# Individual Dose Calculations with Use of the Revised Techa River Dosimetry System TRDS-2009D

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# INDIVIDUAL DOSE CALCULATIONS WITH USE OF
# THE REVISED TECHA RIVER DOSIMETRY SYSTEM TRDS-2009D

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**"Further Studies on Uncertainty, Confounding and Validation of the Doses in
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# ABSTRACT

An updated deterministic version of the Techa River Dosimetry System (TRDS-2009D) has been developed to estimate individual doses from external exposure and intake of radionuclides for residents living on the Techa River contaminated as a result of radioactive releases from the Mayak plutonium facility in 1949–1956.  The TRDS-2009D is designed as a flexible system that uses, depending on the input data for an individual, various elements of system databases to provide the dosimetric variables requested by the user.  Several phases are included in the computation schedule.  The first phase includes calculations with use of a common protocol for all cohort members based on village-average-intake functions and external dose rates; individual data on age, gender and history of residence are included in the first phase.  This phase results in dose estimates similar to those obtained with system TRDS-2000 used previously to derive risks of health effects in the Techa River Cohort.  The second phase includes refinement of individual internal doses for those persons who have had body-burden measurements or exposure parameters specific to the household where he/she lived on the Techa River.  The third phase includes summation of individual doses from environmental exposure and from radiological examinations.  The results of TRDS-2009D dose calculations have demonstrated for the ETRC members on average a moderate increase in RBM dose estimates (34%) and a minor increase (5%) in estimates of stomach dose.  The calculations for the members of the ETROC indicated similar small changes for stomach, but significant increase in RBM doses (400%).  Individual-dose assessments performed with use of TRDS-2009D have been provided to epidemiologists for exploratory risk analysis in the ETRC and ETROC.  These data provide an opportunity to evaluate the possible impact on radiogenic risk of such factors as confounding exposure (environmental and medical), changes in the Techa River source-term data and the change of the approach to individual internal dose estimation ($^{90}$Sr-body burden measurements and family correlations vs. village averages).  Our further plan is to upgrade the TRDS-2009D and to complete a stochastic version of the dosimetry system.

# 1.    INTRODUCTION

Population exposure in the Urals region occurred as a result of failures in the technological processes in the Mayak plutonium facility in the middle of the 20$^{th}$ century.  A major source of environmental contamination was the discharge of about 10$^{17}$ Bq of liquid wastes into the Techa River in 1949–1956.  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.  There are known to be additional sources of exposure for the Urals population.  The most important was an explosion in the radioactive waste-storage facility in 1957 (the so-called Kyshtym accident) that formed the East Urals Radioactive Trace (EURT) due to dispersion of 7.4 × 10$^{16}$ Bq into the atmosphere.  Other sources of exposure include the gaseous aerosol releases from the Mayak facility in 1949–1957 and windblown contamination from Lake Karachay, when this contaminated lake dried out in 1967.

The series of radioactive releases that occurred in the same region in different years and the intensive migration of the population within the contaminated area are specific features of the Urals situation.  This determined the approach to follow-up:  selecting a fixed cohort and tracing all places of residence for each subject in the cohort since the beginning of radioactive contamination.  The Extended Techa River Cohort (ETRC) includes approximately 30,000 members and represents an unselected population consisting of two distinct ethnic groups.  The members of the ETRC were exposed to chronic radiation over a wide range of doses, but at low-to-moderate-dose rates.

Russian and US scientists have been working together to perform dose reconstruction and epidemiologic follow-up for the ETRC since 1995.  Epidemiologic studies on cancer incidence and mortality (JCCRER Project 1.2b and NCI-URCRM Project) are ongoing; the investigators for these projects work together with those of JCCRER Project 1.1, who are charged to provide credible estimates of individual dose for the ETRC members.

The previous version of the Techa River Dosimetry System, TRDS-2000, was created for reconstruction of individualized doses for members of the ETRC (Degteva et al. 2000a, 2000b, 2006b).  Large amounts of environmental and human data were integrated in this system to provide variables requested for environmental dose assessments.  The TRDS-2000 has been used for several epidemiologic studies of the ETRC (Kossenko et al. 2002; Krestinina et al. 2005, 2006, 2007, 2009; Akleyev et al. 2008).  Cancer mortality and incidence rates in the ETRC have exhibited a statistically significant radiation-dose response.  The estimated excess relative risk (ERR) per unit dose in this cohort  (Table 1) is comparable with those seen in recent multi-country analyses of nuclear workers (Cardis et al. 2005, 2007) and in atomic bomb survivors (Preston et al 2004, 2007).

The TRDS-2000 has also been used for epidemiologic studies of the Techa River Offspring Cohort (TROC), which consists of about 10,500 persons exposed in utero and/or the progeny of exposed parents (the ETRC members).  The TROC has the potential to provide direct data on radiogenic health effects in progeny that resulted from exposure of a general population to chronic low-dose-rate radiation.  Mortality in the TROC was analyzed with use of TRDS-

*Table 1. Excess relative risk (ERR) and 95% confidence interval (CI) estimated with use of TRDS-2000-doses for mortality and incidence studies on the members of the ETRC.*

| ETRC Study | ERR at 1 Gy | |
| --- | --- | --- |
| | Solid cancer | Leukemia |
| Mortality | 0.9 (0.2 – 1.7) | 6.5 (1.8 – 24) |
| Incidence | 1.0 (0.3 – 1.9) | 4.9 (1.6 – 14) |

2000-based assessments of parental gonadal doses and postnatal doses to the offspring (Kossenko et al. 2000).

The combined dosimetric and epidemiologic study of the ETRC is deemed important, as this cohort is one of few that can be studied to examine the question of whether there is a dose-rate-reduction factor in the induction of stochastic effects by radiation. This question represents a central issue in radiation protection of workers and the public. The overall scientific hypothesis to be tested by the combined dosimetric and epidemiologic study of the ETRC is 'Radiation dose delivered at low dose rates is equally as effective (in causing cancer and other stochastic effects) as the same dose delivered at high dose rates.'

In order to provide more accurate and precise estimates of individual dose (and thus more precise estimates of radiation risk) for the members of the ETRC, many improvements to the TRDS-2000 have been undertaken. During the period 2000–2009 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 strontium 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 the TRDS 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 deterministic version of the improved dosimetry system TRDS-2009D was basically completed in April 2009 (Degteva et al. 2008; Degteva et al 2009).

This report describes the first results of the application of the TRDS-2009D system for re-assessment of individual doses for approximately 30,000 persons in the ETRC, and in the Extended Techa River Offspring Cohort (ETROC), which has been increased to a size of more than 20,000 persons.

The purposes of the report are

1. To present the results of individual-dose calculations performed with use of the new TRDS-2009D system for members of the ETRC and the ETROC; and

2. To analyze changes in individual dose estimates obtained with use of the old (TRDS-2000) and the new (TRDS-2009D) systems.

## 2.    BRIEF DESCRIPTION OF THE TECHA RIVER DOSIMETRY SYSTEM-2009

### 2.1.    BASIC EQUATIONS FOR DOSE CALCULATIONS

The method being used for individual-dose calculations can be written as a single equation in three parts.  The absorbed dose to an individual's organ $o$ of individual $i$ accumulated through calendar year $Y$ is

$$D_{o,Y,i} = \sum_{y=y_{min}}^{P \leq Y} \left[ \sum_L M_{y,L,i} \begin{bmatrix} \left[ \left( \sum_r I^*_{y,r,L}(\tau_i) DF_{r,o,Y-y}(\tau_i) \right) + A_o D_{Riv,L,y} \left( T_1(\tau_i) + R_{out/Riv,L} (T_2(\tau_i) + R_{in/out} T_3(\tau_i)) \right) + \\ G_{Sr,L} \delta_y \left\{ \sum_r E_{r,y}(\tau_i) DF_{r,o,Y-y}(\tau_i) + A_o(\tau_i) D_{Sr,y} [(1-T_3) + R_{in/out} T_3(\tau_i)] \right\} \\ + \sum_{e_i} X_{o,i}(e_i, y, \tau_i) \end{bmatrix} \right]$$

Here the upper line in the internal brackets represents the dose from the Techa River, the middle line represents dose from exposure to fallout from the East Urals Radioactive Trace (EURT), and the lower line represents dose from medical x-ray examinations.  (Note that doses from ingestion of iodine from Mayak releases are theoretically included in the TRDS, but the values for such parameters will only be available upon the completion of JCCRER Project 1.4.)  The individual components of the above equation are

$D_{o,Y,i}$ = absorbed dose (Gy) in organ $o$ accumulated through calendar year $Y$ to individual $i$;

$Y$ = the calculation time endpoint for a particular individual (can vary according to the analyst's wishes within the range 1950–2015);

$b_i$ = the year of birth of individual $i$;

$y$ = year of environmental exposure (external irradiation and intake of nuclides). The minimum value of $y$ in the summation is $y_{min}$ = MAX{1950, $b_i$, year of first moving to the Techa River or EURT};

$P$ = the endpoint of external exposure and intake of radionuclides for a particular individual (can vary within the range 1950–$Y$, $P \leq Y$).

$L$ = location (settlement) identifier;

$M_{y,L,i}$ = fraction of year $y$ spent in location $L$ by individual $i$;

$r$ = identifier of ingested radionuclide ($^{89}$Sr, $^{90}$Sr, $^{140}$Ba, $^{95}$Zr, $^{95}$Nb, $^{103}$Ru, $^{106}$Ru, $^{137}$Cs, $^{141}$Ce, $^{144}$Ce or $^{131}$I);

$\tau_i$ = $y - b_i$, the age of individual $i$ in year $y$ (years);

$I^{*}_{y,r,L}$ = intake function (Bq) for year $y$, radionuclide $r$, and location $L$ (function of age $\tau$, related to $y$);

$I^{*} = I \times \xi_i$, where $\xi_i$ is a modifier predetermined for individual $i$ equal to 1.0 (village average), $IMR_i$ (*Individual-to-Model Ratio*), or $HSR_i$ (*Household-Specific-Relationships*), discussed below;

$DF_{r,o,Y-y}$ = conversion factor (Gy Bq$^{-1}$) for dose accumulated in organ $o$ in year $Y$-$y$ from intake of radionuclide $r$ in year $y$ (function of gender and age, related to $y$);

$Y$-$y$ = time since intake, years;

$A_o$ = conversion factor from absorbed dose in air to absorbed dose in organ $o$ (function of age, related to $y$);

$D_{Riv,L,y}$ = absorbed dose in air near river shoreline at location $L$ received in year $y$ (Gy).

$R_{out/Riv,L}$ = ratio of dose rate in air outdoors at homes to the dose rate by the river at location $L$;

$R_{in/out}$ = ratio of dose rate in air indoors to that outdoors;

$T_1$ = time spent on river bank (relative to whole year) (function of age, related to $y$);

$T_2$ = time spent outdoors (relative to whole year) (function of age, related to $y$);

$T_3$ = time spent indoors (relative to whole year) (function of age, related to $y$).

$G_{Sr,L}$ = surface deposition (Bq m$^{-2}$) of $^{90}$Sr at location $L$ from fallout from the EURT;

$\delta_y$ = 0 or 1 depending on $y$. For the EURT, $\delta_y = 0$ for $y < 1957$;

$E_{r,y}$ = intake function (Bq) per unit-surface deposition of $^{90}$Sr from fallout from the EURT for year $y$, radionuclide $r$ (function of age, related to $y$);

$D_{Sr,y}$ = absorbed dose in air (Gy) received in year $y$ per unit-surface deposition of $^{90}$Sr from fallout from the EURT; and

$X_o(e,y,\tau)$ = absorbed dose to organ $o$ (Gy) from medical examination $e$ in year $y$ for age $\tau$.

In order to account for the rapid changes in exposure conditions that occurred during the initial periods of exposure on the Techa River in 1950–1951 and on the EURT in 1957–1958, these periods are subdivided into several time slices, the duration of which is a few months. Values of parameters $I_{y,r,L}$ and $D_{Riv,L,y}$ (intake function and external exposure rate for the Techa River) are different for each time slice within 1950–1951, and values of the parameters $E_{r,y}$ and $D_{Sr,y}$ (intake function and external exposure rate for the EURT) are different for each time slice within 1957–1958. For these years, $M_{y,L}$, the fraction of time spent in location $L$, is calculated with account taken for the dates of the beginning and the ending of each time slice.

The intake function $I_{y,r,L}$ for each year $y$ is calculated as

$$I_{r,L} = I_R^{Sr90} \times \alpha_{Age,R}^{Sr90} \times f_L^{Sr90} \times f_L^{r} \, ,$$

where

$I_R^{Sr90}$ = annual $^{90}$Sr intake for adult residents of the reference settlement (Muslyumovo);

$\alpha_{Age,R}^{Sr90}$ = annual 90Sr intake for other age groups relative to that for adults living in the reference settlement;

$f_L^{Sr90}$ = annual ratio of 90Sr intake for location L to 90Sr intake for residents of the reference settlement; and

$f_L^{r}$ = annual ratio of nuclide-to-90Sr in the intake for location L.

Metlino is a special case because this settlement was the closest to the site of radioactive release and the time pattern of the intake for the residents of Metlino differed from other villages because of early remedial measures. Thus, the parameters $I_R^{Sr90}$ and $\alpha_{Age,R}^{Sr90}$ for Metlino were estimated separately.

## 2.2.    TRDS-2009 AS SYSTEM OF CODES AND SUPPORTING DATABASES

To realize computations of individual doses for tens of thousands of persons in accordance with the basic equation, several computer codes and supporting databases were created. Several steps are required for individual-dose calculations with use of different codes included in the new version of TRDS-2009.

The first phase consists of external and internal dose calculations with use of a common protocol for all cohort members based on village-average-intake functions and external dose rates. The deterministic code, named TRDS-2009D, is used for computations at this stage. To run the code, a user has to select an organ $o$ from a list that includes 23 organs/tissues: red bone marrow, bone surfaces, esophagus, stomach wall, small intestinal wall, upper large intestinal wall, lower large intestinal wall, lungs, uterus, testes, ovaries, breast, liver, kidneys, pancreas, bladder wall, spleen, adrenals, thymus, thyroid, brain, muscle, and skin.

The input data are the individual age, gender, and residence history available for all cohort members. The structure of the TRDS-2009D code is demonstrated in Figs. 1 and 2. As illustrated, the first step is checking and filtering of residence-history data by comparison with the roster of the communities on the Techa River. Then, individualized internal and external doses are calculated on the basis of age and personal residence-history information. Parallel calculations are also carried out for the ETRC and ETROC members who were exposed to EURT radionuclides. Output data include organ doses for each calendar year for each member of the cohorts.

The TRDS-2009D relies on extensive databases in order to compute the doses for each cohort member. These databases were calculated and modeled during the course of research performed in the framework of Project 1.1. A full description of the models and data sets used for the production of the TRDS databases is provided in Degteva et al. (2009). The list of databases used in TRDS-2009D for calculation of doses from the Techa River is longer than the list from TRDS-2000 described in (Degteva et al. 2000a,b; 2006). Separate databases were

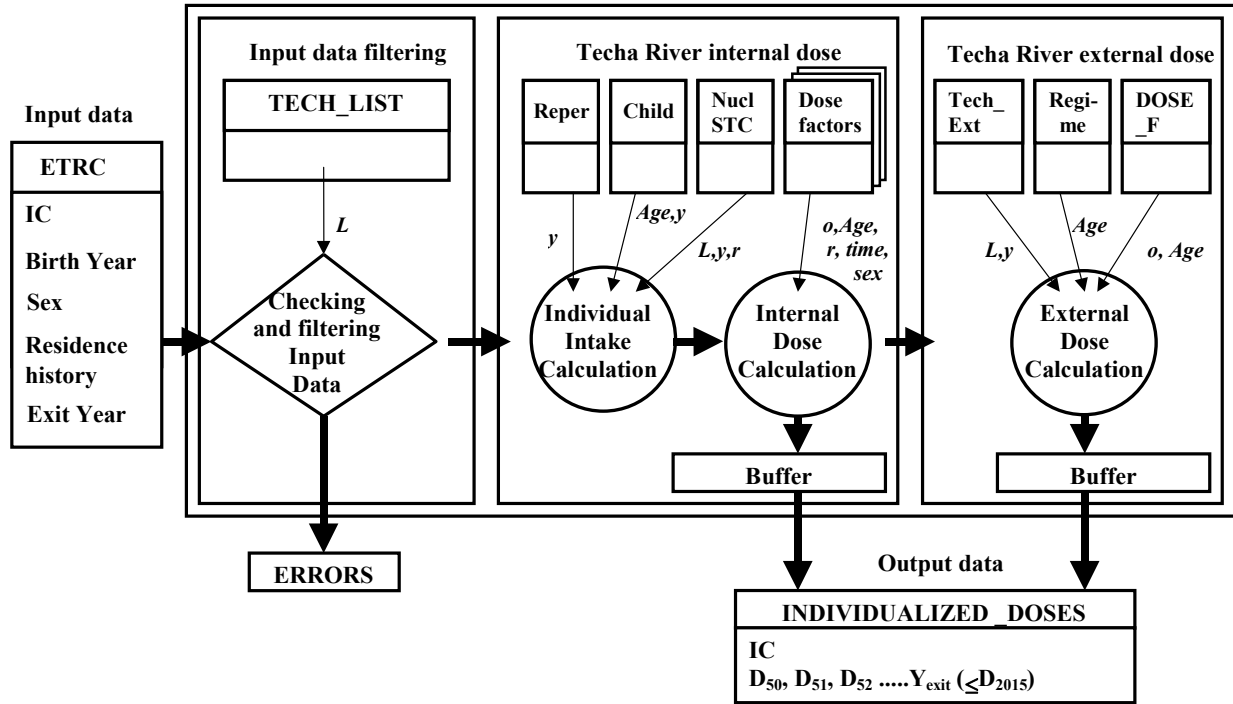## Techa River Dosimetry System: River Dose



*Fig. 1. Schematic diagram of the Techa River Dosimetry System-2009D code for exposures within riverside villages.*
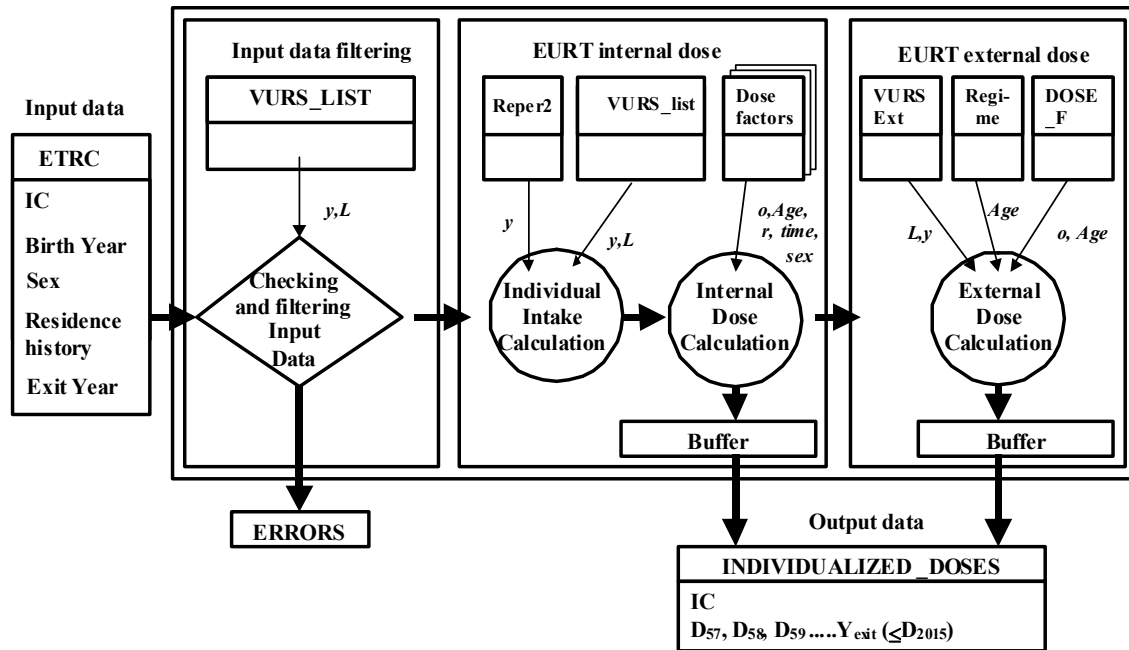
## Techa River Dosimetry System: EURT Dose



*Fig. 2. Schematic diagram of the Techa River Dosimetry System-2009D code for exposures within EURT villages.*

created for the first two years of exposure (1950–1951) in order to take into account rapid changes in the source-term parameters. Also, separate databases were established for Metlino, which is a special case because this settlement was the closest to the site of radioactive release and the time pattern of the intake for the residents of Metlino differed from that in other villages. In addition, special databases were established to give a more precise definition to $^{137}$Cs intake. And also, gender-specific databases were prepared for $^{90}$Sr and $^{137}$Cs internal dose coefficients. Finally, tables of radionuclides and organs considered in the system were extended.

Significant changes compared with TRDS-2000 estimates are incorporated for such internal exposure parameters as the time and age-dependent intake functions of radionuclides and for the external exposure parameters that characterize for each location the time-dependent dose rate in air near the river shoreline and outdoors near homes. Other parameters of external exposure (such as typical life patterns and shielding, as well as conversion factors from dose in air to dose in organs) are of the same type as used in TRDS-2000.

Additional parameters characterizing exposure in the EURT were introduced. These data were described in detail in our reports for Milestones 11–13 (Tolstykh et al. 2006; Vorobiova et al. 2006). Data Directories of $^{90}$Sr-contamination density of Urals settlements were created through an evaluation of existing data on radionuclide contents in food and human tissues that supported development of the necessary input parameters for time- and location-dependent intake rates of radionuclides (Tolstykh et al. 2006). The approach for the reconstruction of internal doses employs conversion factors based on the dose per unit-ground deposition. The approach is based upon measurements of radionuclides in local foodstuffs. For external dose calculations, dose rates in air per unit-deposition density of $^{90}$Sr for the EURT area derived by Vorobiova et al. (2006) are used.

Thus, village-averaged dose estimates that take into account individual-life histories are obtained as a result of the use of TRDS-2009D.

The second phase includes refinement of individual doses of internal exposure for those cohort members who have individual measurements of $^{90}$Sr and/or data on the household where he/she lived (a list of cohabitants; the location of household relative to the contaminated river). This phase includes

- Calculations of internal doses and their uncertainties for persons having individual $^{90}$Sr measurements with use of Individual-to-Model Ratios (*IMR*) and for persons having measured cohabitants from the same household with use of Household-Specific Relationships (*HSR*) (Shagina et al. 2007); and

- Selection of the best estimate of individual internal dose (that with the least uncertainty) in accordance with the algorithm described in Milestone 18 (Shagina et al. 2007);

Two specific computational protocols (*IMR*-based and *HSR*-based) described by Shagina et al. (2007) are used in the second phase in order to reduce the uncertainty in estimates of internal dose. Four computer codes supported by databases containing measurements of $^{90}$Sr-

body burdens for individuals and lists of households with associated cohabitants were developed to perform the calculations of refined individual doses of internal exposure (Table 2).

The third phase includes summation of individual doses from environmental exposure (coming from the second phase) and individual doses from medical exposure calculated separately with use of the special computer code MEDS (Medical Exposure Dosimetry System) described in Milestone 19 (Degteva et al. 2007). Input data for MEDS include individual histories of medical exposure coming from the "X-Ray Diagnostic Procedures" Registry (Vorobiova et al. 2003). Thus, individual doses due to x-ray diagnostic exposure can be calculated for any person examined in the URCRM clinics. The results of individual medical dose calculation for the members of the Extended Techa River Cohort (ETRC) and the Techa River Offspring Cohort (TROC) have been described in Degteva et al. (2007). These results will be considered as a possible confounding factor in future risk analysis for these cohorts.

*Table 2. The list of codes used for calculations of individual dose within the Techa River Dosimetry System-2009D.*

| Code name | Output data | Current status of the code |
|---|---|---|
| TRDS-2009D | Deterministic estimates of individual doses derived from residence histories on the Techa River and the EURT area based on village-average parameters | Done, but should be extended to treat EURT evacuees |
| IMR-calculation | Registry of Individual-to-Model Ratios (IMR) and their uncertainties for those who have measurements of 90Sr-body burden | Done |
| IMR-house | Registry of persons with IMR associated according to their households | Done |
| HSR-calculation | Registry of Household Specific Relations (HSR) and their uncertainties for those associated in a household with measured cohabitants | Done |
| Selection | Registry of dose-individualized coefficients and their uncertainties for internal exposure | Done |
| MEDS | Registry of individual medical doses for those exposed in the URCRM clinic | Done |
| External-house | Registry of household-based deterministic estimates of individual external doses | In preparation, completion after FY2009 |
| TRDS-2009MC | Stochastic (Monte Carlo) estimates of individual total doses | In preparation, completion after FY2009 |

The fourth phase, yet to be completed, is derivation of stochastic estimates of individual doses. The TRDS calculation of uncertainty will be based on a Monte Carlo approach to implement calculation of the basic dose equation. Preliminary assignment of uncertainty types and the planned approach to uncertainty propagation were described by Napier et al. (2008).

As can be seen from Table 2, six codes from the planned eight have been completed. These six codes allow computation of individual external doses based on residence history and of refined internal doses for members of the ETRC and TROC; included are doses from environmental exposure on the Techa River and the EURT, as well as individual doses of medical exposure in the URCRM clinics.

## 3. RESULTS OF INDIVIDUAL DOSE COMPUTATION WITH THE USE OF TRDS-2009D

### 3.1. INDIVIDUAL DOSE DISTRIBUTIONS FOR MEMBERS OF THE ETRC

Input data on residence histories and vital status for the ETRC members (29,743 persons) were extracted from the URCRM database on August 3, 2009. Individual doses were calculated for the ETRC members with the use of program system TRDS-2009D (TRDS-2000 code was also used for comparison of old and new estimates).

*The first phase* of dose computation with use of TRDS-2009D is deterministic estimates of doses for all cohort members who resided on the Techa River and for those persons who lived on the East Urals Radioactive Trace (EURT). These first phase estimates are based on village-average-intake functions and external dose rates with consideration of an individual's residence history, age, gender and the date of vital status or migration from the catchment area (the area of epidemiologic follow up). The results of red bone marrow (RBM) and stomach dose estimates in comparison with TRDS-2000 computations are shown in Figs. 3 and 4.

As can be seen, there is strong correlation between the new and the old estimates of individual dose. This correlation is explained by impact on dose accumulation of individual data on residence history on the contaminated Techa River, age and end point of dose accumulation. Nevertheless, on average the new RBM doses are 26% higher and new stomach doses are only 2% higher than those based on TRDS-2000.

The differences can be explained by giving an example of dose estimates due to major exposure pathways for permanent residents of the Techa Riverside communities located at different distances from the site of radioactive release (Figs. 5 – 8). The same age is assumed for all persons. Each person lived in one and the same settlement during the maximal possible period of exposure: from 1949 up to the last evacuation date for evacuated settlements and up to 2005 for settlements still in existence. The end point of dose accumulation is year 2005.

As can be seen from Fig. 5, RBM dose estimates due to $^{90}$Sr intake are similar for TRDS-2000 and TRDS-2009D. Both kinds of estimates are based on $^{90}$Sr measurements in human teeth and body averaged for each settlement. Significant variations from settlement to settlement are explained mainly by different conditions of drinking-water supply (Techa River, wells or both

*Fig. 3. Correlation of RBM-individual doses for the ETRC members (29,743 persons) calculated with use of TRDS-2009D in comparison with those calculated with TRDS-2000 on the basis of residence-history data.*
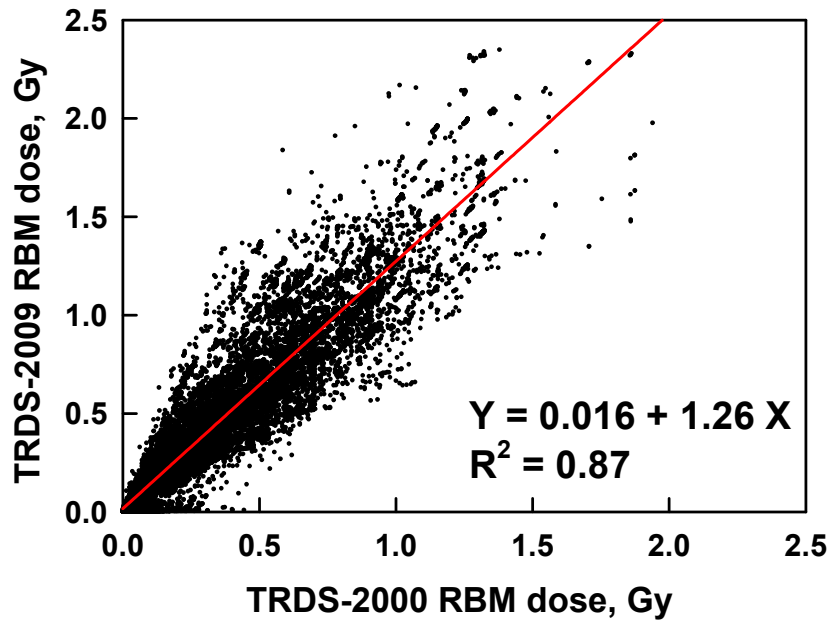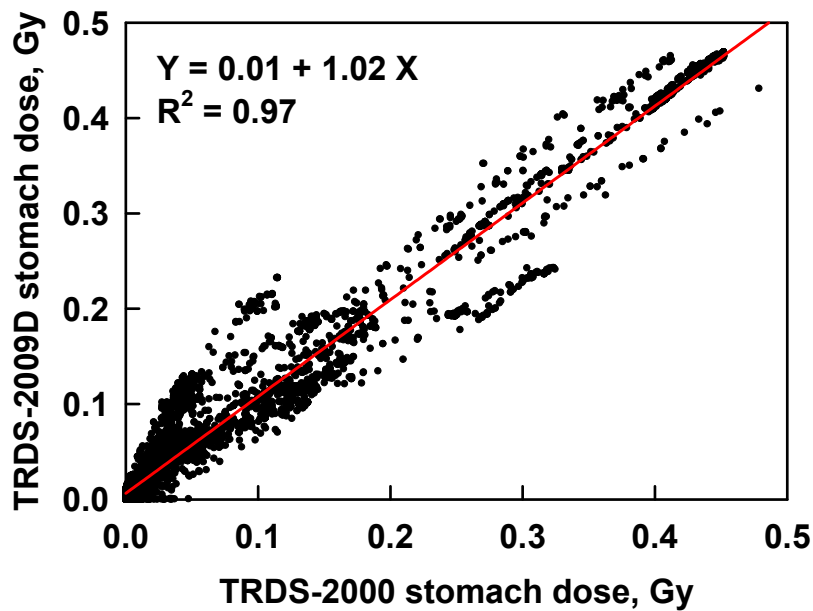


*Fig. 4. Correlation of stomach individual doses for the ETRC members (29,743 persons) calculated with use of TRDS-2009D in comparison with those calculated with TRDS-2000 on the basis of residence-history data.*

*Fig. 5. Internal dose from $^{90}$Sr intake for permanent residents of the Techa Riverside communities located at different distances from the site of radioactive release.*
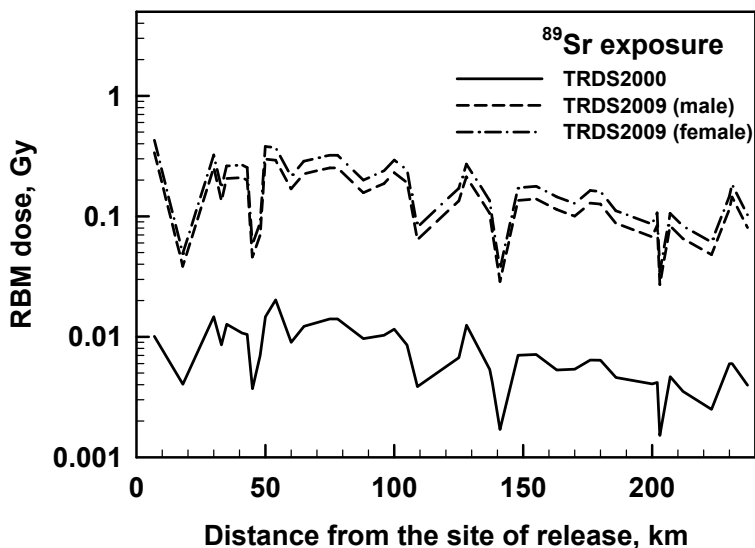


*Fig. 6. Internal dose from $^{89}$Sr intake for permanent residents of the Techa Riverside communities located at different distances from the site of radioactive release.*

sources). The levels have a tendency to decrease with distance from the release site, which is explained by lowering of $^{90}$Sr concentration in the river water (mainly due to dilution).

The new system includes gender-dependent differences in $^{89,90}$Sr metabolism, which is not considered in TRDS-2000 (Figs. 5 and 6). As can be seen from Fig. 6, new estimates of dose from $^{89}$Sr exposure are significantly higher in comparison with those derived with use of TRDS-
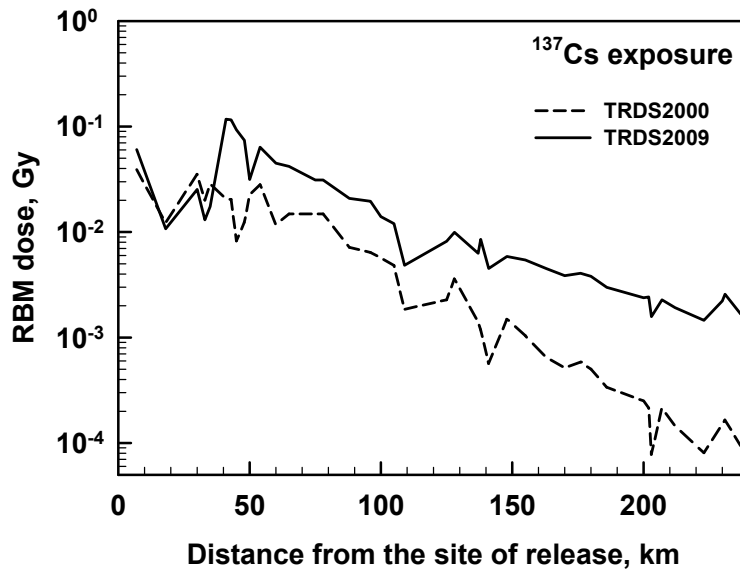
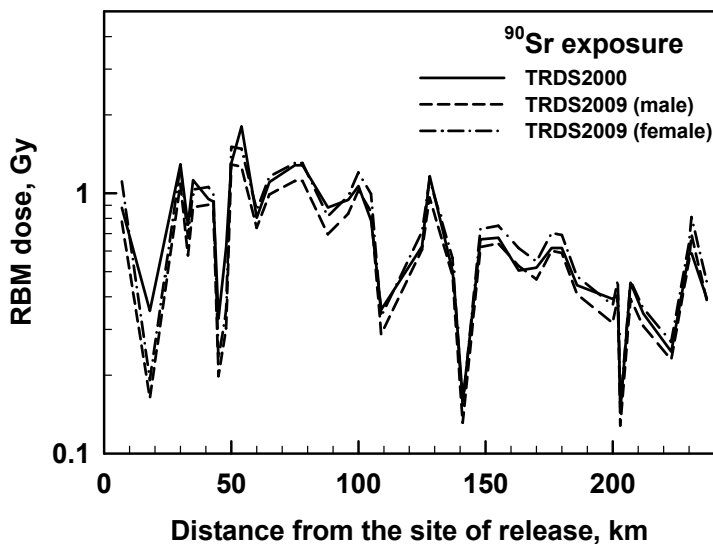*Fig. 7. Internal dose from $^{137}Cs$ intake for permanent residents of the Techa Riverside communities located at different distances from the site of radioactive release.*



*Fig. 8. External dose from contaminated river shore and flood lands for permanent residents of the Techa Riverside communities located at different distances from the site of radioactive release.*

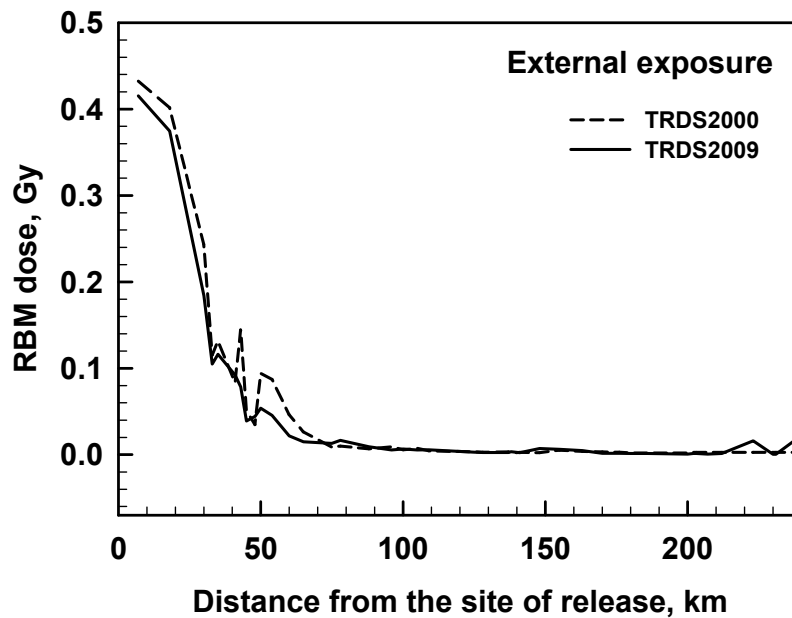2000. This is due to a higher $^{89}Sr$-to-$^{90}Sr$ ratio in the Mayak releases and in the river water, correspondingly. Because strontium intake occurred predominantly with river water, this figure

illustrates the impact on dose estimates of the changes in source-term evaluation (Degteva et al 2008b).

In addition to the 'water pathway,' a significant contribution to $^{137}$Cs intake and $^{137}$Cs-doses (Fig. 7) was made by the 'milk pathway.' Ingestion of milk from cows drinking river water and/or pastured on meadows contaminated in 1951 as a result of an extraordinary flood was first accounted for in TRDS-2009D. The contribution of the 'milk pathway' depends on the level of soil contamination, the area of flood-lands and the reliance on such pasture in different settlements along the river. As can be seen from Fig. 7, the 'milk pathway' was not significant for the first 40 km from the release site, because the riverbed here was vastly waterlogged and was not used for pasture and haymaking. In all settlements located downstream of this river segment the 'milk pathway' played a significant role, and new estimates of internal doses from $^{137}$Cs are systematically higher than in the TRDS-2000 assessments. The decrease of $^{137}$Cs doses with distance along the river is more marked than for strontium. Cesium-137 was intensively absorbed by bottom sediments and flooded soils, and its concentration in the river water sharply decreased with distance.

Accumulation of gamma-emitting radionuclides in the bottom sediments and flooded soils resulted in external exposure of the riverside residents (Fig. 8). As can be seen from Fig. 8, external doses sharply decreased with distance from the release site, and there is no significant difference between TRDS-2000 and TRDS-2009D estimates.

In addition to exposure on the Techa River, TRDS-2009D includes doses of confounding exposure due to residence on the EURT area contaminated in 1957; 4,695 members of the ETRC (16% of the entire cohort) were exposed on the EURT. Nevertheless, additions to individual RBM doses for these persons were low: 5.5 mGy on average and 44 mGy at most.

It should be noted that the Techa Riverside residents who lived in the more contaminated EURT settlements were purposely excluded while the ETRC was being established. Thus, we did not expect a strong impact of this exposure source on this cohort. At the same time the EURT is considered as an important source for dose estimation in the offspring of the Techa Riverside residents (see below).

Combined external and internal exposure of the ETRC resulted in an extremely uneven dose distribution throughout human bodies (Table 3). As can be seen, significant intakes of beta-emitting $^{89,90}$Sr resulted in larger exposures of intestines (especially the large intestine) and skeletal tissues (RBM and BS).

*The second phase* of dose computation with use of the TRDS-2009D includes refinement of individual internal dose based upon a person's or a co-inhabitant's measurement of $^{90}$Sr-body burden. Internal doses have been verified for 7,903 members of the ETRC (27% of the entire cohort) in accordance with Individual-to-Model Ratios (*IMR*) and Household-Specific Relationships (*HSR*). The resulting changes in individual dose distributions for the ETRC are shown in Tables 4 – 8. As can be seen from Tables 4, 7 and 8, the maximum individual doses for the tissues significantly impacted by $^{89}$Sr and $^{90}$Sr became much higher after implementation of the second phase of the computation schedule. It should be noted that there are only a few

*Table 3. Statistical characteristics of TRDS-2009D individual-dose distributions in different organs for the ETRC members (29,743 persons) calculated on the basis of residence-history data (the first phase of computation schedule).*

| Organ/tissue | Absorbed dose, mGy | | |
|---|---|---|---|
| | Median | Mean | Maximum |
| Red bone marrow (RBM) | 264 | 379 | 2,349 |
| Bone surfaces (BS) | 387 | 708 | 5,996 |
| Low large intestine walls (LLI) | 336 | 557 | 4,298 |
| Stomach | 10 | 35 | 469 |
| Lungs | 9 | 34 | 502 |

*Table 4. Statistical characteristics of individual-dose distributions in RBM for the ETRC members (29,743 persons) calculated in accordance with three phases of TRDS-2009D.*

| Phase of dose computation | Absorbed dose, Gy | | |
|---|---|---|---|
| | Median | Mean | Maximum |
| First | 0.264 | 0.379 | 2.35 |
| Second | 0.270 | 0.427 | 9.01 |
| Third | 0.274 | 0.433 | 9.03 |

*Table 5. Statistical characteristics of individual-dose distributions in stomach for the ETRC members (29,743 persons) calculated in accordance with three phases of TRDS-2009D.*

| Phase of dose computation | Absorbed dose, Gy | | |
|---|---|---|---|
| | Median | Mean | Maximum |
| First | 0.010 | 0.035 | 0.469 |
| Second | 0.011 | 0.036 | 0.964 |
| Third | 0.012 | 0.043 | 0.964 |

*Table 6. Statistical characteristics of individual-dose distributions in lungs for the ETRC members (29,743 persons) calculated in accordance with three phases of TRDS-2009D.*

| Phase of dose computation | Absorbed dose, Gy | | |
|---|---|---|---|
| | Median | Mean | Maximum |
| First | 0.009 | 0.034 | 0.502 |
| Second | 0.009 | 0.036 | 0.893 |
| Third | 0.011 | 0.042 | 0.893 |

*Table 7. Statistical characteristics of individual-dose distributions in LLI for the ETRC members (29,743 persons) calculated in accordance with three phases of TRDS-2009D.*

| Phase of dose computation | Absorbed dose, Gy | | |
|---|---|---|---|
| | Median | Mean | Maximum |
| First | 0.336 | 0.557 | 4.30 |
| Second | 0.340 | 0.633 | 13.7 |
| Third | 0.345 | 0.635 | 13.7 |

*Table 8. Statistical characteristics of individual-dose distributions in BS for the ETRC members (29,743 persons) calculated in accordance with three phases of TRDS-2009D.*

| Phase of dose computation | Absorbed dose, Gy | | |
|---|---|---|---|
| | Median | Mean | Maximum |
| First | 0.388 | 0.709 | 6.0 |
| Second | 0.409 | 0.793 | 22.2 |
| Third | 0.417 | 0.802 | 22.2 |

cohort members with such high levels (32 persons with $D_{RBM}$ >4 Gy, 31 persons with $D_{LLI}$ >7 Gy, and 27 persons with $D_{BS}$ > 9Gy); nevertheless, *IMR*s for these persons were derived from reliable measurements of $^{90}$Sr-body burden.

*The third phase* of dose computation with use of the TRDS-2009D combines environmental exposures with confounding medical exposures obtained by the ETRC members as a result of a special diagnostic procedures in the URCRM clinics. Six thousand four hundred and fourteen (6,414) members of the ETRC (22% of the entire cohort) were additionally exposed to x rays for diagnostic purposes. Additions to individual doses in different organs of these persons were 30–35 mGy on average and 650–750 mGy at the most. Thus, this source of confounding exposure can have an impact on risk factors. The results of the third phase are also shown in Tables 4 – 8.

As seen from Tables 4, 7 and 8, the third phase of the computation schedule has resulted mainly in some increase of the cohort mean and median values.

Comparisons of distributions of individual doses for the ETRC members (29,743 persons) calculated in accordance with TRDS-2000 and TRDS-2009D (after the third phase) are shown in Figs 8 – 10.

As can be seen, individual-dose distributions have increased for all organs. The changes in individual-dose estimates on average fall into a range between 5% (for stomach) and 34% (for the RBM).

*Fig. 8. Distributions of individual-RBM doses for the ETRC members (29,743 persons) calculated in accordance with TRDS-2000 and TRDS-2009D (third phase).*

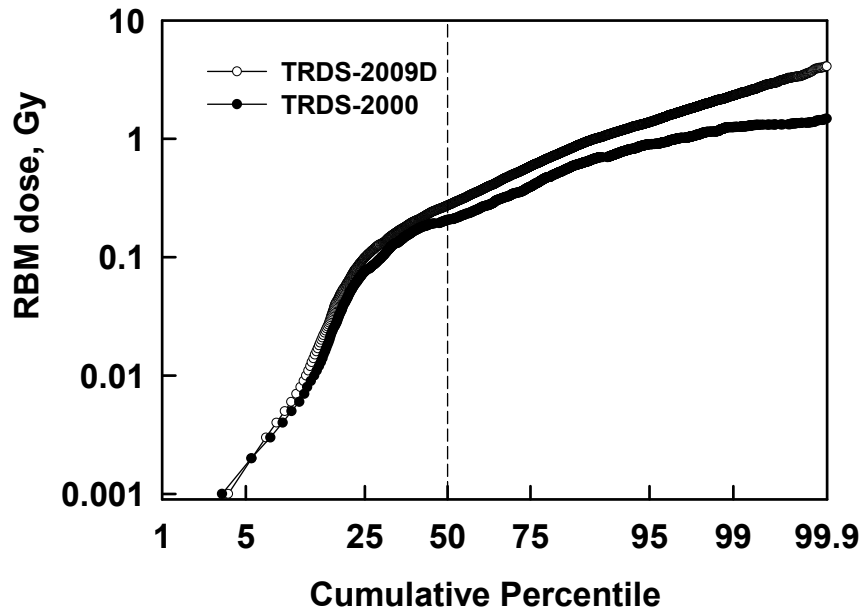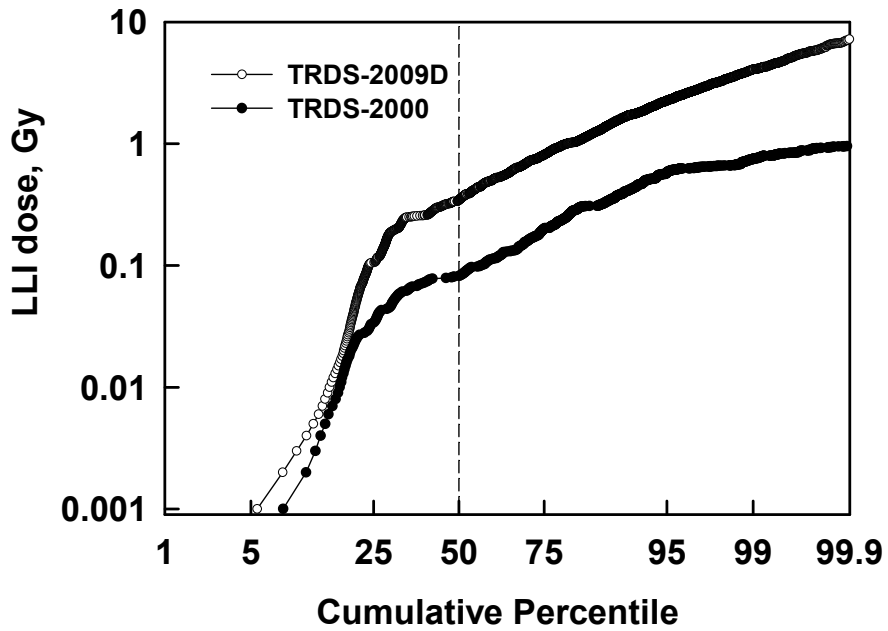

*Fig. 9. Distributions of individual-LLI doses for the ETRC members (29,743 persons) calculated in accordance with TRDS-2000 and TRDS-2009D (third phase).*
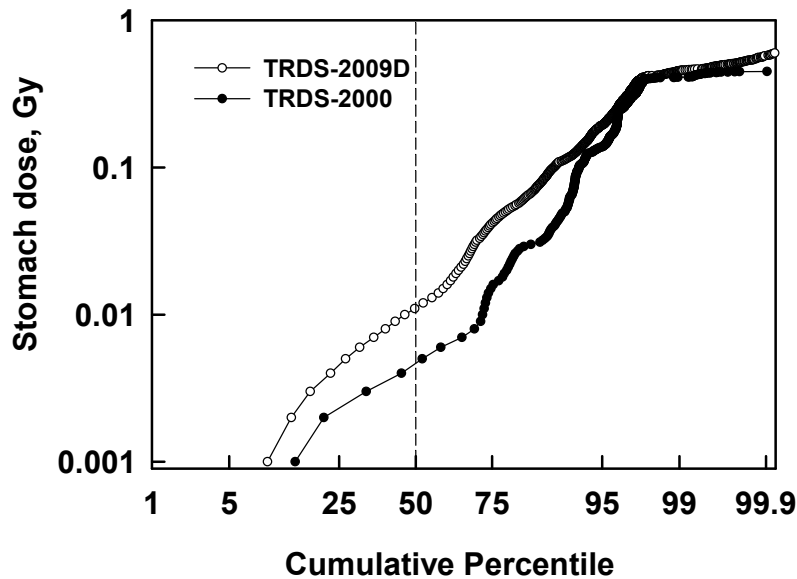
*Fig. 10. Distributions of individual-stomach doses for the ETRC members (29,743 persons) calculated in accordance with TRDS-2000 and TRDS-2009D (third phase).*

3.2.    INDIVIDUAL-DOSE DISTRIBUTIONS FOR MEMBERS OF THE ETROC

Input data on residence histories and vital status for the ETROC members (24,243 persons) were extracted from the URCRM database on September 3, 2009.  Individual doses of postnatal exposure were calculated for the ETROC members with the use of TRDS-2009D and TRDS-2000 (for comparison of old and new estimates).  Records of input data for 954 members of the ETROC had mistakes and were excluded from calculations.  As a result, individual doses have been calculated for the remaining 23,289 ETROC members.

*The first phase.*  The estimates of RBM and stomach doses on the basis of individual-residence-history data in comparison with TRDS-2000 computations are shown in Figs. 11 and 12.  As can be seen, there is strong correlation between old and new estimates of individual doses.  This correlation is explained by impact on dose accumulation of individual data on residence history on the contaminated Techa River, age and end point of dose accumulation.  Nevertheless, on average the new RBM doses are four times higher and new stomach doses are only 5% higher than TRDS-2000-based estimates.  The large difference in the new and old RBM dose estimates are the result of several factors acting together.

The first factor is a higher $^{89}$Sr-to-$^{90}$Sr ratio in the Mayak releases and in the river water and milk correspondingly (the same as for the ETRC).  The second is the inclusion into the new dosimetry system of an additional pathway, which is intake of $^{90}$Sr and $^{89}$Sr with breast milk.  This pathway is not significant for the ETRC members (born before the onset of the river contamination), but is a very important contributor to cumulative dose for the ETROC members
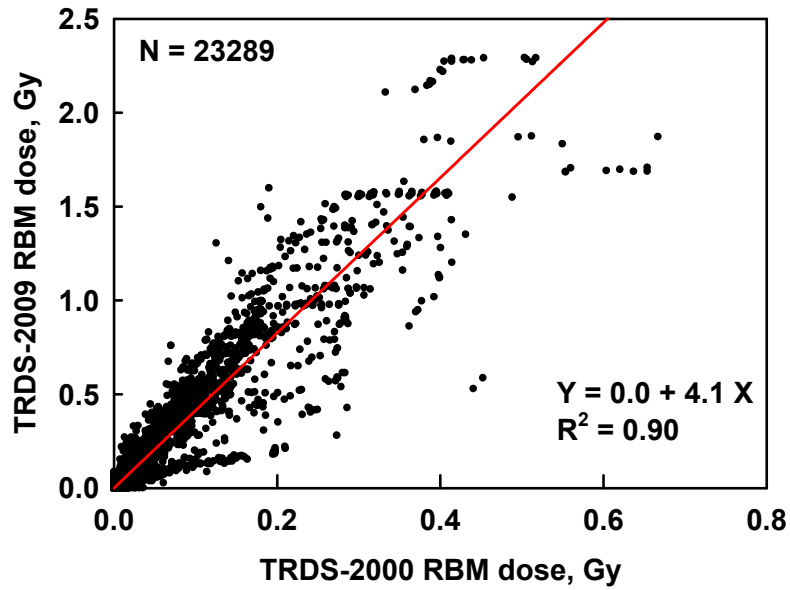
*Fig. 11. Correlation of RBM-individual doses for the ETROC members (23,289 persons) calculated with use of TRDS-2000 and TRDS-2009D on the basis of residence-history data.*
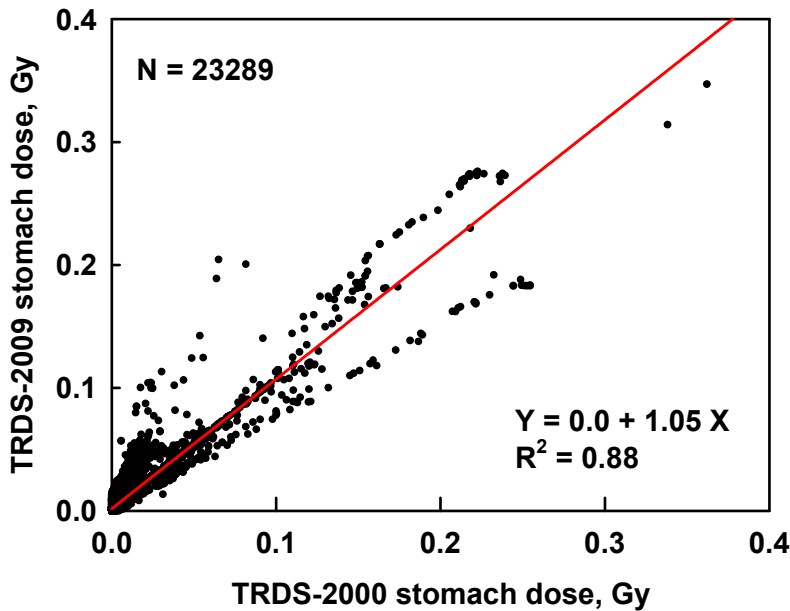


*Fig. 12. Correlation of stomach-individual doses for the ETROC members (23,289 persons) calculated with use of TRDS-2000 and TRDS-2009D on the basis of residence-history data.*

born during the period of the highest river and flood-plain contamination. The third factor is the age dependence of dose-per-unit intake for ^{89}Sr, which has a strong maximum in the first year of human life. Thus, the third factor reinforces the impact the first two on the total dose. The fourth factor is confounding ^{90}Sr intake as a result of living in the EURT area: Twenty-one percent (4,982 members) of the ETROC were exposed in the EURT area. Additions to individual-RBM doses for these persons were 6.8 mGy on average and 88 mGy at the most.

Statistical characteristics of individual-dose distributions for the ETROC members are shown in Table 9. As can be seen, maximum values of exposure reached about 0.35 Gy for soft tissues and about 2.3–2.5 Gy for RBM and LLI. The low levels of the mean and median are explained by a significant number of persons with zero postnatal doses (they are included in the ETROC due to in utero exposure and/or parental preconception exposure).

*The second phase* of dose computation with use of the TRDS-2009D is not applied to the ETROC for the following reason. All ETROC members measured with the WBC have very low levels of ^{90}Sr-body burden (lower than the reliable detection level). This is due to rapid elimination of strontium during the first years of human life. Thus, there are no persons with estimated *IMR*s in this cohort. As for *HSR*, this parameter reflects mainly the source of drinking water (river or well) in a particular household before the use of the Techa River was prohibited in 1951–1953. Many of the ETROC members were born after the prohibition. Also, the major pathway of radionuclide intake for the ETROC members was milk. Thus, the household-specific relationships derived from WBC measurements for the ETRC members born before 1950 are not applicable for children born in 1950 and later.

*The third phase* of dose computation with use of the TRDS-2009D combines environmental exposures with confounding medical exposures. Eight percent (1,809 members) of the ETROC were additionally exposed to x rays for diagnostic purposes. Additions to individual doses in different organs of these persons were 4.5–9.5 mGy on average and 160–300 mGy at most. The results of the third phase of dose computation for the members of the ETROC are shown in Table 10.

*Table 9. Statistical characteristics of TRDS-2009D individual-dose distributions in different organs for the ETROC members (23,289 persons) calculated on the basis of residence-history data (the first phase of the computation schedule).*

| Organ/tissue | Number of persons with zero doses | Absorbed dose, mGy | | |
| --- | --- | --- | --- | --- |
| | | Median | Mean | Maximum |
| Red bone marrow (RBM) | 7,114 | 3.0 | 51 | 2,294 |
| Lower large intestinal wall (LLI) | 7,114 | 0.9 | 32 | 2,462 |
| Stomach | 9,361 | 0.3 | 4.4 | 347 |

*Table 10. Statistical characteristics of TRDS-2009D individual-dose distributions in different organs for the ETROC members (23,289 persons) calculated according to the third phase of the computation schedule (environmental and medical exposure).*

| Organ/tissue | Absorbed dose, mGy | | |
|---|---|---|---|
| | Median | Mean | Maximum |
| Red bone marrow (RBM) | 3.1 | 51 | 2,309 |
| Lower large intestinal wall (LLI) | 1.0 | 32 | 2,491 |
| Stomach | 0.3 | 5.2 | 385 |

Comparison of data from Tables 9 and 10 shows that the inclusion of medical exposure of 8% of the cohort does not significantly change the statistical characteristics of the entire ETROC.

Comparison of distributions of individual doses for the ETROC members with non-zero TRDS-2009D postnatal doses (16,339 persons) after the third phase is shown in Figs 13 – 14. As can be seen, according to TRDS-2009D estimates about half of the members of this subcohort have RBM doses more than 10 mGy, while according to TRDS-2000 only a fourth falls into the dose group >10 mGy (Fig. 13). The RBM-dose distributions for TRDS-2000 and TRDS-2009D are basically parallel in the entire range of doses. Also, a group with RBM doses >1 Gy appears in TRDS-2009D, which was absent in TRDS-2000. As for stomach doses, significant changes occurred mostly in the low dose range while for values more than 100 mGy both curves coincide (Fig. 14).
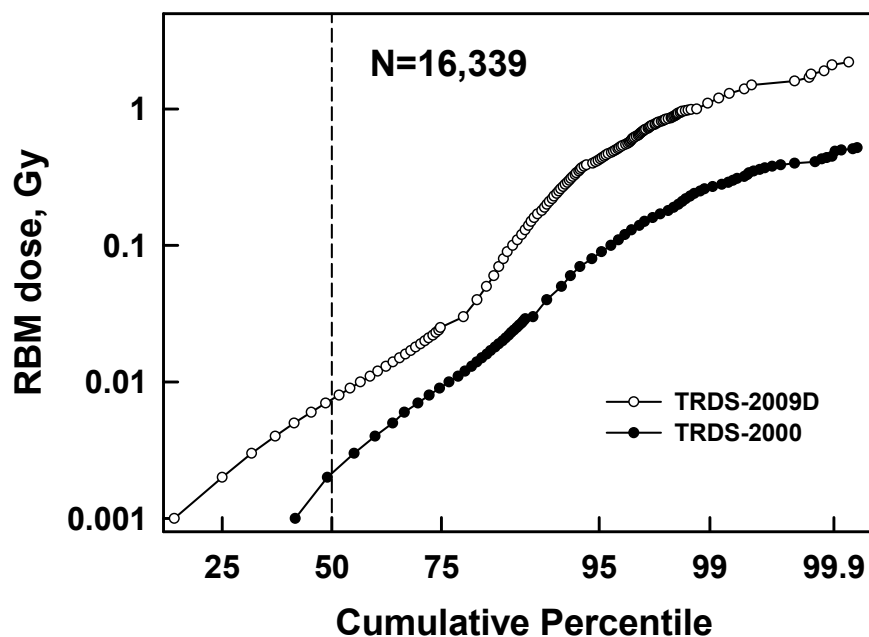


*Fig. 13. Distributions of individual-RBM doses calculated in accordance with TRDS-2000 and TRDS-2009D (third phase) for the ETROC members with non-zero levels of postnatal exposure.*
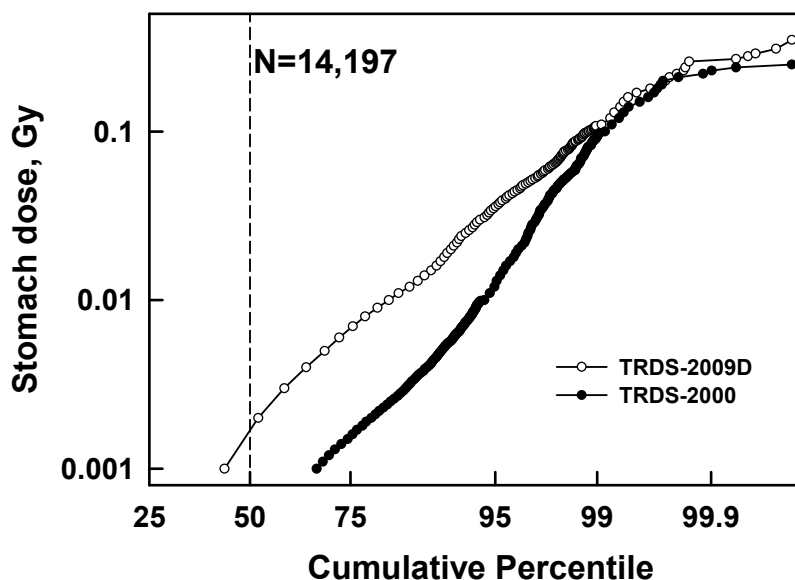
*Fig. 14. Distributions of individual-stomach doses calculated in accordance with TRDS-2000 and TRDS-2009D (third phase) for the ETROC members with non-zero levels of postnatal exposure.*

## 4. DISCUSSION

### 4.1. ANALYSIS OF CHANGES IN INDIVIDUAL-DOSE ESTIMATES

The results of TRDS-2009D dose calculations presented above have demonstrated for the ETRC members a moderate increase in RBM dose estimates (34%) and a minor increase (5%) in estimates of stomach dose. Consideration of the impact of different dose-forming factors (see Figs. 5 – 8 above) reveals that exposure levels due to $^{90}$Sr and external doses practically have not changed for the permanent residents (referent persons). Small changes in $^{90}$Sr-doses in the ETRC are due to verification of intake levels and an improved biokinetic model. Nevertheless, as can be seen from Fig. 3 above, differences in individual doses calculated with use of the TRDS-2000 and TRDS-2009D on the basis of the same residence-history data can be significant for some persons. This is explained by changes in time patterns of $^{90}$Sr intake (Fig. 15) and external dose rate near the river shoreline in 1950–1951 (Fig. 16).

As can be seen from Fig. 15, the new intake function moved to the right as a result of verification of the starting date of the beginning of massive releases into the Techa River (September 1950 versus March 1950). This resulted in significant changes in internal doses for those who lived in the Techa settlements in 1950–1953 and then moved away from the Techa. However, the total intake of $^{90}$Sr for 1950–1980 changed little:  3200 kBq in TRDS-2009D versus 3300 kBq in TRDS-2000.
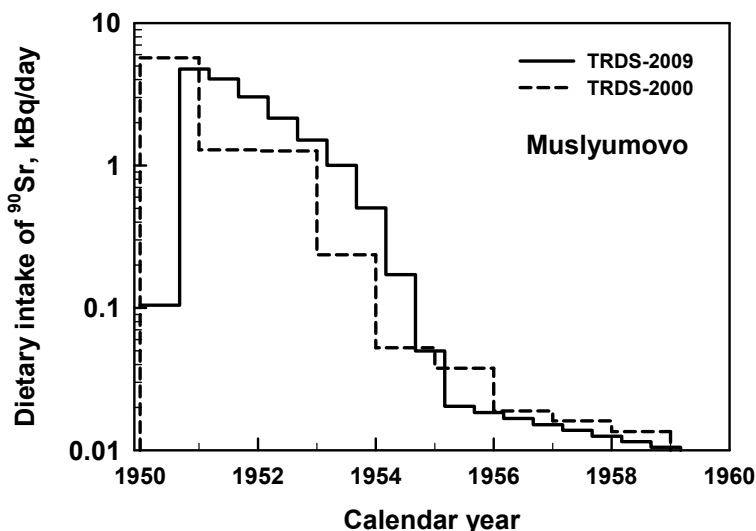
*Fig. 15. Comparison of referent $^{90}$Sr-intake functions for adult residents used in TRDS-2000 and TRDS-2009D for calculations of internal dose.*
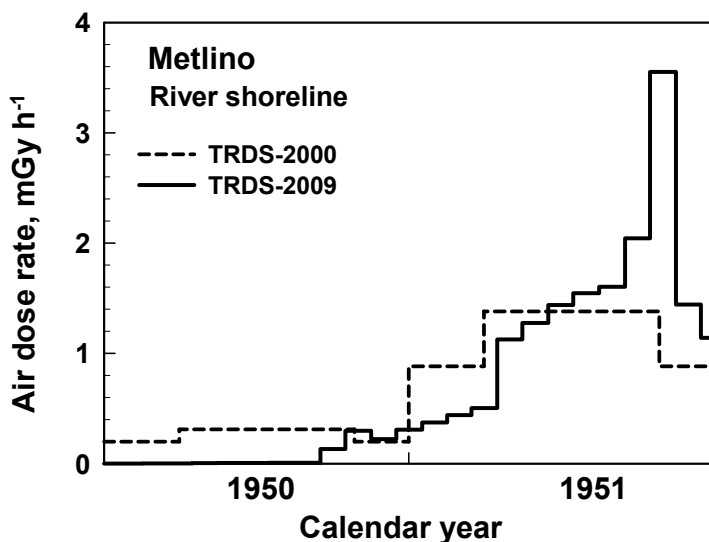


*Fig. 16. Comparison of external dose rate near the river shoreline in Metlino in 1950–1951 used in TRDS-2000 and TRDS-2009D for calculations of external dose.*

The changes in external doses are due to verification of 1950–1951 dose rates near the river shore (Fig. 16) and within residence areas.

As can be seen from Fig. 16, the new curve for dose rates in air also has moved to the right and now has a significant peak corresponding to Autumn 1951. This curve reflects mainly accumulation of gamma-emitting radionuclides in the river-bottom sediments. An absence of significant impact of source-term changes on the total levels of external dose is not so evident,

but can be explained by the opposite action of two factors.  According to the revised source-term estimate, the amount of $^{137}$Cs released into the Techa River became smaller, which decreases the sorption levels of this radionuclide in bottom sediments and exposure rates correspondingly.  The contribution of short- and medium-lived gamma-emitters in the release became higher, but these radionuclides could not reach high concentrations in the bottom sediments due to their decay.  Validation of estimates of external dose requires additional work, and also, we are planning to develop a new river model and to re-estimate radionuclide concentrations in river water, bottom sediments and flood-plain soils.  These tasks are included in our proposal for 2010–2012.

The calculations for the members of the ETROC indicate similar small changes for stomach, while the increase in RBM doses for this cohort is significant (400%).  As discussed in Section 4.2, this is explained by unilateral impact of several factors:  higher $^{89}$Sr-to-$^{90}$Sr ratio in the river water and milk; inclusion of breast milk as an additional pathway; age dependency of dose-per-unit intake for $^{89}$Sr and confounding $^{90}$Sr intake from the EURT.

Thus, a major factor causing an increase in RBM, BS and LLI doses for both cohorts is the significant increase of $^{89}$Sr intake due to changes in the source-term estimates.  As shown in Tables 4, 7 and 8, this resulted in very high levels of maximal doses for some members of the ETRC.  This is not of great concern for RBM and BS, because the doses in bone tissues accumulated during a long time.  Nevertheless, LLI doses were mostly accumulated during the first few years, and possible biological effects of such exposures should be considered separately.

It should be noted that the only evidence that cancer of the rectum can be induced by radiation comes from the study of cervical cancer patients exposed to 30–60 Gy.  It is possible that gross tissue damage is a necessary precursor to the initiation of rectal cancer, as appears to be the case for bone tumors (Gössner 2003).  On the other hand, verification of target-cell location in the large intestine performed in a new ICRP human alimentary tract model (HATM) results in one order of magnitude decrease of dose coefficients for strontium radionuclides (ICRP 2006).  Thus, in the nearest future it will be necessary to re-estimate colon doses for the ETRC with the use of HATM.

### 4.2.   QUALITY-ASSURANCE ISSUES

Much of the work accomplished as the main part of this project is of the nature of quality control/quality assurance.  As described above, the 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.  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, model calculations were used.  Therefore, the reliability of dose estimates mainly depends on the completeness and quality of the basic primary data and reliability of models that describe radionuclide behavior in the environment and humans.

### 4.2.1.  Quality assurance of internal doses

The reconstruction of internal dose relies strongly on the results of measurements of $^{90}$Sr in residents of the Urals region.  These data include 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 *in vivo* measurements of $^{90}$Sr-body burden by means of a unique URCRM whole body counter (WBC) for 20,500 persons (1974–1997).

The situation for this dose-reconstruction effort is highly unusual in that a third of the individuals making up the ETRC have been counted at least once in WBC; thus, the body burdens of the most significant (in terms of dose) radionuclide $^{90}$Sr have been measured directly. The data set on *in vivo* $^{90}$Sr measurements is critical to the success of efforts to provide individual doses and their uncertainties.  In order to provide an accurate evaluation of uncertainty in the internal dose assessments, the detection limits of the WBC method, as well as the uncertainties of routine measurements, have been re-evaluated with the use of Bayes' rule to derive detection limits by analysis of a posteriori data (Kozheurov et al 2002).  In order to check an absence of systematic shift between *in vivo* and *post mortem* estimates of $^{90}$Sr in the skeleton, available pair measurements (performed by the two methods for the same persons) were compared (Fig. 17).

As can be seen from Fig. 17, *in vivo* and *post mortem* estimates of $^{90}$Sr in the skeleton correlate very well ($R = 0.94$, $p < 0.001$) in a wide range of values 1–100 kBq).  The slope ratio is close to unity ($1.17 \pm 0.13$) that confirms an absence of bias.
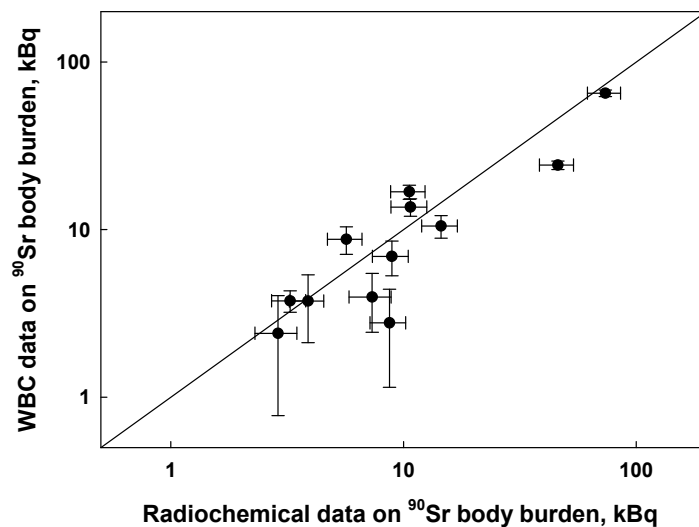


*Fig. 17.  Comparison of individual $^{90}$Sr-body burdens evaluated with use of in vivo (WBC) and post mortem (radiochemical analyses of bone samples) for the same persons.*

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 with use of data on *in vivo* $^{90}$Sr measurements in teeth 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 (Zalyapin et al. 2004). 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, were evaluated on the basis of data on the daily composition of diet (Tolstykh et al. 2006). 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 the intake functions.

An improved age- and gender-dependent biokinetic model for strontium has been developed (Shagina et al. 2003). The new model was verified using numerous data on calcium and strontium content in humans of different age and gender (Shagina et al. 2003). Fig. 18 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. Fig. 19 demonstrates that model predictions, corresponding to intake levels in Metlino, satisfactorily describe $^{90}$Sr-body burdens measured *in vivo* and *post mortem* in adult residents for the period from one to 47 years after the beginning of intake.

The consistency between the model calculations and the results of actual measurements in humans assures the reliability of this model used in TRDS-2009D for the calculation of internal doses due to $^{90}$Sr. Very few human data are available for validation of dose for non-$^{90}$Sr radionuclides. We consider now a possibility to use the data on gross beta activity of excreta measured for Metlino residents since July 1951. This task will be completed during the next stage of our project.

### 4.2.2. Validation of external doses

Validation of external doses calculated with use of the 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. The application of these methods for the Techa River situation required additional work on improvement of methods performed recently in collaboration with European colleagues (Ivanov et al 2005; Fattibene et al 2006; 2007; Wieser et al 2008; Darroudi et al 2008; Woda et al 2009).
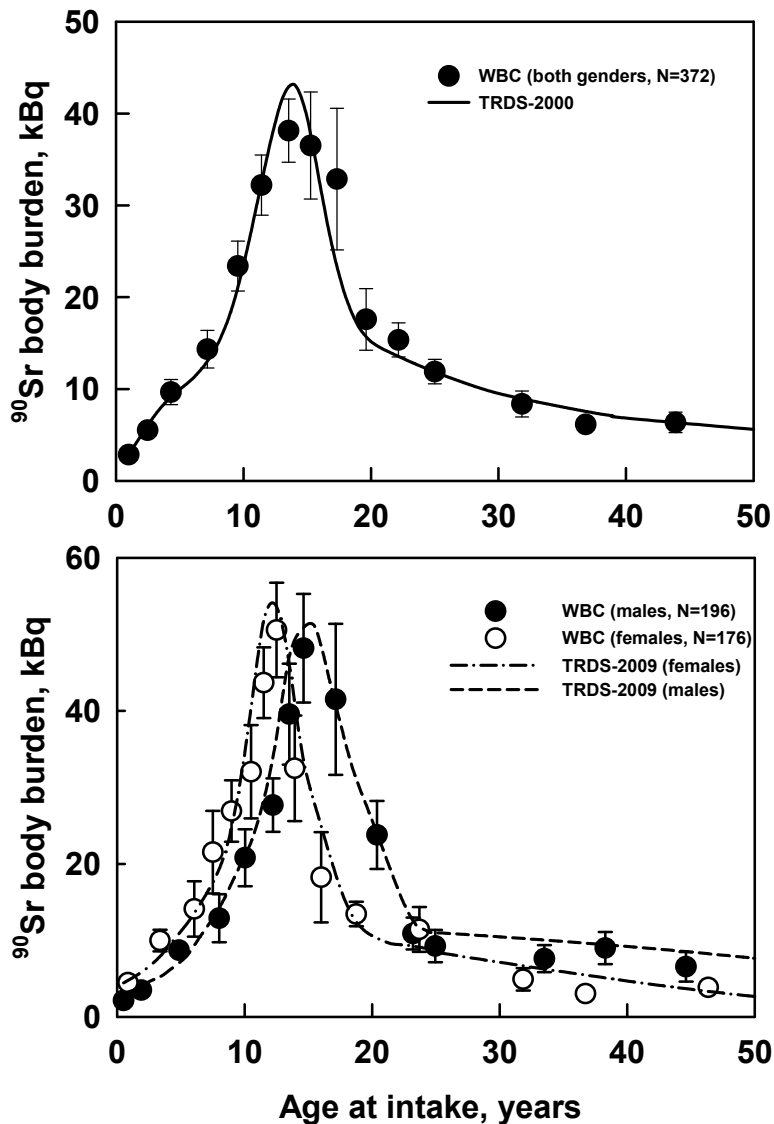
*Fig. 18. Age-dependences in ⁹⁰Sr-body burdens for residents of Muslyumovo 30 years after the beginning of intake. The upper panel shows model predictions obtained with the age-dependent biokinetic model used in the TRDS-2000 compared with WBC data averaged for both genders. The lower panel shows model predictions obtained with the TRDS-2009D age- and gender-dependent model compared with WBC data averaged for males and females separately.*

Reliable estimates of cumulative anthropogenic dose in bricks of the old buildings in Metlino and Muslyumovo were obtained with use of the luminescent method (Jacob et al 2003; Bougrov et al 2009; Degteva et al 2008a; Ulanovsky et al 2009). These estimates converted to air kerma resulted in distributions of integral anthropogenic dose in air at various locations above the floodplain or shorelines. The latter ones were compared with the cumulated dose in air derived from the TRDS-2009D database on external dose rate near the river shoreline (Table 11).
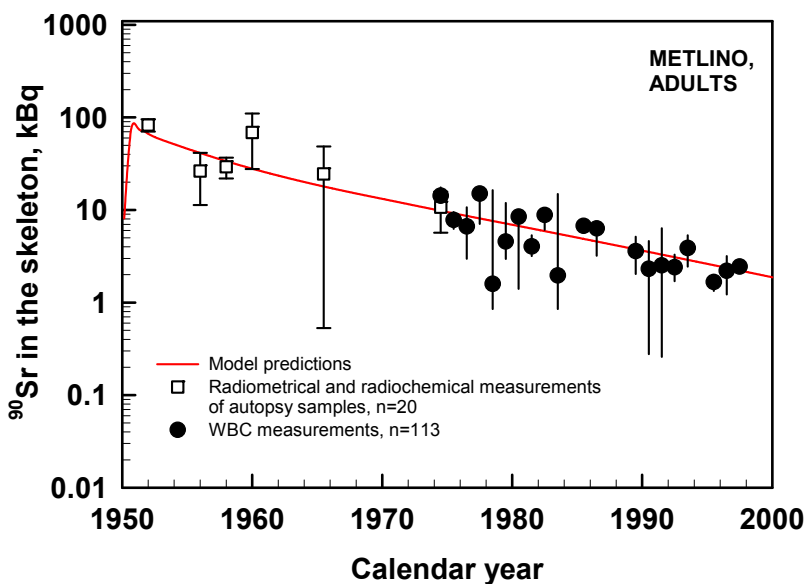
*Fig. 19. Time-dependency of $^{90}$Sr-body burden for adult residents of Metlino for the period 50 years after the beginning of intake. Model predictions are compared with WBC and autopsy data averaged for both genders.*

*Table 11. Comparison of absorbed dose in air derived from luminescence measurements of bricks from the old buildings located near the Techa River shore in Metlino and Muslyumovo and calculated with use of the TRDS-2009D parameters.*

| Location | Absorbed dose in air at the Techa River shore, Gy | |
|---|---|---|
| | Derived from the TRDS-2009D | Estimated from the luminescence data (95% CI) |
| Metlino, 7 km from the release site | 27.7 | 32 (21 – 45)[*] |
| Muslyumovo, 78 km from the release site | 1.4 | 1.0 (0.2 – 1.5) |

Note: Evaluated for the period 1949–1956 without shielding due to snow cover during winter time (Jacob et al 2003).

As can be seen from Table 11, the values of the cumulated dose in air, calculated with TRDS-2009D parameters, lie within the confidence intervals of estimates derived from luminescence data. Thus, it can be concluded that the data on absorbed dose in air on the Techa River banks in Metlino and Muslyumovo used in the TRDS-2009D for external dose assessments are validated by the luminescence measurements.

Significant efforts on the TRDS external dose validation using FISH and EPR methods were made in 2000 – 2006 (Anspaugh et al 2000; Degteva et al 2005, 2006a; Ivanov 2005; Shishkina et al 2003, 2006). These efforts were addressed to the TRDS-2000-based external doses and should be reiterated for TRDS-2009D. In addition, during recent several years there has been a substantial increase in the quantity and quality of the EPR and FISH data. It is planned to revisit the validation task during the third phase of Project 1.1 (2010–2012). Nevertheless, because the difference in external doses between TRDS-2000 and TRDS-2009D is basically small, it is reasonable to remind now of the results of our validation study for the Metlino residents performed as a part of Project 1.1 in 2003–2006 (Degteva et al 2005, 2006a).

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 that the average FISH-based dose for investigated persons from Metlino (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 (Fig. 20a). 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, 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. 20a: (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 three 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. 20b 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. 20b 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. This figure illustrates the approach to external dose reconstruction that is not included yet in the TRDS-2009D and will be used in the enhanced version of the system. Implementation of this approach will result in a substantial reduction of uncertainties in external dose estimates.
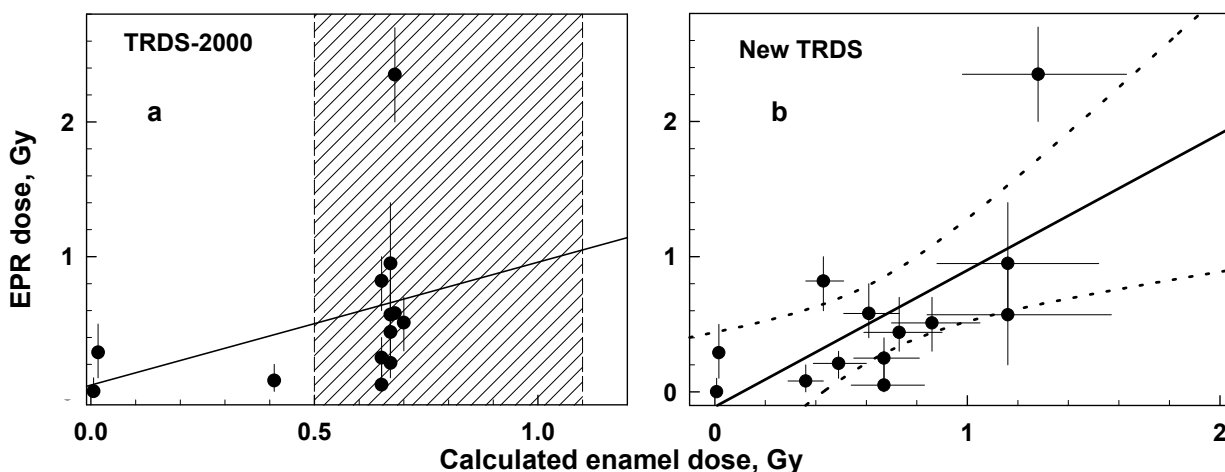
*Fig. 20. Comparison of the calculated external doses for tooth enamel with EPR-based doses obtained for inhabitants of Metlino. The left panel (a) shows dose estimates based on weighted-average distance between households and the river shoreline (TRDS-2000). The right panel (b) shows individual dose estimates that account for the location of a particular person's household in terms of distance from the river shoreline, (to be included in future version of TRDS).*

## 4.3.    POSSIBILITIES TO UPGRADE THE TRDS-2009D

Creation of the first version of the TRDS-2009D accomplishes the second phase of Project 1.1 (2000-2009).  As can be seen from Table 2 above, six codes from the planned eight have been completed.  These six codes allow computation of individual-residence-history based external doses and refined internal doses for the ETRC and ETROC members including environmental exposure on the Techa River and EURT, as well as individual doses of medical exposure in the URCRM clinics.  The completed TRDS-2009D code will be further extended by addition of a module for calculation of doses for EURT evacuees.  This will allow combination of the ETRC with the EURT cohort of 18,000 evacuees in order to achieve greater statistical power for risk estimation.

Implementation of Project 1.1 was seriously impacted by the recent discoveries related to the Mayak releases in 1950–1951 made during ISTC Project #2841.  Verified data on the beginning of the massive releases into the Techa River required a lot of unforeseen efforts on re-evaluation of $^{90}$Sr-intake functions initially assumed to be independent of the source-term parameters.  Intake levels for non-strontium radionuclides and external dose rates on the river banks in 1949–1951 (that strongly depend on the source-term data) have been re-evaluated by modeling of radionuclide transport in the Techa River only in 2009.  The modeling results are included in the TRDS-2009D, but they need careful examination and verification.

It is planned to develop a dynamic model of the processes that occurred in river, ponds and marshes in 1950–1951 to deal with the fine temporal structure of the newly-derived source term.  Such a model will allow testing correlations among different data sets:  modeled

radionuclide concentrations in water and bottom sediments vs. measured gamma- and beta-radionuclide content of water and sediment samples, "forward" estimates of $^{90}$Sr intake vs. "retrospective" ones, etc.  Thus, the best assumptions and estimates can be selected which harmonize all available data.

It is planned to revisit the validation efforts to ensure that revisions made on the basis of the dynamic river model do not invalidate the conclusions already reached regarding the accuracy of the external dose estimates.  The European SOUL project has supported EPR measurements of teeth and FISH measurements of chromosome translocations in circulating lymphocytes of upper-river Techa residents (it is anticipated to obtain about 350 EPR measurements and about 70 FISH measurements by the end of this year).  Individual-dose assessments with use of the TRDS-approach will be performed for all Techa residents whose teeth will be measured by EPR method and whose blood samples will be investigated with use of the FISH method.  External dose calculations will be based on individual-exposure histories and, if possible, on the data on individual's house locations relative to the contaminated river shoreline.  Comparison of TRDS-based estimates with the estimates derived from FISH and EPR data will allow validation and verification of individual dose assessments and, if necessary, updating the modules for external dose calculations.

The proposed activities will update the appropriate modules of the TRDS-2009D databases with the results of the river model, intakes of non-$^{90}$Sr radionuclides, and associated external dose rates.

## 5    CONCLUSIONS

The system of computer codes and supporting databases completed this year (Program system TRDS-2009D) allowed us to realize computations of individual doses for the ETRC and ETROC members according to three phases of our proposed computation schedule.  The first phase provided deterministic estimates of doses from residence on the Techa River and the East Urals Radioactive Trace (EURT) based on village-average-intake functions and external dose rates, with consideration of an individual's residence history.  The second phase included refinement of individual internal dose based upon a person's or a co-inhabitant's measurement of $^{90}$Sr-body burden.  The third phase combined environmental exposures with medical exposures. Thus, the first deterministic version of the TRDS-2009 dosimetry system has been completed and is being used for individual-dose computations.

The results of TRDS-2009D dose calculations have demonstrated for the ETRC members on average a moderate increase in RBM dose estimates (34%) and a minor increase (5%) in estimates of stomach dose.  Nevertheless, differences in individual doses calculated with use of the TRDS-2000 and TRDS-2009D were significant for some ETRC members.  The calculations for the members of the ETROC indicated similar small changes for stomach, but a significant increase in RBM doses (400%).

Individual-dose assessments performed with use of the TRDS-2009D have been provided to epidemiologists for exploratory risk analysis in the ETRC (under NCI-URCRM and JCCRER Project 1.2a) and in the ETROC (under the SOUL project).  These data allow now provide an

opportunity to evaluate the impact on radiogenic risk of such factors as confounding exposure (environmental and medical), changes in the Techa River source-term data and the change of the approach to individual internal dose estimation ($^{90}$Sr-body burden measurements and family correlations vs. village average). Our further plan is to upgrade the TRDS-2009D as mentioned above and to complete a stochastic version of the dosimetry system.

## ACKNOWLEDGEMENTS

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