TECHA RIVER DOSIMETRY SYSTEM: CURRENT STATUS AND THE FUTURE*

M.O. Degteva, E.I. Tolstykh, M.I. Vorobiova, N.B. Shagina, E.A. Shishkina, N.G. Bougrov
Russia, Chelyabinsk, Urals Research Center for Radiation Medicine

L.R. Anspaugh
USA, Salt Lake City, University of Utah

B.A. Napier
USA, Richland, WA, Battelle Pacific Northwest National Laboratory

Abstract

The Techa River Dosimetry System (TRDS) has been developed to provide estimates of external and internal doses for residents living on the Techa River, which was contaminated as a result of radioactive releases in 1949–1956. This system represents a modular database processor that uses, depending on the input data for an individual, various elements of several databases (or modules). Large amount of environmental and human data are integrated to provide the dosimetric variables requested by the user. These modules were created in 2000 (the so-called TRDS-2000). During the period 2000–2005 the TRDS has been improved on the basis of implementation of the following tasks: (a) the intakes of ^{90}Sr have been verified; (b) a new age- and gender-dependent biokinetic model for Sr has been developed; (c) new dose-calculation protocols have been elaborated that allow for reduction in uncertainties of estimates of internal dose; and (d) estimates of external doses for the most contaminated settlement Metlino have been validated by luminescence measurements of quartz extracted from bricks in old buildings, EPR measurements on human teeth, and FISH measurements of human lymphocytes. Some other tasks for the new version of TRDS are close to completion; these include improvement of the dosimetric model of bone and evaluation of additional sources of environmental and medical exposure that could confound analysis of the epidemiologic data. Special attention in our current activities is being paid to a better assessment of the contribution of short-lived radionuclides to the total dose. The results of these studies will be implemented in a new version of the TRDS. These efforts will result in significant improvements in estimates of external and internal dose for the exposed population and will improve the credibility of the doses and the risk assessments they support.

INTRODUCTION

Radioactive contamination of the Techa River occurred in 1949–1956 as a result of liquid radioactive wastes discharges by the Mayak plutonium facility. Residents of many villages downstream from the site of release were exposed via a variety of pathways; the more significant included drinking of water from the river and external gamma exposure due to proximity to bottom sediments and the shoreline. In 1968 the Techa River Registry was created at the Urals Research Center for Radiation Medicine (URCRM, at that time Branch №4 of the Institute of

* This document is a translation of an article published in Radiat Safety Problems (Mayak Production Association Scientific Journal) №1:66–80; 2006.

Biophysics), which includes the "Extended Techa River Cohort" (ETRC) consisting of 30,000 persons. The ETRC has been studied for several decades by scientists from the URCRM, and excess cases of both leukemia and solid cancers have been noted [1, 2]. The first results of joint Russian-American investigations of the assessment of radiation risks from long-term chronic exposure, resulting from long-term follow up of the ETRC and which were later published in reference [2], evoked widespread scientific response in Russia and abroad [3, 4]. The final, published results showed that estimates of the excess relative risks per unit dose for leukemia and solid cancer mortality did not statistically differ between the ETRC study and the Life Span Study of the survivors of the atomic bombings at Hiroshima and Nagasaki [2]. Because the question of effectiveness of chronic exposure at low-to-moderate dose rate relative to acute exposure at high dose rate is of critical importance to radiation protection, the results obtained by the ETRC study have attracted much scientific attention to the Techa River Dosimetry System, TRDS-2000, which is used for the epidemiological studies of the ETRC.

The description of the TRDS basic principles and databases used for dose reconstruction was published in 2000–2001 [5-8]. These results were discussed in detail at a special meeting (Moscow, December 8-10, 2003). An international group of experts participating in the meeting positively evaluated the methodology used in the TRDS-2000 and outlined the difficulties related to uncertainties in the data on source-term and gave specific recommendations on further dose-reconstruction investigations on the Techa River [9].

This paper presents the first results of studies aimed at improvement in the TRDS-2000 with the goal of providing reliable estimates of individual doses for residents of the Techa River settlements. These improvements have been implemented in the following directions:

1. Improvement in the quality and further completion of initial data used in dose-reconstruction efforts for the Techa River population;
2. Improvement of the basic models used for assessments of external and internal doses;
3. Validation of external doses with the use of methods for retrospective dosimetry: luminescence dosimetry of quartz extracted from bricks in old buildings located on river banks, electron paramagnetic resonance (EPR) on tooth enamel, and fluorescent in situ hybridization (FISH) on circulating lymphocytes;
4. Reduction of uncertainties in dose estimates with use of available data on measurements of radionuclide-body burdens and data on specific locations of households on the territory of a specific village relative to the contaminated river and floodplain;
5. More precise estimation of the contribution of short-lived radionuclides to total dose based on in-depth analysis of archival data on the radionuclide composition and physical-chemical properties of the liquid radioactive wastes discharged into the Techa River in 1949–1956;
6. Assessment of additional exposure of the Techa River population due to the East-Urals Radioactive Trace (EURT) formation in 1957, wind transfer of radioactive particles from the Karachay Lake in 1967, and x-ray diagnostic procedures at the URCRM clinics; and
7. Uncertainty analysis in the calculated doses and their influence on the radiation-risk coefficients for the ETRC.

The Techa River Dosimetry System (TRDS) represents a modular database processor that uses, depending on the input data for an individual, various elements of several databases (or modules) thus allowing the calculation of an individual dose [5-8]. The databases currently used for dose calculation were created in 2000; thus, this version of the dosimetry system is called TRDS-2000. The elements of the databases have been obtained on the basis of extensive analysis of primary data on environmental contamination and internal contamination of humans. If measurements were missing (this is especially characteristic for the period of 1949–1951), model calculations were used. Therefore, the reliability of dose estimates mainly depends on the completeness and quality of the input data and reliability of models that describe radionuclide behavior in the environment and humans.

IMPROVEMENTS IN QUALITY OF INPUT DATA

In 2000–2005 intensive work continued on supplementing and checking computer registries of input data that included the results of measurements of radionuclide-body burdens obtained over many years for many residents of the Techa River villages, information extracted from official documents on residential histories, etc.

The reconstruction of internal dose relies strongly on the results of measurements of ^{90}Sr in residents of the Urals region; these results have been compiled in a special registry, which includes the results of nearly 10,000 *post mortem* measurements of radionuclide concentration in bone samples obtained in 1951–1993, the results of *in vivo* measurements of surface-beta activity of teeth for 17,500 persons (1959–1997), and measurements of ^{90}Sr-body burden by means of the SICH-9.1whole body counter (WBC) for 20,500 persons (1974–1997).

In 2001–2004, a so-called Household Registry was established based on information from tax-record books available for the Techa River villages. The Registry includes lists of residents by household, dates of residency in households and family relationships of persons within households. Currently, information is available for 14,300 households for the period of 1949–1960. This information is being used for reconstruction of internal dose for unmeasured ETRC members by using the results of measurements of their relatives who lived in the same household, with the assumption that they have had similar exposure to the same sources of drinking water and food.

For validation of external dose with the use of EPR-dosimetry, tooth samples extracted for dental health reasons from residents of the Urals Region have been collected since 1992. At present 4,200 tooth samples from 2,600 donors have been compiled in a special tooth-tissues bank. Some of the donors were exposed due to residence in villages located on the Techa River banks and/or EURT territory while others lived on uncontaminated territories of the Urals Region and were exposed due to background radiation. Of these samples 820 teeth have been measured by EPR. Tooth samples kept in the tooth-tissues bank can be used for future investigations. The information on EPR measurements and individual data for all donors are kept in a special database “Teeth.”

For reconstruction of medical exposure a special registry of x-ray diagnostic procedures was established in 2002–2005, which includes information on 42,000 procedures for 9,200 exposed inhabitants of the Urals region who had special medical examinations in 1954–2004.

Supplementation of the database "Environment" has also continued. The database includes the results of measurements of radionuclide concentrations in river water (10,500 samples), bottom sediments (2,000 samples), soils (4,200 samples), milk (12,500 samples), other foodstuff (7,900 samples), and measurements of gamma-exposure rates near the shoreline and in living areas (7,000 measurements). Measurements commenced in 1951 and have continued to the present time.

The data described above form an objective basis for reconstruction of individual doses for residents of the Techa River settlements.

IMPROVEMENT OF THE BASIC MODELS

The main dose-forming radionuclide on the Techa River was ^{90}Sr. The following parameters are included in TRDS databases for the calculation of ^{90}Sr intake: 1) $I_R^{Sr90}(t)$ – annual average ^{90}Sr intake for adult residents of the referent settlements; 2) $\alpha_{Age,R}^{Sr90}(t)$ – annual ^{90}Sr intake for other age groups relative to that for adults living in the reference settlements; and 3) f_L^{Sr90} – annual ^{90}Sr intake for other settlements (L) relative to ^{90}Sr intake for residents of the reference settlement. For assessment of these parameters a special *^{90}Sr intake function* was used in TRDS-2000, which was further verified in 2001–2002 [10-11].

The dynamics of ^{90}Sr intake in the referent settlements (Muslyumovo and Metlino) during the first period after discharges into the Techa River commenced was reconstructed using numerous data on in vivo ^{90}Sr measurements in anterior tooth enamel and supplementary data on water consumption and diet composition for adults and children and measurements of ^{90}Sr-body burden in adults. A new method of solving an inverse problem was developed (solution of an integral equation associating ^{90}Sr-intake dynamics with the age-dependency of ^{90}Sr content in teeth), which allowed the assessment of the relative intake function for adult residents of the referent settlements during the period of maximal intake [12]. Parameters of the integral equation, describing ratios of annual ^{90}Sr intake for different age groups to that for adults living in the reference settlements, $\alpha_{Age,R}^{Sr90}(t)$, were evaluated on the basis of data on the daily composition of diet [10-11]. The new method allowed the solution of the integral equation in a general form and proof of its uniqueness and stability. Implementation of this algorithm improved the reliability of relative intake functions. The reconstruction of the intake function for Muslyumovo in subsequent periods, when its inhabitants stopped using river water for drinking, is based on data of ^{90}Sr specific activity measurements in milk. The functions, $I_R^{Sr90}(t)$, were normalized by taking into account the results of ^{90}Sr-body-burden measurements in adult residents of Muslyumovo.

Fig. 1 shows estimates of the verified ^{90}Sr-intake functions for adult residents of Metlino and Muslyumovo compared to TRDS-2000 estimates.

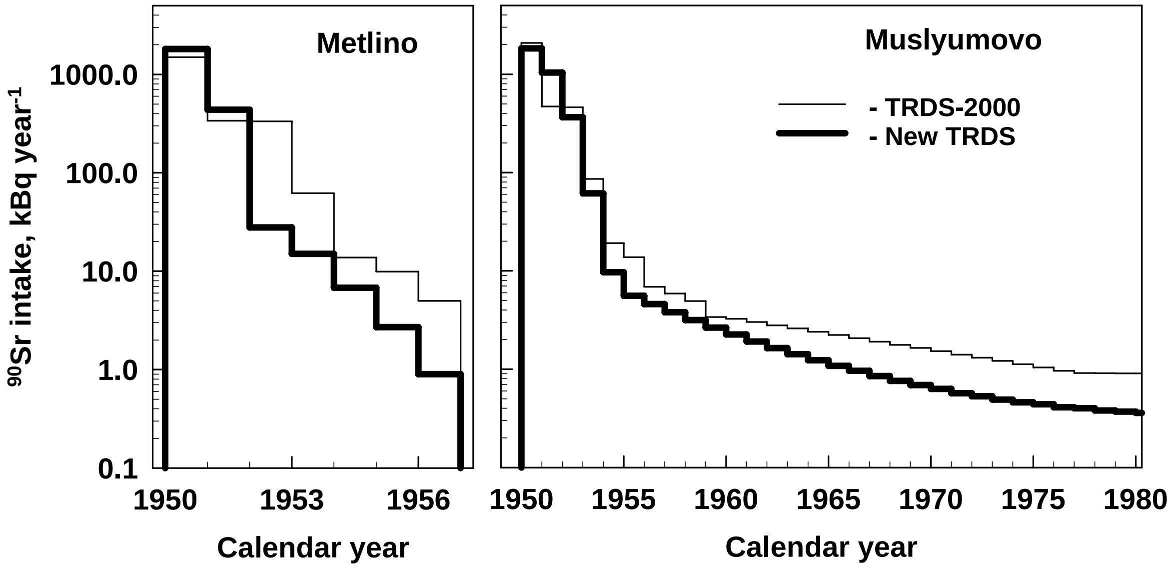

Fig. 1. Comparison of old and new estimates of ^{90}Sr-intake functions for adult residents of referent settlements: Metlino (7 km from the site of releases, evacuated in 1956) and Muslyumovo (78 km from the site of releases, still exists).

It is seen from Fig. 1 that the estimated dynamics of ^{90}Sr intake with time after the beginning of releases has slightly changed; however, the total intake increased by only 2% for residents of Metlino and by 5% for residents of Muslyumovo compared to values used in the TRDS-2000. It also should be noted that average ^{90}Sr intakes in 1950 are comparable in both settlements and in 1951 they are lower in Metlino than in Muslyumovo. This is explained by the fact that some residents of Metlino used non-contaminated drinking water from underground sources. Also, Metlino was the closest village to the point of release, and it was the earliest for which restrictions were placed on the use of water from the river (on August 10, 1951).

The assessment of the average ^{90}Sr intake in other settlements is based on the assumption that the ratio between ^{90}Sr intake in a particular settlement and ^{90}Sr intake in Muslyumovo is equal to the ratio between the average value of ^{90}Sr-body burden for the particular settlement and the corresponding value for Muslyumovo, obtained on the basis of WBC measurements [13]. Fig. 2 shows the old and new estimates of ^{90}Sr relative intake as a function of distance from the site of releases.

A good correlation is demonstrated in Fig. 2 between estimates used in the TRDS-2000 and the new estimates, based on reliable WBC data. It should be noted that dependence of ^{90}Sr intake on distance from the site of releases is not linear. This is mainly explained by the fact that residents of some settlements could have used wells and other sources of non-contaminated drinking water in addition to river water, but in other settlements river water was the only source for drinking and other needs. It should also be noted that for evaluation of the relative ^{90}Sr-

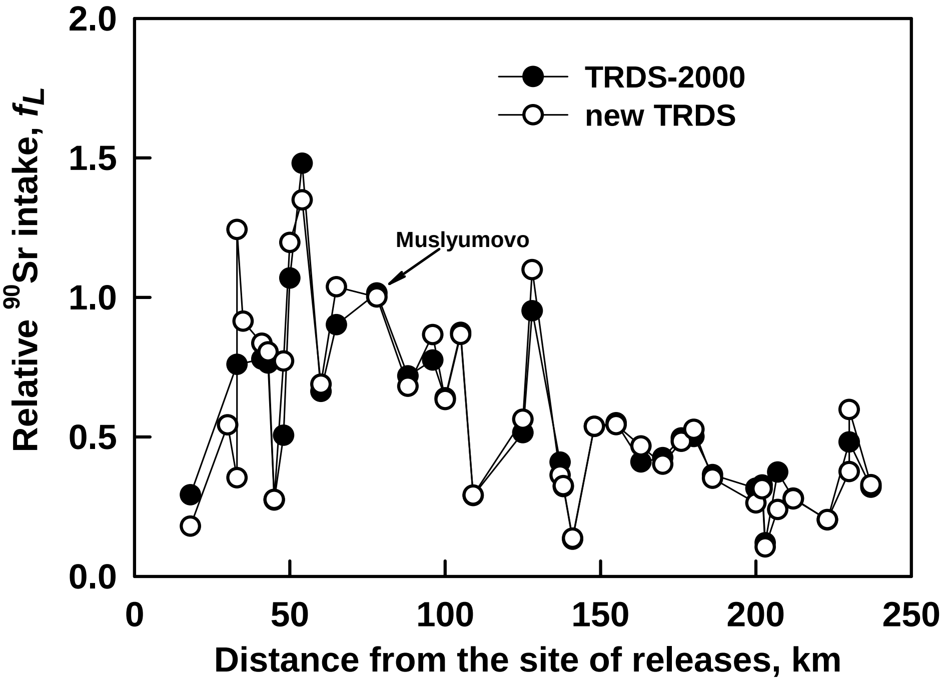

Fig. 2. Relative ^{90}Sr intake for residents of different Techa River settlements located at different distances along the river from the site of releases (except Metlino). Unit ^{90}Sr intake is estimated for Muslyumovo, which served as a referent settlement.

intake functions, f_L^{Sr90}, WBC data for each person were normalized according to their age and gender. For this purpose, strontium biokinetic models, described below, were used.

Analysis of the WBC measurements for permanent residents of the Techa River settlements showed age-dependencies in ^{90}Sr-body burden that differed for males and females (Fig. 3).

The biokinetic model used in the TRDS-2000 did not account for gender features of strontium metabolism. This encouraged us to develop an improved *age- and gender-dependent biokinetic model for strontium* in 2002 [14]. As shown in reference [14], the new model was verified using numerous data on Ca and Sr content in humans of different age and gender. Fig. 3 shows that model predictions, corresponding to intake levels in Muslyumovo, satisfactorily describe ^{90}Sr-body burdens in males and females of all age groups obtained with use of the WBC. Therefore, use of the new biokinetic model will allow better estimation of doses, especially for those residents who were children and teenagers during the period of maximal ^{90}Sr intake. However, to calculate absorbed dose in red bone marrow (RBM) and osteogenic cells from ^{90}Sr incorporated in the mineral part of the skeleton, an *age- and gender-dependent dosimetric model* is needed. The development of such a model commenced in 2005.

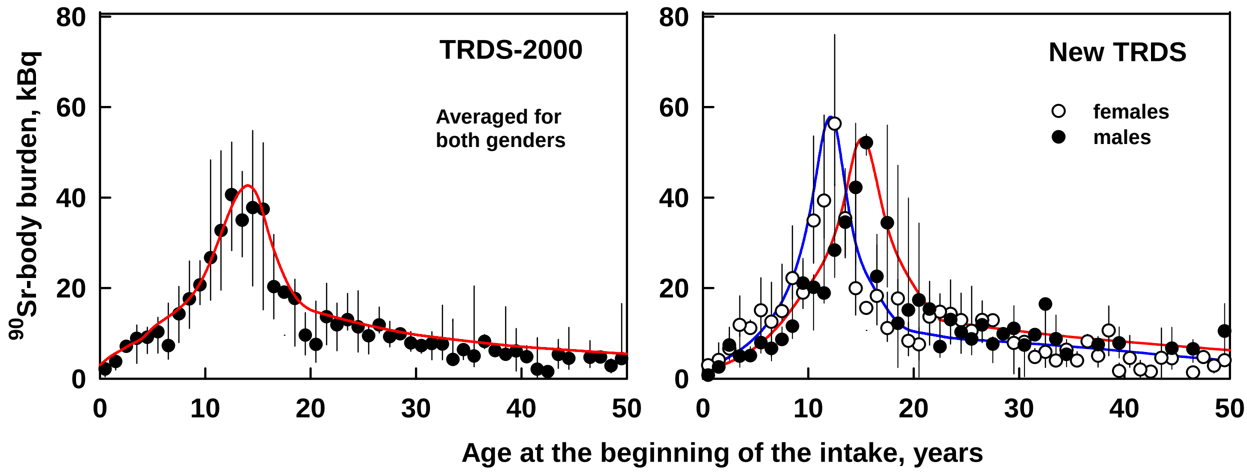

Fig. 3. Age-dependencies in ^{90}Sr-body burdens for residents of Muslyumovo 30 years after the beginning of intake. The left panel shows model predictions obtained with the age-dependent biokinetic model used in the TRDS-2000 compared with WBC data averaged for both genders. The right panel shows model predictions obtained with the new age- and gender-dependent model compared with WBC data averaged for males and females separately.

Radionuclides other than ^{90}Sr were also released into the Techa River, including ^{137}Cs and short-lived uranium-fission products. For reconstruction of radionuclide concentrations in river water and bottom sediments for the first period after the beginning of releases, when the results of measurements were absent, the *Techa River Model* [15] was developed. This model describes radionuclide transport from the site of release; it was further improved in 2003. Comparison of the model predictions with the results of measurements performed in 1951 (Fig. 4) shows that the new (two-compartment) model describes more satisfactorily the decrease in radionuclide concentrations in river water as a function of distance along the river.

The model for radionuclide transport in the Techa River is used for calculation of the concentration of specific radionuclides in river water and bottom sediments during the first period of contamination (1949–1951). Because river water was the main source of internal exposure, ratios of radionuclide concentrations (^{137}Cs and short-lived radionuclides) to that of ^{90}Sr, calculated using the Techa River Model, allow assessment of their intakes with river water. However, this approach doesn't allow the assessment of additional intake of ^{137}Cs with cows' milk. Work [15] on estimating additional intake of ^{137}Cs with cow milk, which was not considered in TRDS-2000, is now underway.

Application of models developed for strontium, together with published biokinetic and dosimetric models for other radionuclides, allow the assessment of *internal doses* for individuals of any age and gender.

Reconstruction of *external doses* is based on measurements of gamma-exposure rates in air at the shoreline and in living areas; such measurements were performed systematically since

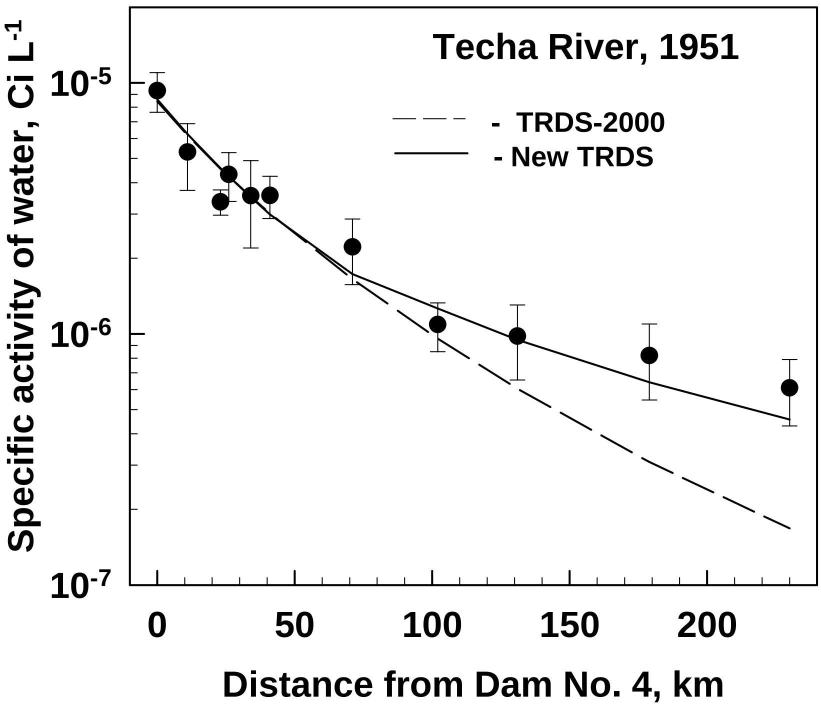

Fig. 4. Measured and modeled radionuclide concentrations in Techa River water in 1951 as a function of distance along the river. Modeled values were obtained with one-compartment (TRDS-2000) and two-compartment (developed for the new version of the TRDS) models.

1952. For the period before such measurements commenced, dose rates in air on the river banks were calculated on the basis of modeled radionuclide concentrations in bottom sediments; for this purpose coefficients [16] obtained by Monte Carlo simulations of air kerma were used. Fig. 5 shows the results of gamma-dose-rate calculations using the one-compartment (TRDS-2000) and the two-compartment Techa River Models.

It is seen from Fig. 5 that the new estimates show somewhat of a difference in the decrease of gamma-dose rates with distance downstream from the site of releases; this can be associated with the changes in modeled concentrations of radionuclides in bottom sediments. The new estimates additionally use data on evaluated measurements of the width of the riverbed, performed by I.A. Koloskov (the Institute of Applied Geophysics, Moscow), which resulted in a local "peak" near Nadyrov Most village (48 km downstream) due to the contraction of the riverbed at this site of the river.

A *behavioral model* of typical life-style patterns for different age groups of Techa Riverside residents was used for the reconstruction of external doses. According to information derived from observational data from M.M. Saurov (the Institute of Biophysics, Moscow), residents of the settlements spent most of their time near their residences (working in individual households, eating, sleeping) or far away doing farm work and not near the river (swimming,

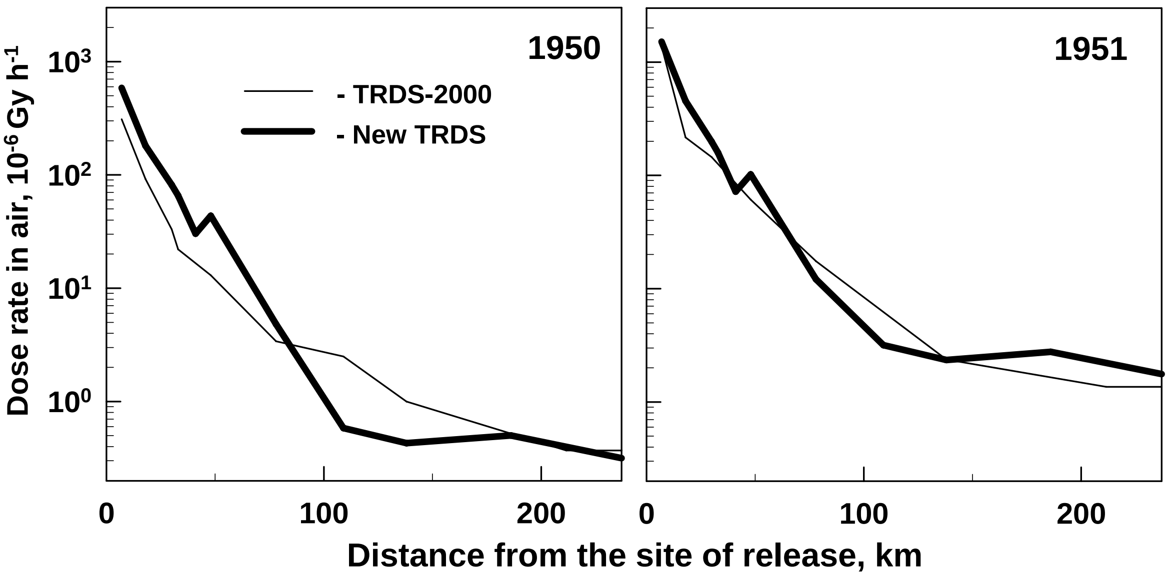

Fig. 5. Modeled gamma-dose rates in air along the Techa River shoreline in 1950 and 1951, obtained with the one-compartment (TRDS-2000) and the two-compartment (developed for the new version of the TRDS) models.

laundering, fishing etc.) [7]. Therefore, the main factor contributing to external dose was the distribution of gamma-exposure rates in the residence areas compared to the rates on the riverbanks.

The decrease of dose rate with distance from the shore is dependent on the topography of the bank and was specific for each location. Assessment of external doses is based on the assumption that patterns of gamma-exposure rates as a function of distance from the shoreline in a specific settlement were similar in various years; therefore, an averaged value could be estimated with use of measurements performed in 1952–1954. A rough point estimate of the gamma-dose rate at the residence territory relative to that on the shoreline is used in the TRDS-2000 to calculate the contribution to external dose due to residence on the territory of a specific village. This point estimate corresponds to the average distance between the shoreline and households for a specific village. Such an average value is more reliable than the former procedure of assuming that everyone lived in the row of houses next to the shoreline, but the new procedure is still subject to fairly large uncertainty. Therefore, electronic schemes of the Techa River villages were created [17] based on available archival maps. The use of electronic maps of Techa River villages allows for the evaluation of *distributions of gamma-dose rates* relative to the river shoreline for individual households (including a house and a garden), a group of households or the whole residence area [17]. Fig. 6 shows the distributions of gamma-dose rates in air (relative to shoreline) for households located in Metlino and Muslyumovo. For comparison, the average values used in TRDS-2000, describing residence/shoreline gamma-dose rate ratios, were 0.01 for Metlino and 0.02 for Muslyumovo. It is clear that the use of these distributions allows better assessment of the average external doses in a settlement and of

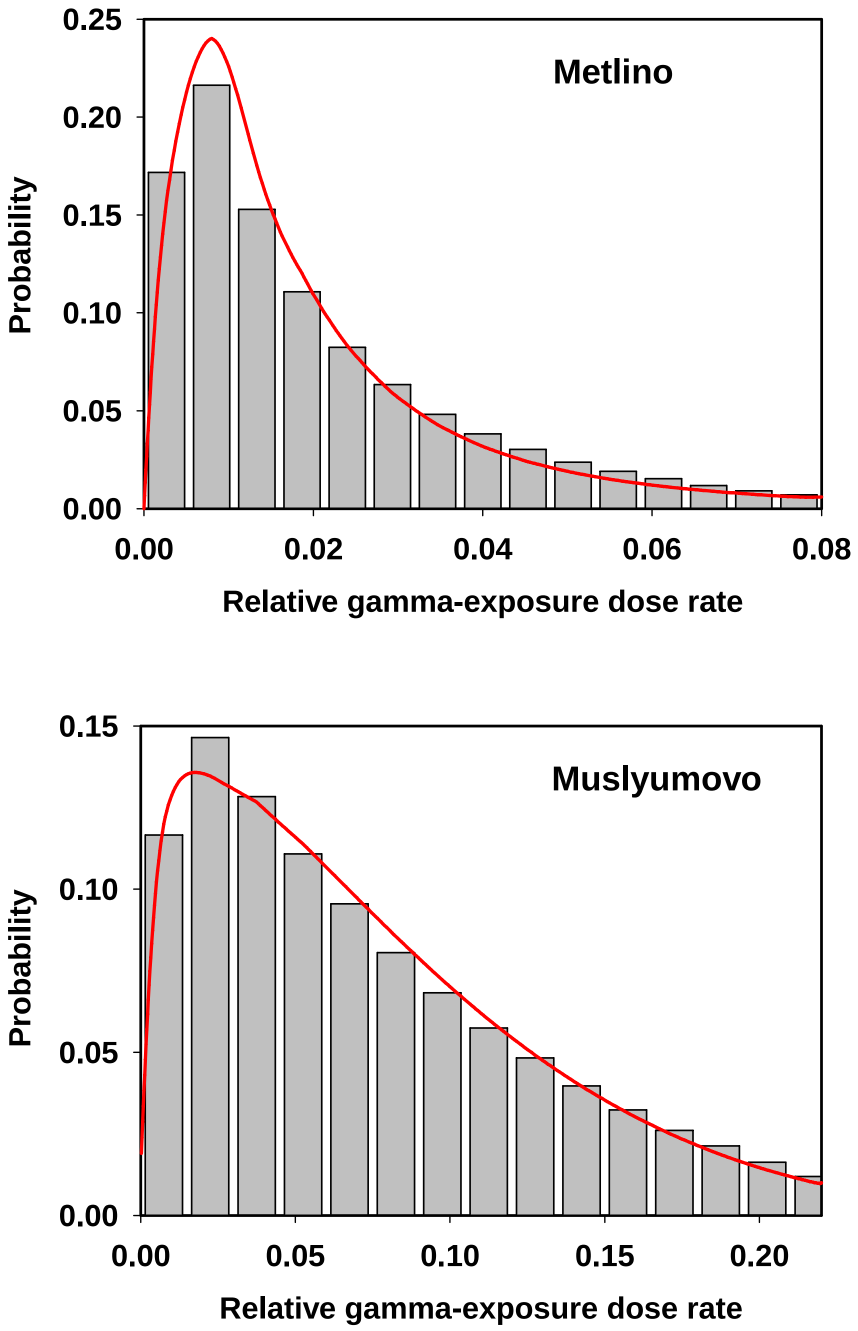

Fig. 6. Distributions of relative gamma-dose rates in households located at different distances from the water's edge for Metlino and Muslyumovo (gamma-dose rate near the shoreline is taken to be unity). These values can be compared with average estimates used in the TRDS-2000 of 0.01 for Metlino and 0.02 for Muslyumovo.

individual doses for people who have information on the location of their households in a settlement during the time of exposure.

Finally, dose coefficients published in reference [18] were taken for the calculation of absorbed doses in organs and tissues from the data on gamma-dose rates in air. The values of the dose coefficients were obtained by photon transport modeling in *human geometrical models* (mathematical phantoms of people of different ages) applicable for the case of environmental contamination by uranium-fission products.

To conclude, the assessment of *internal doses* is based on a large number of measurements taken over a long time period of ^{90}Sr-body burdens in Techa Riverside residents (available for 33% of the members of the ETRC). The assessment of *external doses* (formed during the first period after the beginning of the releases) is mostly based on modeling. For this reason, validation of the calculated external doses with the use of modern methods for retrospective dosimetry is one of the more important tasks for continuing and future work.

VALIDATION OF EXTERNAL DOSES

Validation of external doses calculated using TRDS databases is being performed by comparison of calculated values with experimental data obtained by different dosimetric methods. These methods include luminescence measurements of quartz extracted from bricks in old buildings located on the banks of the river, EPR measurements on human teeth, and FISH measurements of human lymphocytes in peripheral blood of exposed individuals. The results of investigations showed that each method possesses restrictions in its application for complex (external and internal) radiation exposure, especially for low-dose exposure [19-24]. Further application of these methods for the Techa River situation requires additional work on improvement of methods, which is ongoing at the present time. Nevertheless, for Metlino Village—the nearest to the site of the releases—where maximal levels of external exposure have been observed, we succeeded in obtaining good agreement between calculated and measured doses [21-24], described below.

Reliable estimates of anthropogenic dose in bricks of the old mill were obtained using the luminescent method [21]. The value of the cumulated dose in air, calculated with TRDS-2000, lies within the confidence intervals for doses measured from quartz in bricks from old buildings [22-23]. Thus, values of the accumulated dose in air on the Techa River banks in Metlino Village, used in the TRDS-2000, are in agreement with those derived from the luminescence measurements.

The FISH method is based on measuring the frequency of translocations in circulating lymphocytes extracted from human blood. Doses estimated using this method cannot be definitely associated with the exposure of a specific organ. It is known that from 5 to 15% of circulating lymphocytes originate in the red bone marrow (RBM), while another significant fraction originates in the thymus. The combined internal and external exposure of Techa River residents resulted in an extremely heterogeneous distribution of doses in human organs and tissues. For this reason, the results of FISH-based dosimetry were compared to both external dose (which is similar for most soft tissues) and the RBM dose (which is significantly higher due to the additional contribution from beta-particles of $^{90}Sr/^{90}Y$, incorporated in the skeleton). The results of the analysis showed [24], that the average FISH-based dose for investigated persons from Metlino Village (0.38±0.10 Gy) is close to the TRDS-2000 calculated external dose for soft tissues (0.31±0.03 Gy), but is lower than the estimated RBM dose (0.79±0.08 Gy). Although these results should be interpreted further in terms of hematology and origin of circulating blood cells as a function of age, it is evident that FISH-based doses do not exceed the TRDS-2000 calculated doses.

Comparison of EPR-based doses with enamel doses calculated with use of the TRDS-2000 also showed good agreement for investigated persons from Metlino Village [24]. The average TRDS-2000-based enamel dose, 0.55±0.07 Gy, is in agreement with the value based on EPR-measurements (0.55±0.17 Gy). The slope of the regression, describing individual data (Fig. 7a), is close to unity with statistically significant value of the correlation coefficient (p<0.05). It should be noted that estimates of individual doses, obtained with the TRDS-2000, are village-averaged values and the only specific individualization is for residence history in particular villages. Three clusters of points are evident in Fig. 7a: (1) two points are close to zero dose (these are people who lived in Metlino for less than a year); (2) one point is in an intermediate dose range (this person lived 3 years in Metlino) and (3) ten points with similar calculated dose estimates are in the range of 0.65–0.72 Gy (permanent residents of Metlino). Fig. 7b shows the same EPR data compared with calculated doses that account for the location of households (relative to shoreline), where the individuals actually lived during the exposure.

It is seen in Fig. 7b that the range of calculated dose estimates has significantly increased and most of the EPR-measured doses are now within the confidence intervals of the regression.

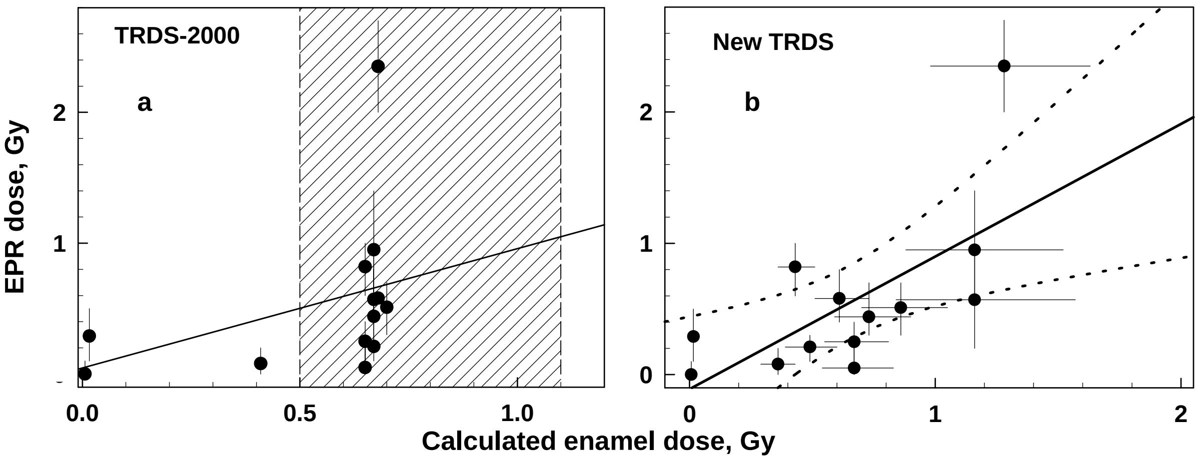

Fig. 7. Comparison of the calculated external doses for tooth enamel with EPR-based doses obtained for inhabitants of Metlino Village. The left panel (a) shows dose estimates based on weighted-average distance between households and the river shoreline (TRDS-2000). The right panel (b) shows individual dose estimates that account for the location of a particular person's household in terms of distance from the river shoreline, (future version of the TRDS).

Fig. 7b illustrates the approach to external dose reconstruction that will be used in the next version of the TRDS. Implementation of this approach will result in a substantial reduction of uncertainties in dose estimates. This is discussed further below.

REDUCTION OF THE UNCERTAINTIES IN DOSE ESTIMATES

As described in references [5-8], a unified algorithm (a single basic dose equation) is being used in the TRDS-2000 calculations of dose. The annual averaged values of the dose equation parameters specific for settlements and individual ages are compiled in TRDS databases. Input data necessary for the calculation of individual dose include the following information for each member of the ETRC: year of birth, residence history in the Techa River villages, and year of exit from follow-up (as a result of migration from the catchment area or death). Example calculations of uncertainty (performed outside of the TRDS-2000) have been based on Monte Carlo simulations with parameters that are random variables approximated by distribution functions that reflect the variability in a referent ("averaged") group of residents of a given age and residence history [25]. It is evident that calculation of individual dose instead of average dose will result in a significant reduction of uncertainty in dose estimates. Data necessary for calculation of individual doses are available for the majority of the members of the ETRC. The prospective on the reduction of uncertainties in external and internal doses are described briefly below.

The uncertainty in *external dose* of a particular individual is significantly determined by location of an individual household where he/she spent most of his/her time. In TRDS-2000 a uniform probability that a person lived in a household located in a particular village on any distance from the shoreline was implied in the calculation of the uncertainty in the external dose [25]. For example, for permanent residents of Metlino Village the confidence interval (CI) of the external dose, estimated using Monte Carlo simulations (shown in Fig. 7a), is wide and constitutes 0.5-1.1 Gy. This is mostly influenced by the differences in gamma-dose rates in the residence area (some households were located near the contaminated shoreline while others were located 300-400 meters from the shoreline). Work on associating individual inhabitants with a specific home in Metlino was performed in 2002–2005. For this purpose information (tax and census records, etc.) on the location of their homes (by address within the village) was used where available. As a result, about 90% of 1,738 persons who lived in Metlino in 1950–1956 were associated with a geographic location. This allowed better assessment of an individual's external dose. As seen in Fig.7b, the CIs of individual external doses (shown with horizontal bars) are significantly reduced and the implementation of the new approach allowed identification of the group of residents with maximal doses of external exposure (more than 1 Gy).

The uncertainties in *internal doses* can be significantly reduced through the use of the results of individual measurements of ^{90}Sr in whole body and bone samples. Assessment of the internal doses in TRDS-2000 is performed by using statistical distributions of measured ^{90}Sr-body burdens for residents of specific settlements normalized for age [25]. For most villages the statistical distributions could not be described by standard distribution functions, because intake of ^{90}Sr was very heterogeneous (some inhabitants used river water while others used well water in 1950–1952). The new version of the TRDS will be using individual estimates of internal doses based on individual measurements of ^{90}Sr in the body, rather than on village averages. Fig. 8 shows the approach on estimating individual doses for permanent adult residents of Muslyumovo Village. The TRDS-2000-based estimate of RBM internal dose of 0.76 Gy with a wide CI (0.08-1.87 Gy) is an average for the entire group of adult permanent residents. As seen in Fig.8, the new approach allows the reduction of the CIs of individual-dose estimates and identification of people with minimal and maximal doses. The CIs of individual dose estimates are influenced by the number of WBC measurements and their uncertainties [11].

On the whole, individual reconstruction of internal doses for members of the ETRC will reduce the uncertainty about five times on average for the 33% of members who have individual measurements of ^{90}Sr (Table 1). For those members of the ETRC who do not have individual measurements, the uncertainties in dose estimates could be reduced by using measurements of their relatives who lived in the same household. For this purpose, average estimates of ^{90}Sr-body burdens normalized for age and gender have been obtained for inhabitants of specific households within each Techa River village [13]. In this case, the reduction in uncertainty is attributed to the allocation of similar sources of water and food to all members of a specific home.

It is seen in Table 1, that "household" reconstruction of internal doses for ETRC members will reduce uncertainty about two times for 25% of the cohort members. Therefore, the future TRDS version strongly relies on the significant improvement of the internal dose estimates for the majority of the ETRC members.

IMPROVEMENT IN ESTIMATES OF THE CONTRIBUTION OF SHORT-LIVED RADIONUCLIDES

In the TRDS-2000 the assessment of doses from short-lived radionuclides is based on data concerning radionuclide composition of discharges into the Techa River provided in official Mayak documents and reports published before 2000 [26-27]. However, another estimate of the Techa River source term was published recently that implies an increased contribution from short-lived radionuclides [28-29]. To resolve this problem of the Techa River source term, the

Table 1. Anticipated reduction in uncertainties of estimates of internal doses expected in the next version of the TRDS.

Subcohort	% of the entire ETRC	Estimated coefficient of variation
1. Persons with individual ^{90}Sr-body measurements	33%	0.25
2. Persons living in the same households with their relatives having individual ^{90}Sr-body measurements	25%	0.83
3. Persons, for whom only residence history information is available	42%	1.23[a]

[a] Corresponds to the uncertainty in TRDS-2000-based dose estimates.

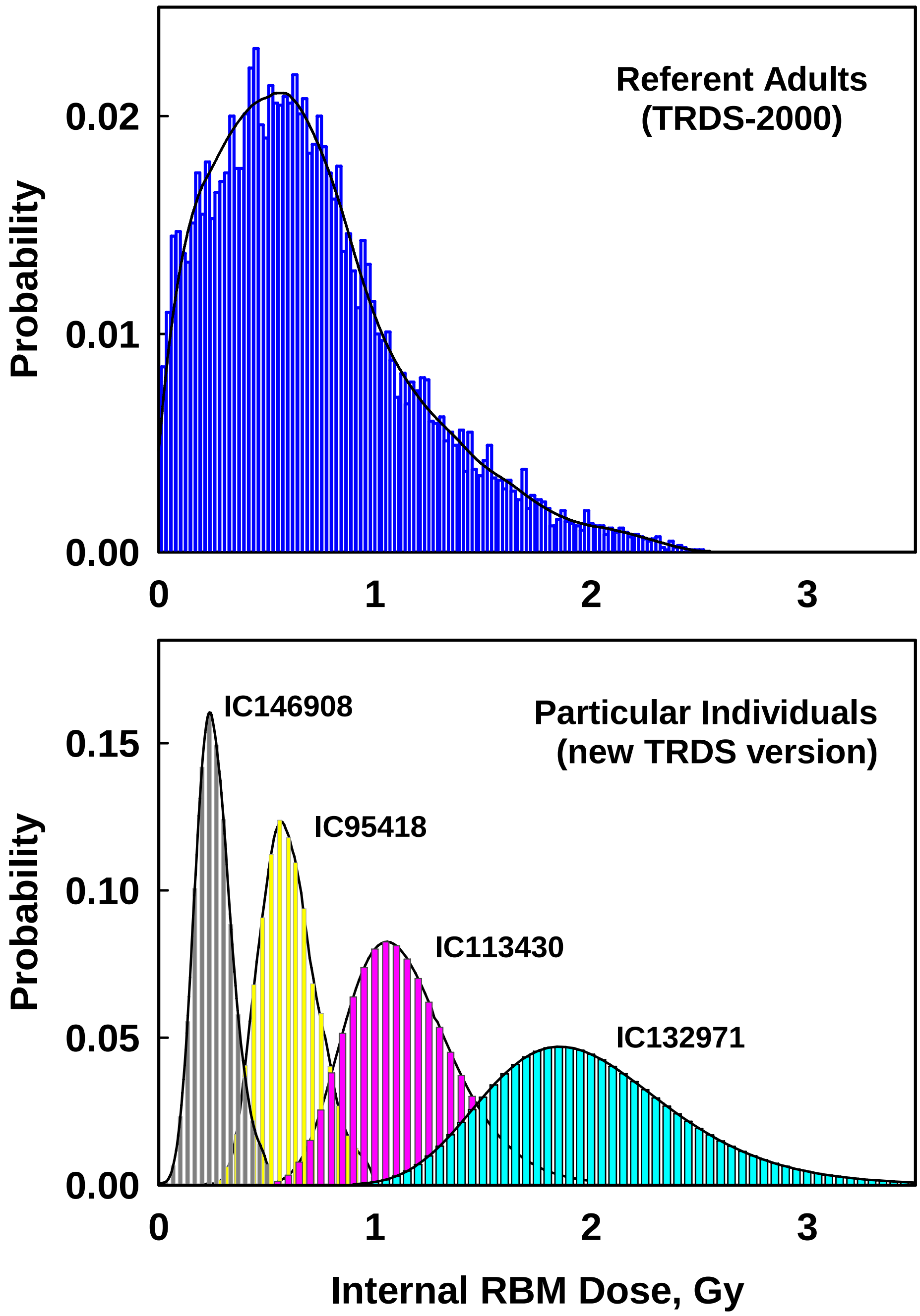

Fig. 8. Distributions characterising the uncertainty in estimates of red bone marrow internal dose for adult permanent residents of Muslyumovo Village. The upper panel shows village-averaged dose estimates based on ^{90}Sr-body burden distributions in a group of residents having individual WBC measurements (TRDS-2000). The lower panel shows examples of individual dose estimates for four persons from the entire group (their identification codes are indicated). Individual estimates are based on statistical analysis of individual data.

TRDS-2000 authors, in collaboration with MPA experts and experts from two additional institutes, initiated a project under the International Science and Technology Center (ISTC); the results of this project are anticipated by the end of 2007 [30]. These studies include in-depth analysis of archival data on radionuclide composition and physical-chemical properties of the liquid radioactive wastes discharged into the Techa River in 1949–1956. The results of these studies will be used for the development of a new version of the TRDS. However, any revision of the contribution of short-lived radionuclides will not change the dose estimates from long-lived ^{90}Sr and ^{137}Cs. It is also expected that any revision of the source term will not influence the TRDS-2000-based estimates of accumulated external doses, which have already been verified for residents of the upper-Techa region with use of three independent methods (luminescence, EPR and FISH). A revision of the contribution of short-lived radionuclides can result in changes in estimates of internal doses for RBM and gastrointestinal tract organs due to increased intake of ^{89}Sr and rare-earth radionuclides.

Evaluation of additional sources of exposure

It is known that 2,700 ETRC members were evacuated from the upper-Techa regions in 1955–1956 to territories that were later contaminated as a result of an explosion in the Mayak radioactive waste-storage facility in 1957. This resulted in additional exposure of these members of the ETRC, due to residence on the East-Urals Radioactive Trace territory. Moreover, some members of the ETRC, living in Chelyabinsk Oblast, were additionally exposed as a result of windblown activity from Karachay Lake in 1967, to which effluents had been diverted after the contamination of the Techa River became known. In both situations additional exposure occurred for all groups of residents, who had already received major doses due to residence in the Techa River settlements. In such a situation, underestimation of the total dose for these members of the ETRC can result in an increase in estimates of risk coefficients per unit dose for the entire ETRC. Therefore, evaluation of additional exposures for the members of the ETRC is an important task. The database "Environment" already contains a compilation of environmental radiation monitoring data performed on the EURT and Karachay Trace areas in 1958–2003. These data, together with individual information available for every ETRC member on residential history on contaminated areas, will be used in the new version of the TRDS for the reconstruction of additional exposure for members of the ETRC.

The other source of additional exposure was diagnostic x-ray procedures received by inhabitants of the Techa River settlements during special medical examinations and treatment courses at the URCRM clinics. Before the 1980s (when limitations were introduced with the aim of reducing doses from medical exposure), patients were examined repeatedly during each hospitalization in order to trace the changes in their health conditions. Persons who were diagnosed as having (or suspected to have) chronic radiation syndrome and persons with high ^{90}Sr-body burdens were hospitalized more frequently. As a result of this focus of medical attention, persons known or suspected to have had higher levels of radiation exposure were examined by various kinds of diagnostic x-ray procedures more frequently than the members of the ETRC with lesser amounts of exposure. This factor can be a source of bias in the risk-derivation study for this population. The "X-Ray Diagnostic Procedures" Registry has been established, and corresponding dose-calculation procedures were developed in order to reconstruct the medical exposure for members of the ETRC [31]. Thus, additional medical exposure of the ETRC members will also be accounted for in the new TRDS version.

CONCLUSION

Development of a new version of the TRDS is aimed at further verification of system databases and improvement of the algorithms for dose calculation. This will allow better assessment of the individual external and internal doses to support epidemiologic studies of radiation risks in the residents of the Techa River settlements.

ACKNOWLEDGEMENTS

This work has been funded by the US Department of Energy's Office of Health, the US Environmental Protection Agency's Office of Radiation and Indoor Air, and the Federal Medical-Biological Agency of the Russian Federation.

REFERENCES

1. Kossenko MM, Preston DL, Krestinina LY, Degteva MO, Startsev NV, Thomas T, Vyushkova OV, Anspaugh LR, Napier BA, Kozheurov VP, Ron E, Akleyev AV. Studies on the Extended Techa River Cohort: Cancer risk estimation. Radiat Environ Biophys 41:45–48; 2002.
2. Krestinina LYu, Preston DL, Ostroumova EV, Degteva MO, Ron E, Vyushkova OV, Startsev NV, Kossenko MM, Akleyev AV. Protracted radiation exposure and cancer mortality in the Techa River Cohort. Radiat Res 164:602-611; 2005.
3. Kellerer AM. The Southern Urals radiation studies. A reappraisal of the current status. Editorial. Radiat Environ Biophys 41:307–316; 2002.
4. Keirim-Markus IB, Youganova TI. On radiation risk evaluation for the population of Techa River catchment-area contaminated due to "Mayak" Production Association activities. Med Radiol Radiat Safety 50:18–24; 2005 (in Russian).
5. Degteva MO, Vorobiova MI, Tolstykh EI, Shagina NB, Anspaugh LR, Napier BA. Dosimetry of the Techa River System: Dose reconstruction for radiation consequences risk assessment. Radiat Safety Problems (Mayak Production Association Scientific Journal) № 4:36–46; 2000 (in Russian).
6. Degteva MO, Tolstykh EI, Vorobiova MI, Shagina NB, Kozheurov VP, Anspaugh LR, Napier BA. Improving the dose reconstruction system for estimating the risk of late effects in the Techa River population. Med Radiol Radiat Saf 46:9–21; 2001 (in Russian).
7. Degteva MO, Vorobiova MI, Kozheurov VP, Tolstykh EI, Anspaugh LR, Napier BA. Dose reconstruction system for the exposed population living along the Techa River. Health Phys 78:542–554; 2000.

8. Degteva MO, Kozheurov VP, Tolstykh EI, Vorobiova MI, Anspaugh LR, Napier BA, Kovtun AN. The Techa River Dosimetry System: Methods for the reconstruction of internal dose. Health Phys 79:24–35; 2000.
9. Balonov M, Alexakhin R, Bouville A, Liljinzin JO. Report from the Techa River Dosimetry Review Workshop held on 8-10 December, 2003 at the State Research Centre Institute of Biophysics, Moscow, Russia. Health Phys 90:97–113; 2006.
10. Tolstykh EI, Zalyapin VI, Krivoshchapov VA, Shagina NB, Peremyslova LM, Degteva MO, Kozheurov VP, Safronova NG, Anspaugh LR, Napier BA. Verification of referent-intake levels for strontium-90. Chelyabinsk and Salt Lake City: Urals Research Center for Radiation Medicine and University of Utah; Final report for Milestone 3, Part 1; September 2001 (in Russian and English).
11. Shagina NB, Tolstykh EI, Zalyapin VI, Degteva MO, Kozheurov VP, Tokareva EE, Anspaugh LR, Napier BA. Statistical analysis of repeated measurements of strontium-90 body burdens and evaluation of age- and sex-dependencies of strontium-elimination rate during a period 25–45 years after intake. Chelyabinsk and Salt Lake City: Urals Research Center for Radiation Medicine and University of Utah; Progress Report for Milestone 4; January 2002.
12. Zalyapin VI, Krivoshchapov VA, Degteva MO. Numerical analysis of an applied biophysics inverse problem. Inverse Probl Science Engin 12:379–392; 2004.
13. Tolstykh EI, Zalyapin VI, Shagina NB, Krivoshchapov VA, Degteva MO, Tokareva EE, Anspaugh LR, Napier BA. Evaluation of ETRC subcohorts with different algorithms for 90Sr body burden estimation and assessment of their uncertainties. Chelyabinsk and Salt Lake City: Urals Research Center for Radiation Medicine and University of Utah; Final report for Milestone 8; September 2003 (in Russian and English).
14. Shagina NB, Tolstykh EI, Degteva MO. Improvements in the biokinetic model for strontium with allowance for age and gender differences in bone mineral metabolism. Radiat Prot Dosim 105:619–622; 2003.
15. Vorobiova MI, Degteva MO, Tolstykh EI, Safronova NG, Peremyslova LM, Anspaugh LR, Napier BA. Verification and evaluation of uncertainties for intake levels for non-strontium radionuclides with use of an improved Techa River Model. Chelyabinsk and Salt Lake City: Urals Research Center for Radiation Medicine and University of Utah; Final Report for Milestone 5; March 2003 (in Russian and English)..
16. Eckerman KF, Ryman JC. External exposure to radionuclides in air, water, and soil. Washington: U.S. Environmental Protection Agency; Federal Guidance Report No. 12, EPA 402-R-93-081; 1993.
17. Degteva MO, Vorobiova MI, Akhramenko BN, Shagina NB, Safronova NG, Anspaugh LR, Napier BA. Report on the uncertainties in TRDS external dose estimates evaluated on the basis of modeling data and the distributions of external exposure components of EPR measurements. Chelyabinsk and Salt Lake City: Urals Research Center for Radiation Medicine and University of Utah; Final report for Milestone 9; April 2005.
18. Petoussi N, Jacob P, Zankl M, Saito K. Organ doses for fetuses, babies, children and adults from environmental gamma rays. Radiat Prot Dosim 37:31–41; 1991.

19. Bougrov NG, Göksu HY, Haskell E, Degteva MO, Meckbach R, Jacob P. Issues in the reconstruction of environmental doses on the basis of thermoluminescence measurements in the Techa Riverside. Health Phys 75:574–583; 1998.

20. Shishkina EA, Degteva MO, Shved VA, Ivanov DV, Bayankin SN, Knyazev VA, Vasilenko EK, Smetanin MY, Gorelov MV. Problems and prospects of EPR researches in the Southern Urals. Radiat Safety Problems (Mayak Production Association Scientific Journal) № 2:59−70; 2003 (in Russian).

21. Bougrov NG, Degteva MO, Göksu HY, Meckbach R, Jacob P. Retrospective thermoluminescence dosimetry in the riverside territories of the upper-Techa River. Radiat Safety Problems (Mayak Production Association Scientific Journal) № 3:51−62; 2001 (in Russian).

22. Taranenko V, Meckbach R, Degteva MO, Bougrov NG, Göksu Y, Vorobiova MI, Jacob P. Verification of external exposure assessment for the Upper Techa Riverside by luminescence measurements and Monte Carlo photon transport modeling. Radiat Environ Biophys 42:17–26; 2003.

23. Jacob P, Göksu Y, Taranenko V, Meckbach R, Bougrov NG, Degteva MO, Vorobiova MI. On an evaluation of external dose values in the Techa River Dosimetry System (TRDS) 2000. Radiat Environ Biophys 42:169–174; 2003.

24. Degteva MO, Anspaugh LR, Akleyev AV, Jacob P, Ivanov DV, Weiser A, Vorobiova MI, Shishkina EA, Shved VA, Vozilova AV, Bayankin SN, Napier B. Electron paramagnetic resonance and fluorescence in situ hybridization-based investigations of individual doses for persons living at Metlino in the upper reaches of the Techa River. Health Phys 88:139 - 153; 2005.

25. Napier BA, Shagina NB, Degteva MO, Tolstykh EI, Vorobiova MI, Anspaugh LR. Preliminary uncertainty analysis for the doses estimated using the Techa River Dosimetry System – 2000. Health Phys 81:395–405; 2001.

26. JNREG. Sources contributing to radioactive contamination of the Techa River and areas surrounding the "Mayak" Production Association, Urals, Russia. ∅steras: Joint Norwegian-Russian Expert Group for Investigation of Radioactive Contamination in the Northern Areas; Report; 1997.

27. Mokrov Yu, Glagolenko Yu, Napier B. Reconstruction of radionuclide contamination of the Techa River caused by liquid waste discharge from radiochemical production at the Mayak Production Association. Ozersk and Richland: Mayak Production Association and Pacific Northwest National Laboratory; Final Report for JCCRER Project 1.3; 1999.

28. Mokrov YuG. On reconstruction of the radionuclide composition of the liquid radioactive wastes released into the Techa River in 1949–1951. Radiat Saf Prob (Mayak Production Association Scientific Journal) № 3:32–38; 2001 (in Russian).

29. Mokrov YuG. Reconstruction of the radionuclide spectrum of liquid radioactive waste released into the Techa River in 1949-1951. Radiat Environ Biophys 42:7–15; 2003.

30. Vorobiova MI, Glagolenko YuV, Trapeznikov AV, Cherepanova EI. Source-term reconstruction for the Techa River: Problems and resolution pathways. In: Proceedings of

the XIth international symposium, ‘Ural Atomic, Ural Industrial.’ Ekaterinburg: Institute of Industrial Ecology; 2005:19-22 (in Russian and English).

31. Degteva MO, Golikov VYu, Vorobiova MI, Barkovsky AN, Zubkova TI, Kozyreva OV, Anspaugh LR, Napier BA. Development of a protocol for the reconstruction of individual medical doses for members of the Extended Techa River Cohort. Chelyabinsk and Salt Lake City: Urals Research Center for Radiation Medicine and University of Utah; Final report for Milestone 17; September 2005 (in Russian and English).