Paper

A SUMMARY OF EVIDENCE ON RADIATION EXPOSURES RECEIVED NEAR TO THE SEMIPALATINSK NUCLEAR WEAPONS TEST SITE IN KAZAKHSTAN

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Abstract—**The presently available evidence about the magnitude of doses received by members of the public living in villages in the vicinity of Semipalatinsk nuclear test in Kazakhstan, particularly with respect to external radiation, while preliminary, is conflicting. The village of Dolon, in particular, has been identified for many years as the most highly exposed location in the vicinity of the test site. Previous publications cited external doses of more than 2 Gy to residents of Dolon while an expert group assembled by the WHO in 1997 estimated that external doses were likely to have been less than 0.5 Gy. In 2001, a larger expert group workshop was held in Helsinki jointly by the WHO, the National Cancer Institute of the United States, and the Radiation and Nuclear Safety Authority of Finland, with the expressed purpose to acquire data to evaluate the state of knowledge concerning doses received in Kazakhstan. This paper summarizes evidence presented at that workshop. External dose estimates from calculations based on sparse physical measurements and biodosimetric estimates based on chromosome abnormalities and electron paramagnetic resonance from a relatively small sample of teeth do not agree well. The physical dose estimates are generally higher than the biodosimetric estimates (1 Gy or more compared to 0.5 Gy or less). When viewed in its entirety, the present body of evidence does not appear to support external doses greater than 0.5 Gy; however, research is continuing to try and resolve the difference in dose estimates from the different methods. Thyroid doses from internal irradiation, which can only be estimated via calculation, are expected to have been several times greater than the doses from external irradiation, especially where received by small children.**
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INTRODUCTION

The Semipalatinsk Test Site (STS) was formerly a nuclear test site of the Soviet Union (USSR). Created in 1949, the STS is situated in Kazakhstan in eastern Asia and covers about 19,000 km^2. The site of atmospheric testing was about 150 km west of Semipalatinsk City and approximately 200 km (southwest) from the border of the Russian region of Altai. The Soviet Union began atmospheric tests of nuclear devices at the Semipalatinsk Test Site on 29 August 1949. During the period of nuclear weapons testing, 456 tests of nuclear devices were carried out there (Mikhailov 1997). Among those, there were 88 atmospheric tests and 30 surface tests. The last atmospheric test was conducted on 24 December 1962. The total energy yield of atmospheric nuclear explosions at the Semipalatinsk Test Site was about 6.6 megatons (UNSCEAR 2000).

The main contributions to the local and regional environmental radioactive contamination are attributed to the atmospheric nuclear tests that were conducted on August 29, 1949 (22 kt), September 24, 1951 (38 kt), August 12, 1953 (400 kt), March 16, 1956 (14 kt) and August 24, 1956 (27 kt). These tests are estimated to have contributed more than 85% of the collective dose of the population living close to the STS (Gusev et al. 1997).

The implications for public health of these exposures are of concern to the Government of Kazakhstan and the populations living in the Semipalatinsk area. Consequently, in 1997 the Regional office for Europe of the World Health Organization (WHO) held an expert group meeting in Rome to evaluate the then current estimates of dose, which were about 2 Gy (external) up to 4.5 Sv (effective dose) (Rozenson et al. 1995; Rozenson et al. 1996; Gusev et al. 1997) for the most highly exposed population, namely the inhabitants of Dolon, who were in the path of fallout from the 1949 test.

Dolon is a small village located northeast of the STS about 55 km from its boundary and about 120 km from the site where the atmospheric tests were conducted. The predominant ethnic representation is Russian. The population at the time of the 1949 test was about 840, including 35 children of 1–2 y of age, and 180 of 3–12 y of age. The village produced its own milk supply from about 300 cows (Stepanov et al. 2002).

Based on limited data available in 1997 on residual ^{137}Cs in the environment, the WHO expert group concluded, with some abstentions, that the external component of dose to the whole body in Dolon was unlikely to have exceeded 0.5 Gy. After the 1997 meeting, it became apparent that additional investigations were ongoing and new data were becoming available to further evaluate exposures received in Kazakhstan villages. In 2001, the WHO, together with the National Cancer Institute in the U.S. and the Radiation and Nuclear Safety Authority in Finland, held a second expert group workshop in Helsinki to review the latest data. This paper summarizes the presently available evidence regarding external exposure in the village of Dolon, Kazakhstan, drawing on data presented at the 2001 Helsinki workshop as well as recent publications in the open literature.

REVIEW OF DATA

Physical dosimetry

Table 1 summarizes five different estimates of external dose for residents of Dolon. These estimates are classified as "physical dosimetry" indicating that all rely primarily on physical measurements for their basis. To produce the five estimates, however, measurements of only three different quantities were used: (1) the exposure rate following the 1949 test at one location, (2) present-day ^{137}Cs inventory (Bq m^{-2}) in the soil, and (3) present-day thermoluminescence in brick. This section discusses and compares the various reported estimates.

Estimates of external dose from the 1949 test as shown in Table 1 were obtained from four sources (Simon 2000; Stepanov et al. 2002; Gordeev[§]; Gordeev et al. 2002) that were based on the integration of measured exposure rate. All three papers used the same input data, which was a single measurement of exposure rate [2.58×10^{-5} C kg^{-1} of air (0.1 R h^{-1}) at H+173 h] from an unknown location close to Dolon (Stepanov et al. 2002). Though estimating cumulative exposure from exposure rate is a straightforward calculation, there can still be considerable uncertainty in the estimate. The uncertainty in the estimated cumulative exposure from the available data is due primarily to four sources: 1) the precision of the measurement (unknown), (2) the representativeness of the reported value for the entirety of the village (unknown), (3) the exposure-rate at time of fallout deposition which must be extrapolated from the data obtained at time of measurement (in this case, at 173 h following the detonation), and (4) the assumed functional form of the time-dependence of the exposure-rate. The exposure-rate at time of deposition and the functional form of the exposure-rate are both particularly important since the estimation of cumulative exposure is essentially an integration of the exposure-rate function from time of deposition to infinity. Two of the sources of information[§] (Stepanov et al. 2002) used the familiar $t^{-1.2}$ formulation to describe the time dependence of exposure-rate, while one publication (Simon 2000) used a normalized 10-term exponential function for data from the U.S. TRINITY test fit by Henderson (1991). The decay-rate function from the TRINITY test was selected because it has been reported (Mikhailov 1996) that the 1949 test at the STS was a replicate of the TRINITY design. All the estimates assumed that exposed subjects spent 8 h d^{-1} indoors. The two estimates using the $t^{-1.2}$ equation were similar, with a midpoint of 1,200 mGy, while the estimate using the 10-term exponential was somewhat lower, about 720 mGy.

The second source of estimated external dose to Dolon residents was Simon (2000), which used the measurement data of Gastberger et al. (2000) and was the only report that had multiple measurements on which to rely. The data used were from measurements of total ^{137}Cs inventory in 1996 in eighteen soil profiles sampled at nine locations in the village of Dolon,. The average areal deposition (in 1996) of eight undisturbed sites was about 5,300 Bq m^{-2}. Simon (2000) corrected for ^{137}Cs deposited from global fallout (based on UNSCEAR 1993 data) and decay corrected the net activity to 1949, giving an average deposition density then of 7,400 Bq m^{-2}. The correction for global fallout, however, likely assumes too much rainfall for eastern Kazakhstan, and, hence, the net fallout deposition and resulting external dose may be too low. Assumptions also included a fallout transit time of 2.5 h (Stepanov et al. 2002), a building shielding factor (indoor/outdoor) of 0.33, 8 h per day spent indoors, and either of two values of normalized deposition factors (Hicks 1981) that allowed for different assumptions on the ratio of volatile to refractory elements in the fallout. The predicted external dose in Dolon covered a range from 0 to 750 mGy as a consequence of the variation of soil inventory and the choice of normalized deposition factors. The lower end of zero resulted from some of the soil samples not being above the global fallout estimate. The median dose estimates were 110 mGy (using the

[§] Gordeev, K. I. Radiation exposure to the population of the Semipalatinsk region from Semipalatinsk weapons tests. IV. Assessment of realistic doses to whole-body from external gamma irradiation and doses to thyroid from internal radiation for the populations living in the number of settlements of Kazakhstan as a result of radiation exposure from nuclear explosions conducted at the Semipalatinsk polygon. Report to the National Cancer Institute, Bethesda, MD, 2001.

Table 1. Summary of evidence of the magnitude of external whole-body dose received in the village of Dolon (Kazakhstan).

Type of input data	Estimate of dose (mGy)	Sample size	Source of information	Comments on methodology and findings
		PHYSICAL DOSIMETRY		
^{137}Cs (Bq m^{-2}) in soil cores	0 to ≈750, median of 320	18 (at 9 sites)	Simon (2000)	Converted contemporary measurements of areal deposition of soil cesium (Gastberger et al 2000) to exposure rate at time of deposition, range of dose reflects variation of cesium measurements. Assumed 8 h d^{-1} indoors.
Historical exposure rate measurement	720	1	Simon (2000)	Used TRINITY test decay curve to simulate decay rate of 29 August, 1949 test (both were plutonium bombs of same design). Used single available historical measurement of exposure rate. Assumed 8 h d^{-1} indoors.
Historical exposure rate measurement	930–1,500	1	Stepanov et al. (2002)	Used $t^{-1.2}$ decay rate model. Range of dose depends on assumptions for calculating effective dose. Used single available historical measurement of exposure rate. Assumed 8 h d^{-1} indoors.
Historical exposure rate measurement	1,200	1	Gordeev[§]; Gordeev et al. (2002)	Based on calculations from Gordeev[§]; Gordeev et al. (2001) and $t^{-1.2}$ decay rate model. Used single available historical measurement of exposure rate. Assumed 8 h d^{-1} indoors.
Thermoluminescence of brick	≈1,000	1	Takada et al. (2002)	Measurement not yet corroborated.
		BIOLOGICAL DOSIMETRY		
FISH (fluorescence in situ hybridization)	<500	10 "exposed"[b]	Bersimbaev et al. (2002); Salomaa et al. (2002)	Chromosome translocation frequency was equal to matched controls from non-contaminated area in South Kazakhstan. Upper limit of dose determined by statistical variation of translocation frequency among controls. An average of 1,920 metaphases per person were scored.
FISH	Not greater than background	10 "exposed"[b]	Stephan et al. (2001)	Frequencies of chromosome aberrations were equal or less than a control value based on German population. An average of 2,240 metaphases per person were scored.
EPR (electron paramagnetic resonance) of teeth	143 (average); ≈80 adjusted for background[a]	9 "exposed"[b]	NIST (2002)[‡‡]	Average age of subjects was 63 y
EPR of teeth	176 (average); < 136 adjusted for background[a]	3 "exposed"[b]	Ivannikov et al. (2002)	Ages of subjects were > 40 y

[a] 1 mSv y^{-1} assumed for background dose rate.
[b] "Exposed" means that the subjects were present in Dolon in August, 1949.

nominal value of the normalized deposition factor used in U.S. studies) or 320 mGy (using a greatly reduced value of the normalized deposition factor to account for the close distance of Dolon). Lower values of the normalized deposition factor would be reasonable at close distance to account for the larger proportion of refractory radionuclides than is typical at locations that are more distant.** Maximum dose estimates based on soil cesium were about three times the median values and reflected the spatial variation of the measured cesium inventory within or around Dolon.

Finally, Takada et al. (2002) reported on a measurement of thermoluminescence (TL) in brick obtained from a building in Dolon built prior to the nuclear testing program. The TL technique based on quartz inclusions has previously been used both for archaeological dating purposes (Aitken 1985) and for assessment of environmental exposures (Haskell and Bailiff 1990; Stoneham et al. 1993). Preparations prior to measurement included removing a 10-mm layer and then extracting a 20-mm layer for measurement. The measurements were corrected for natural background radiation exposure. The authors estimated that the brick had received 1 Gy from the entire nuclear testing program. The limitation of that assessment is the small sample size (n = 1) and lack of corroborating measurements. Additional brick samples are presently under analysis.

Biological dosimetry

Table 1 also presents findings from two cytogenetic studies using the FISH (fluorescence in situ hybridization) technique on peripheral blood lymphocytes from people who lived in Dolon at the time of the first explosion in August 1949. One study (Bersimbaev et al. 2002; Salomaa et al. 2002) was of 31 persons from 7 villages in the fallout area of the first test. The frequency of translocations was similar to the control cohort from an uncontaminated area in South Kazakhstan. The ten subjects from the village of Dolon also showed a translocation frequency equal to controls. The minimum detection level of the FISH technique is highly age-dependent, and due to the statistical variation in translocation frequencies by age, a positive dose effect can be considered if, roughly, a doubling of the control level is observed. A doubling of the translocation frequency of the controls of similar age as the Dolon subjects would correspond to a minimum average dose of 0.5 Gy. The conclusion based on the 31 persons studied was that the cumulative average dose was less than 0.5 Gy.

In another study, Stephan et al. (2001) reported on translocation frequencies in ten Dolon inhabitants. Their data did not deviate from values based on German controls of the same age and, based on those findings as well as the considerations discussed above, it was concluded that previously reported estimates of effective doses of about 3 Sv were too high. However, a significantly higher level of complex aberrations was observed in the ten persons from Dolon compared with controls. This was conjectured by Stephan et al. (2001) to be related to the incorporation of radionuclides, mainly $^{239+240}$Pu, in the liver where peripheral lymphocytes pass and can be exposed.

Table 1 also reports measurements of the electron paramagnetic resonance (EPR) signal in teeth from Dolon residents as determined in two different studies (Ivannikov et al. 2002, NIST††). In this context, the EPR signal is considered a type of biologically-based dosimetry measurement. The EPR technique quantifies the concentration of free radicals that are produced by ionizing radiation in tooth enamel and that are captured by defects in the crystal lattice of the enamel in numbers proportional to the absorbed dose. Such measurements are useful to compare with physical dosimetry measurements or with calculations from analytic dose reconstruction, which relies primarily on environmental transfer models. The two studies reported similar average absorbed doses for Dolon residents, unadjusted for background: 176 mGy (n =3, Ivannikov et al. 2002) and 143 mGy (n=9).†† The contribution of natural background radiation to the EPR dose can be accounted for by knowing each individual's age and by assuming an average of background dose of 1 mSv per year. The average measured doses above natural background from the two EPR studies were 136 mGy or less for the data from Ivannikov et al. (2002), and about 80 mGy for the data from NIST.††

DISCUSSION

Evaluation of the results of physical and biological dosimetry for whole body dose

As can be seen from Table 1, the physical dose estimates, with the exception of doses estimated from the soil cesium data, are greater than 0.5 Gy, whereas the doses based on biodosimetry are well below that value (~0.2 to 0.4 Gy).

The physical dosimetry estimates based on a single historical exposure rate measurement and a TL measurement in brick were similar, about 1 to 1.2 Gy. The weakness of both of those estimates stems from the small amount of input data (1 exposure-rate measurement for the dose calculations) and small sample size for the TL

** Personal communication, H. L. Beck to Steven Simon, National Cancer Institute, Bethesda, MD; August 2002.

†† Report from the National Institutes of Standards and Technology (NIST) to the National Cancer Institute, 2002.

measurements (1 brick). The paucity of data makes it extremely difficult to assess how representative the estimated doses are for the population of the village. Moreover, the extremely sparse data prevent determining what the average dose received might have been or the range of likely doses. In contrast, the estimates of cumulative exposure (Simon 2000) from soil cesium contents (Gastberger et al. 2000) are based on measurement data collected at nine sites within the village of Dolon and, hence, are likely to be more representative of the range of doses received. The variation of the inventory of soil cesium at the nine sampled locations indicates that some parts of the village of Dolon may not have received fallout or may have not have been exposed uniformly. That conclusion is in agreement with various reports in the literature (Shoikhet et al. 1998; Izrael et al. 2000) that indicate the width of the fallout cloud passing over Dolon was very narrow. Moreover, the weather at the time was characterized by strong winds and patchy rain.[‡‡] Under such conditions, a narrow fallout track, within which the deposition was non-uniform due to rain out and turbulence, is exactly what would be expected.

True doses depend on behavior of the individuals in the exposed population while estimates of dose rely on assumptions about average behavior of the population, particularly with respect to the amount of time spent outdoors. The amount of time spent outdoors would be a particularly important factor in the initial days following the test and deposition of fallout. About 50% of the infinite-time exposure is received in the first 2 d following the deposition for locations as close as Dolon and about 90% is received in the first 2 mo. Time spent away from the contaminated area would result in a dose reduction over that based on the assumption that 100% of time was spent in the contaminated zone. Moreover, the onset of winter and the likelihood of ground cover by snow may also have reduced exposure in the first few months. That could have affected the exposure received, for example, from the 38 kt test conducted in late September of 1951. It would not be unreasonable to assume, considering these behavioral and environmental factors, that true doses for some individuals could be as small as one-tenth the average dose.

The advantage of biological dosimetry is that the dosimeter is always with the exposed person; thus, assumptions of behavioral factors are not necessary. The biological dosimetry estimates will also include, to some extent, the internal dose from long-lived isotopes such as ^{90}Sr and ^{137}Cs. However, there are two key questions with respect to the FISH analyses. One is related to the selection of individuals for FISH analysis. How representative of the entire village population were they? That, of course, is difficult to determine but it can be stated that there was no obvious selection bias in either of the studies. The second is whether, some 40 y after the exposure commenced the signal, the number of stable translocations is maintained. Retrospective biodosimetry with the help of FISH is based on the assumption that stable translocations persist in the long-term in contrast to, for example, dicentrics. In several studies using this approach, the FISH translocations seem to be persistent from 11 y up to almost 50 y after exposure (Lloyd et al. 1998; Stephan and Pressl 1997; Lucas et al. 1992, 1996). In others, however, translocation frequencies were much lower than the initial dicentric frequencies (Natarajan et al. 1998), or the doses calculated using translocation frequencies were, in general, lower than the estimations of accumulated external doses derived from film dosimeters (Bauchinger et al. 2001). The most appropriate approach to investigate translocation persistence is to follow their frequency in victims of radiation accidents. This has been possible to perform in a few cases during a relatively short period of a few years, and the results have shown a relatively stable frequency of translocations (Lindholm et al. 1998; Sevan'kaev et al. 1999).

The experimental data available so far imply that several factors may affect the persistence of translocations, such as homogeneity of exposure, dose, dose-rate, as well as individual differences in the turnover of lymphocyte subpopulations. On the basis of the results obtained from the FISH assay of present-day Dolon residents who resided in the village at the time of the first nuclear testing, we believe that the weight of evidence precludes values as high as the physical dosimetry methods suggest, at least for the external component alone. By comparing translocation frequencies between those "exposed" with a set of controls, a maximum dose of 0.5 Gy is deduced from the statistical variation among samples (Salomaa et al. 2002).

There is much less uncertainty about the persistence of the dose signal in the case of the tooth enamel measurements. Those data indicate a mean dose of 0.080 to 0.14 Gy after accounting for background radiation exposure, which, to some extent, will include the internal component of exposure.

The median estimate of 0.32 Gy, as derived from the soil cesium (Simon 2000), is in better agreement with estimates from biological dosimetry than with other physical dose estimates. It can, therefore, be stated that presently there is little evidence to indicate that whole body doses received by the population of Dolon were more than 0.5 Gy, and such doses probably were closer to the range 0.1 to 0.3 Gy on average. This is, not

[‡‡] Personal communication, V. Stepanenko to K. F. Baverstock, World Health Organization, Helsinki, Finland; October 2001.

withstanding, the theoretical possibility for doses five or more times higher for an individual who remained at a single location in the village where external exposure rate was maximal. In practice, however, movement around and outside the village in areas of lower contamination would probably have led to lower doses.

Doses to the thyroid

Nuclear weapons give rise to substantial quantities of the isotopes of iodine, particularly the short-lived ^{132}I, ^{133}I, and ^{134}I as well as ^{131}I and ^{132}Te, which decays to ^{132}I. The initial exposures in Dolon commenced only a few hours after detonation so thyroid doses from inhalation might be expected to be significant. However, presently accepted Russian dosimetry models predict that the inhalation doses at Dolon would be less than 10% of the total dose (Gordeev[§]; Gordeev et al. 2002) because only relatively large particles would be deposited at close-in sites like Dolon. Such particles do not transfer effectively to the deep lung such that the radioactivity could be transferred to the blood stream. However, milk from cows that were grazed on contaminated land would generally have been consumed fresh with little time delay, and this foodchain route probably resulted in significant ingestion doses to local residents. Reconstruction of thyroid doses so long after the exposure is both difficult and uncertain; however, preliminary estimates have been made for a cohort presently under study (Carr et al. 2002) by the U.S. National Cancer Institute. The calculations of thyroid absorbed doses at Dolon using the data and methods of Gordeev et al. (2001) and Gordeev[§] are approximately 1.2 Gy external plus 2.3 Gy internal for an infant at the time of the 1949 test (Simon et al. 2002). The estimated doses are considered preliminary and are undergoing critical review, particularly in light of the biodosimetry findings discussed here; however, only the external dose would contribute to the biological dosimetry endpoints that were studied.

Public health significance

On the reasonable assumption that radiation doses received in Dolon from the nuclear testing conducted at Semipalatinsk will add to the cancer risk of that population, the issue for public health maintenance is by how much will those dose rates add to the natural background radiation dose rates? Assuming that the annual dose from external irradiation due to natural background is about 1 mGy (UNSCEAR 2000), over a lifetime the average natural background radiation dose is about 0.07 Gy. Current dose estimates suggest that fallout added between 0.1 and 0.5 Gy, with a likely value of about 0.2–0.3 Gy. This increment would produce a total lifetime dose still within the range of geographical variation in natural background radiation levels globally. On this basis, it does not appear that the external radiation exposure from the Semipalatinsk test site was a significant contributor to public health detriment, especially in the context of other environmental and public health priorities in Kazakhstan.

Dosimetry estimation carried out by knowledgeable individuals of the Soviet testing program era identified Dolon as the most highly exposed village in the vicinity of the STS.[§] Because of the small population there, the collective external dose in the village of Dolon has been estimated to be only about 770 person-Gy (Stepanov et al. 2002; Simon and Bouville 2002) and somewhat lower (200 to 300 person-Gy) according to the conclusions of this paper. The collective dose from external radiation in the other nearby areas, e.g., the combined raions (administrative districts) of Abay (south of the test site) and Beskaragay (northwest of the test site), were reported by Tsyb et al. (1990) to be about 2,600 person-Sv. Only in the much larger city of Ust-Kamenogorsk (population then of about 130,000) has the collective dose reported to be relatively large, about 41,200 person-Gy (Shoiket et al. 1998, 1999), though that value has not been validated.

A recent paper (Dubrova et al. 2002) reports an approximate doubling in germ line mutation rate in a three-generation study of residents in the Semipalatinsk region. The frequency of mutations was assessed in the highly mutable minisatellite DNA. Significantly elevated germline mutation rates were observed in all P_0 parents (born between 1926 and 1948) and F_1 parents born between 1950 and 1956, i.e., in the most exposed cohort of parents. These results confirm earlier studies in the children of parents irradiated after the Chernobyl accident (Dubrova et al. 1996). However, the health significance of minisatellite mutations is not known, and they may be acting more as an indicator of exposure rather than as a cause of health detriment.

A further concern to some is the presence of plutonium in soil above that from global fallout, as has been verified in soil samples taken from Dolon and other places in the Semipalatinsk region (Yamamoto et al. 2002). Uptake of plutonium into the food chain is not a significant hazard, but if agricultural practices change and plowing of contaminated land becomes an established practice, inhalation of plutonium in the resultant dust may become a public concern and potentially a true health hazard. In such circumstances monitoring might be appropriate.

CONCLUSION

The present evidence, while somewhat conflicting, indicates that whole body doses from fallout originating at the STS to the inhabitants of Dolon are unlikely to have exceeded 0.5 Gy on average. Hence, conclusions from evidence presented at the 2001 Helsinki workshop are consistent with the conclusions of the 1997 WHO expert group meeting. However, ongoing research will attempt to resolve differences between physical and biologically-based dose estimates and increase our understanding of doses received near the STS. If the present external dose estimates for Dolon of less than 0.5 Gy are realistic, there likely has not been a measurable increase in radiogenic disease there, except possibly for thyroid abnormalities. Whole-body exposures in other villages and locations in the Semipalatinsk region have been estimated to be less than at Dolon; hence, they are also unlikely to be of significance in collective terms and not at all on an individual basis. As stated, doses to the thyroid gland of residents of Dolon at the time of testing probably were significant and, although they are difficult to reconstruct, attempts are currently underway. Experience from the Nevada Test Site in the U.S. would suggest that thyroid doses and risk of nodules and possibly thyroid cancer throughout the Semipalatinsk region and beyond may have been elevated as a result of the nuclear testing, especially in infants and children alive at the time of the testing.

Finally, it is worth taking note of the difficulties we have observed in resolving differences between physical dose estimates and/or analytic dose reconstruction compared with doses estimated from biodosimetric measurements. The resolution of such comparisons is of fundamental importance to the radiation protection and risk assessment community, and in the case of Semipalatinsk resolution will undoubtedly assist in better understanding the true radiation-related health risk there.

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Authors note: Literature references in STUK report A187 are available online at http://www.stuk.fi/julkaisut/stuk-a/stuk-a187.pdf.

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