therefore, in some cases there was not enough material for high quality EPR measurements. The amplitude of the EPR dose response is proportional to sample mass. For a small amount of a sample, the signal-to-noise ratio was low, which increased the error of dose estimation considerably. The optimal amount of the sample for dose reconstruction is 100–200 mg. The minimal amount of the sample which was used in the EPR measurements in this study was 30 mg. The parameters of spectrum recording were as follows: 100 kHz modulation frequency, 0.45 mT modulation amplitude, 10 mT field scan. The precision of the individual EPR measurement of the amplitude was ±10%. The EPR spectra were recorded at 13 and 2 mW. For subtracting the broad background signal from the total spectrum, the method of selective saturation[19] was used. This exploits the different microwave power dependences on the EPR intensity of the two main spectral components, i.e. the dosimetric and the background ones. Subtraction of the EPR spectrum of tooth enamel recorded at a relatively low microwave power (2 mW) from the one recorded at the higher microwave power (12 mW) improves the resolution of the EPR spectrum by a factor of 10 with a concomitant reduction in the signal-to-noise (by a factor of 2) and lower limit of EPR dosimetry (to about 100 mGy).

Calibration of the EPR radiation response was done by the additive dose method. The irradiations were made with a medical ^{60}Co source at Ekaterinburg regional cancer clinic with an accuracy of 5% at the

Table 1. Results of dose reconstruction for the Totskoye nuclear eyewitnesses.

Sample number	Tooth position (type)	Year of birth (age)	Place of residence, distance from the site of explosion* (km)	Dose reconstructed (Gy)	Natural radiation background component (Gy)	Dose received from test (Gy)
1	2 (incisor)	1934 (63)	Totskoye, 14	3.1 ± 0.3	0.19	2.91
2	3 (canine)	1934 (63)	Totskoye, 14	2.9 ± 0.3	0.19	2.71
3	6 (molar)	1946 (51)	Pristantsionyy, 20	0.92 ± 0.15	0.15	0.77
4	6 (molar)	1913 (84)	Kinzelka, 26	0.55 ± 0.10	0.25	0.30
5	2 (incisor)	1941 (56)	Kinzelka, 26	0.50 ± 0.10	0.17	0.33
6	7 (molar)	1934 (63)	Voznesenka, 30	0.24 ± 0.08	0.18	0.06
7	7 (molar)	1934 (63)	Donskoi, 49	0.40 ± 0.10	0.16	0.24
8	6 (molar)	1938 (59)	Aleksandrovka, 70	0.12 ± 0.10	0.15	—
9	8 (molar)	1930 (67)	Kinzelka, 26	0.19 ± 0.10	0.10	0.09
10	8 (molar)	1939 (58)	Yashkino, 30	0.07 ± 0.10	0.07	—

*The estimation of distance from the site of explosion was done approximately based on the Prof. Vasilyev's personal expertise because of the absence of the official maps with geographic location of Totskoye test site.

95% confidence level. Dose calibration of this source is checked monthly with a UNIDOS dosemeter (Germany, Siemens), whose uncertainty is 0.5% dose. The main sources of the uncertainty at the determination of exposed dose for the used source are the errors of the determination of dose rate and exposure time. The declared accuracy of our source was determined as standard deviation at linear back extrapolation of the 10 exposed doses. The dose rate was 57.5 $mGy.min^{-1}$. The size of the irradiation field was 20×20 cm^2. Every sample was exposed alone in the middle of the irradiation field. To have a maximum of ionisation starting from the sample surface a plate of 0.5 cm thickness prepared from bone tissue-equivalent was adjusted to the sample surface during its additional calibration exposures. Here, six measurements were taken sequentially after known doses (one original and five after additional irradiations by 0.1–0.5 Gy) were given to the sample. Because the EPR signal intensity linearly increases with dose, the six measurements were then used for dose determination by back extrapolation. Back extrapolation at the dose reconstruction was performed with unweighted linear least squares fit[3].

RESULTS AND DISCUSSION

The results of EPR dose reconstruction from the samples are listed in Table 1 and Figure 2. At least two of the people with the highest reconstructed doses were exposed to the nuclear explosion directly. One of the individuals (samples Nos 1 and 2 in Table 1) was fishing at the bank of the Totskoye village river and was observing the blast directly. In the first moments after the detonation, the donor of sample No 3 was inside a school building of the village Pristantsionnyi. When the walls of the building began to shake, all the children ran out of the school and also directly observed the blast.

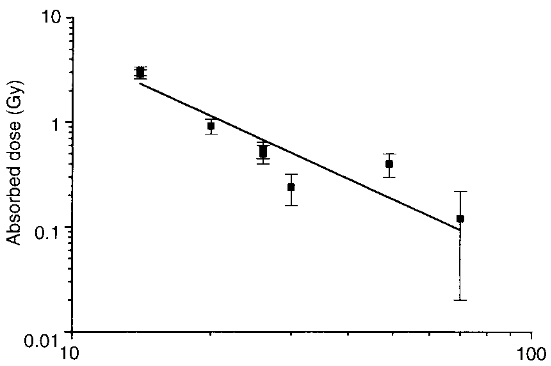

Figure 2. Dose reconstructed with EPR relative to the ground distance between Totskoye test site and place of tooth donor's residence. The distances were determined on the basis of Prof. A.G. Vasilyev's expertise. Squares show the original results of the dose reconstruction. Solid line shows a prediction of the dependence of the dose on distance based on the quadratic distance law.

There were three front teeth among the investigated samples (Table 1). As mentioned above, there is a problem of dose overestimation with them because of sunlight exposure. Therefore, it was important to estimate the possible influence of this factor on the interpretation of the results obtained. According to the data published by Nakamura *et al* in 1998, the differences between doses absorbed in the buccal and lingual parts of the tooth enamel were 0.10–0.34 Gy for position 2 and 0.08–0.42 for position 3. This means that, in the case of the pooled tooth enamel sample (buccal and lingual parts combined), the possible dose overestimation will be in the range 0.05–0.17 and 0.04–0.21 Gy for positions 2 and 3, respectively. Similar numbers have been reported elsewhere[18], when the estimated mean difference between doses absorbed in front teeth and molars was 200 mGy. Thus, the expected dose overestimations for our samples prepared from front teeth (Nos 1, 2 and 5) will be in the range of the given experimental error (Table 1).

The annual natural radiation background dose rate for Southern Urals was estimated by Romanyukha *et al*[3] in 1996 as 2–4 mGy. This value is in agreement with the EPR dose reconstruction results obtained from the two wisdom teeth (samples Nos 9 and 10 in Table 1). The doses obtained for these samples seem to be low in comparison with other samples from the same village, e.g. samples Nos 4 and 5 (0.55 ± 0.10 Gy and 0.50 ± 0.10 Gy respectively). This can be explained by the fact that at the time of the Totskoye test (1954) the teeth Nos 9 and 10 had not yet erupted. Similar observations were made for wisdom teeth of Hiroshima atomic bomb survivors[6]. The typical age for eruption of wisdom teeth in Russia is about 25 y. Hence, the natural radiation background dose rate estimated from these two samples is about 3–5 $mGy.y^{-1}$. Thus, it is reasonable to suppose that the Orenburg oblast upper limit of annual dose rate is approximately 3 mGy. The calculated individual radioactive background doses are given in Table 1. The difference between the reconstructed dose and the radioactive background component can be attributed to exposure from the nuclear test. By subtracting the predicted background dose from that reconstructed, we can estimate the total dose acquired due to the nuclear test. These values are listed in the last column of Table 1 and also in Figure 2.

One can see a strong dependence of the dose on the distance between the donor's location and the explosion site. Figure 2 shows how this dependence correlates with the quadratic distance law (solid line). The normalised ratio of the reconstructed doses is 47 : 13 : 6 : 1. The ratio of the inverse square distances between the tooth donors location and the explosion site are 4.59(14) : 2.25(20) : 1.33(26) : 1(30). The numbers in parenthesis are the respective distances (in kilometres) of the donors from the blast site. Because the ratio of the doses is definitively higher than that of the inverse square distances, this indicates the presence of an additional dose contribution to the tooth donors. This component of the doses can be attributed to the delayed radiation dose due to fallout. The contribution from short-lived radionuclides like ^{131}I, ($T_{1/2}$ = 8.040 d), ^{134}Cs ($T_{1/2}$ = 2.062 y) and ^{99}Mo ($T_{1/2}$ = 67 h) etc. are known to have large dose potentials. There is also some information[9] about considerable contamination by ^{60}Co ($T_{1/2}$ = 5.2719 y) after the Totskoye test. ^{60}Co was used as a material for the shell of the nuclear filler in some types of Soviet nuclear bombs. All the above mentioned radionuclides were virtually absent in the 1995–1996 contamination measurements, whose official results were published[14]. This helps to explain the observed discrepancy in the official dose assessments and the doses reconstructed by EPR. In an attempt to validate the EPR dose estimates, Dr Snigiryova (Russian Scientific Centre of Roentgenology and Radiology of the Ministry of Health Russian Federation, Moscow) reconstructed the dose obtained by the donor of the sample No 3 (Table 1) by FISH (fluorescent *in situ* hybridisation)[20]. A total of 495 cells were scored and 3 translocations were found. FISH dose estimation was done on the basis of a calibration curve created *in vitro* by exposure from a ^{137}Cs source with the 0.5 $Gy.min^{-1}$ dose rate. The calibration curve used and the method of dose calculation were developed by Professor M. Bauchenger's group, Institute of Radiation Biology, GSF-Research Centre for Health and Environment, Munich, Germany[1]. The FISH reconstructed dose was estimated to be 0.5±0.3 Gy at the 95% confidence level. This result is in reasonable agreement with the one obtained by EPR in tooth enamel, 0.92 ± 0.15 Gy. Some repair processes (FISH analysis was done 43 y after the exposure event) could be responsible for the lower value of the FISH dose as compared with that produced by EPR. However, only one FISH dose is certainly not enough to draw any final conclusions about the reasons for the observed discrepancy.

Typically, the doses received by eyewitnesses at nuclear explosions comprise an essential contribution from neutrons. The sensitivity of tooth enamel to neutron exposure was estimated as 0.03 of its sensitivity to γ exposure[21]. Therefore, the neutron contribution to the dose absorbed by tooth enamel should have been negligible as compared with the others.

Finally, our EPR measurements from the Totskoye nuclear test eyewitnesses have shown unexpectedly high doses of radiation (up to 3 Gy). The discrepancy with the official dose evaluation can be explained by the contributions from short-lived radionuclides to the local population. The observed substantial excess of the doses reconstructed by EPR over the official estimations can probably explain the relatively high level of the specific cancer rates in the Totskoye and Sorochinskii raions of Orenburg oblast. Thus, our investigations have demonstrated a potential ability of EPR retrospective dosimetry to provide additional independent dose estimations for the population exposed during the Totskoye nuclear test. It is very probable that this method, when used in combination with the FISH technique, will provide more reliable dosimetric information than is currently available. Of course, 10 samples are not enough to draw final conclusions, but certainly enough to conclude that all the children and adults who were in the school together with the donor of sample No 3 received about 1 Gy. Moreover, our measurements strongly suggest that further dose reconstructions in the area should be performed. The crucial issue to be borne in mind in sample collecting appears to be the distance between the donor and the explosion at the time of the explosion.

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