

## Development of an Improved Dose Reconstruction System for the Techa River Population Affected by the Operation of the Mayak Production Association

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The Techa River Dosimetry System (TRDS) has been developed to provide estimates of dose received by approximately 30,000 members of the Extended Techa River Cohort (ETRC). Members of the ETRC were exposed beginning in 1949 to significant levels of external and internal (mainly from <sup>90</sup>Sr) dose but at low to moderate dose rates. Members of this cohort are being studied in an effort to test the hypothesis that exposure at low to moderate dose rates has the same ability to produce stochastic health effects as exposure at high dose rates. The current version of the TRDS is known as TRDS-2000 and is the subject of this paper. The estimated doses from <sup>90</sup>Sr are supported strongly by ~30,000 measurements made with a tooth  $\beta$ -particle counter, measurements of bones collected at autopsy, and ~38,000 measurements made with a special whole-body counter that detects the bremsstrahlung from <sup>90</sup>Y. The median doses to the red bone marrow and the bone surface are 0.21 and 0.37 Gy, respectively. The maximum doses to the red bone marrow and bone surface are 2.0 and 5.2 Gy, respectively. Distributions of dose to other organs are provided and are lower than the values given above. Directions for future work are discussed. © 2006 by Radiation Research Society

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### INTRODUCTION

Russian and United States scientists have been involved in collaborative research programs under the sponsorship of the U.S.–Russian Joint Coordinating Committee on Radiation Effects Research (JCCRER) since 1995. JCCRER Project 1.1 is a comprehensive program to develop improvements in the dosimetry system for the population exposed as a result of releases from the Mayak Production

Association (MPA) by providing more in-depth analysis of existing data, further search of existing records for useful data, model development and testing, evaluation of uncertainties, verification of procedures, and validation studies of existing and planned results.

The specific aim of this project is to enhance reconstruction of external and internal radiation doses for about 30,000 individuals who resided in the valley of the Techa River, which was contaminated in 1949–1956 by discharges of liquid radioactive wastes from the MPA. The purpose of the enhanced dose reconstruction is to support companion epidemiological studies of radiogenic leukemia and solid cancers (1–4) and of radiogenic disease in an offspring cohort (5).

The purposes of this paper are

1. To provide a description of an improved dosimetry system referred to as the Techa River Dosimetry System-2000 (TRDS-2000).
2. To summarize updated assessments of external and internal doses calculated for members of the Extended Techa River Cohort (ETRC) using the TRDS-2000.
3. To describe quality-assurance work accomplished for the main databases and to describe work on the verification and validation of the models used in the TRDS-2000.
4. To describe preliminary approaches to uncertainty assessments for external and internal doses.
5. To outline additional work being undertaken to provide further improvements in the dosimetry system.

Population exposure in the Urals region occurred as a result of failures in the technological processes in the Mayak plutonium facility in the late 1940s and early 1950s. 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 (Fig. 1 and Table 1) were exposed through a variety of pathways; the more significant included drinking of water from the river and external  $\gamma$ -ray exposure due to proximity to bottom sediments and the shoreline. There are known to be additional sources of exposure for the members

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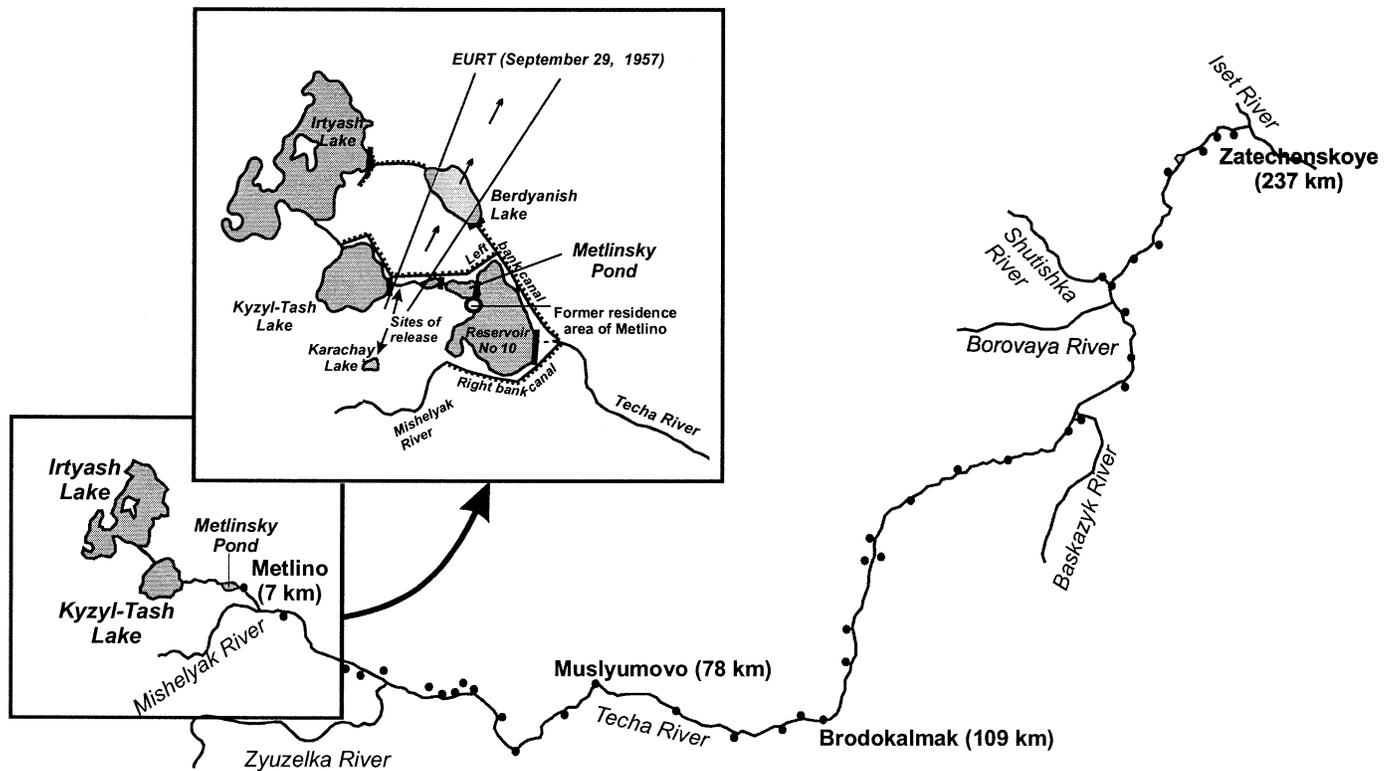


FIG. 1. Schematic map of the Techa River (approximate scale) and the villages located on its banks before contamination occurred (1949). The names of the major settlements and the distances from the release site are also indicated. Schematic diagrams of the upper reaches of the Techa River and the East Urals Radioactive Trace (EURT) formed in 1957 are shown in the upper panel; the straight lines indicate the region of  $^{90}\text{Sr}$  deposition density greater than  $740 \text{ MBq m}^{-2}$  ( $20 \text{ Ci km}^{-2}$ ). The location of the MPA is indicated by "Sites of release".

of the cohort. One of the more important may be medical exposure that was biased toward those who were known to be more exposed to the liquid effluents from the MPA. These persons were followed closely by a special medical clinic, and they received frequent medical examinations that included medical diagnostic radiation.

Another possibly important source of confounding exposure 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  $7.4 \times 10^{16}$  Bq of radioactive materials into the atmosphere. Some of this material contaminated villages to which persons exposed on the Techa River had been relocated. Other possible sources of confounding exposure include the gaseous aerosol releases from the Mayak facility in 1949–1957 and the windblown contamination from Lake Karachay when it dried out in 1967.

The series of radioactive releases that occurred in the same region in different years and the intensive migration (many persons were evacuated or relocated) of the population within the contaminated area are specific features of the situation in the Urals. 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 Cohorts of Interest

In 1968, the Techa River Registry was created at the Urals Research Center for Radiation Medicine (URCRM) with the goal of including residents of villages along the Techa River who lived there during the period of high exposure from 1949 through 1952. The registry now includes data on 24,988 such persons, and these persons have been identified as members of the original Techa River Cohort (TRC). The TRC has been studied for several decades by scientists from the URCRM, and an increase in both leukemia and solid cancers with radiation dose has been noted (1, 4). These findings suggest that, with continuing improvements in the quality of the follow-up and dosimetry, study of the TRC has the potential to provide quantitative estimates of the risks of stochastic health effects produced by chronic low-dose-rate radiation exposure in the general population.

In more recent times, the Extended Techa River Cohort (ETRC)<sup>2</sup> has been created; it includes the original TRC and

<sup>2</sup> The exact number of the members of the cohort has changed over time, as analysis and verification have proceeded. For example, a substantial number of duplicate entries has been eliminated, most of which were due to inclusion of maiden and married names of women. More details concerning the composition and number of the members of the cohort are given in refs. (3, 4).

**TABLE 1**  
**The Settlements along the Techa River Involved in this Study (Status in September 2004)**

Settlement	Distance from site of release, km	Population <sup>a</sup>	Date of relocation
Metlino	7	1,185	1956
Techa Brod	18	75	1955
Asanovo and Nazarovo	33	845	1955–1956
M. Taskino	41	116	1955
Gerasimovka	43	329	1957
GRP	45	472	1957
Nadyrov Most	48	181	1956
Nadyrovo	50	174	1955
Ibragimovo	54	152	1955
Isaev	60	391	1956
Podssobnoe hoz.	65	531	1961
Muslyumovo (village and station)	78	3,841	Exists
Kurmanovo	88	1,151	1959–1960
Karpino	96	255	1959–1961
Zamanikha	100	364	1959
Vetrodujka	105	205	1959–1960
Brodokalmak	109	4,124	Exists
Osolodka	125	471	1960–1961
Panovo	128	161	1960
Cherepanovo	137	210	1959–1960
Russkaya Techa	138	1,537	Exists
Baklanovo	141	466	1959–1960
Nizhnepetropavlovskoye	148	1,213	Exists
Beloyarka-2	155	368	1960–1961
Lobanovo	163	705	Exists
Anchugovo	170	1,120	Exists
Verkhnyaya Techa	176	1,065	Exists
Skilyagino	180	498	Exists
Bugaev	186	1,120	Exists
Dubasovo	200	692	1960–1961
Bisserovo	202	495	Exists
Shutikhinskoye	203	1,170	Exists
Progress	207	201	1960–1961
Pershinskoye	212	1,176	Exists
Klyuchevskoye	223	1,347	Exists
Ganino and Markovo	230	233	1960–1961
Zatechenskoye	237	1,234	Exists
All villages		29,873	

<sup>a</sup> Number of members of the Extended Techa River Cohort assigned to this location.

4,885 persons who migrated to the villages after the period of high exposure but before 1960; the late entrants in the ETRC have been restricted to those born before 1949 as for the original TRC. This ETRC is the master cohort from which subcohorts can and are being drawn for analysis and for whom it is desirable and possible to calculate individualized<sup>3</sup> internal and external doses. The development of this cohort has been described in refs. (3, 4); the number of cohort members in September 2004 was 29,873.

<sup>3</sup> We use the term “individualized” dose in this paper to describe doses that are calculated by taking into account the residence history and age of a person. However, the doses are not yet truly individual in the sense that a particular person’s body burden measurements and intra-village locations are not used directly. Rather, village averages of intake functions and distances from the contaminated river are used; improvements are under way that will allow for the calculation of “individual” doses.

The ETRC has many desirable features in terms of its continuing epidemiological study:

1. The cohort consists of unselected members of the general population.
2. Members of the cohort are relatively old at this time; the youngest member is more than 50 years old.
3. The years at risk are relatively large, about 50 years.
4. The doses received by this population are relatively large; 3.2% of the members have total red bone marrow doses of >1 Gy; in addition, some members of the cohort have external doses of up to 0.4 Gy.

Further, the URCRM Registry includes data on about 29,700 persons exposed *in utero* and/or the progeny of exposed parents. Twelve thousand such persons who are the children of TRC members have been identified as the Techa

River Offspring Cohort (TROC). Study of the TROC has the potential to provide direct data on radiogenic health effects in progeny due to the exposure of their parents to chronic low-dose-rate radiation.

## MATERIALS AND METHODS

The method of dose reconstruction used is the traditional one of considering the source term, following the releases through the environment, and evaluating the exposure pathways to humans. However, in this case, the source-term data are limited, because the releases were not recognized immediately; dependence upon the limited source-term data and the application of environmental transfer models alone would result in estimated doses with large uncertainties. Therefore, the traditional approach has been supplemented to the extent possible by reliance upon measurements of external  $\gamma$ -ray exposure rates and of radionuclide concentrations in the environment. Of most value were the measurements of long-lived  $^{90}\text{Sr}$  in the teeth and skeleton of the members of the cohort.

### *Instrumental and Radiochemical Measurements*

Over the years a variety of measurements have been made, including the external  $\gamma$ -ray exposure rate along the banks of the Techa River and in the affected villages, the  $\beta$ -particle activity in sediments, and the  $^{90}\text{Sr}$  activity in samples of bones and teeth collected at autopsy (or teeth extracted for reasons of dental health). Other than the two specific measurement systems described below, these measurements and their results have been tabulated in ref. (6) and will not be described further here. Two measurement systems, the tooth  $\beta$ -particle counter (TBC) and the bremsstrahlung whole-body counter, have been particularly useful in defining the patterns and amounts of intake of the main dose-forming radionuclide,  $^{90}\text{Sr}$ ; these two systems are described in more detail below.

#### *1. Tooth $\beta$ -particle counter*

Because the radionuclide of primary interest is  $^{90}\text{Sr}$ , which is incorporated into tooth tissue as well as into bones, a variety of methods have been sought to quantify the occurrence of  $^{90}\text{Sr}$  in tooth tissue. One of the more useful techniques has been the use of specially developed gas-flow Geiger-Müller detectors (7, 8) for *in vivo* measurement of surface  $\beta$ -particle activity of the four front teeth. The diameter of the tooth  $\beta$ -particle counter was 1 cm. Such measurements were performed from 1959 through 1997, and about 30,000 measurements have been performed on more than 15,000 individual persons. These data, while relative in nature, have been extremely useful in defining the periods of intake, i.e., the periods when the releases to the river were occurring.

#### *2. Whole-body counter*

The data set of whole-body counter measurements is critical to the success of efforts to provide individual doses. The URCRM whole-body counter, the SICH-9.1, was used from 1974 to 1998 to measure  $^{90}\text{Sr}$ ,  $^{137}\text{Cs}$  and  $^{40}\text{K}$  in people (9). Quantification of  $^{90}\text{Sr}$  was achieved by measuring with a phoswich detector the bremsstrahlung of  $^{90}\text{Y}$  (decay product of  $^{90}\text{Sr}$ )  $\beta$  particles of high energy; for this purpose, scanning-bed geometry enclosed in a special shielding room was used (9). Analyses of  $^{137}\text{Cs}$  and  $^{40}\text{K}$  were accomplished at the same time with the same detector by the measurement of their photopeaks (photons with energy ranges 620–740 keV and 1400–1580 keV, respectively). After the original calibration of the whole-body counter in 1973, about 38,000 measurements were carried out during the next 25 years on about 20,000 people; the number of persons measured with both the tooth  $\beta$ -particle counter and the whole-body counter was 14,306. The lower limit of reliable detection for  $^{90}\text{Sr}$  with the whole-body counter has been evaluated as 2.0 kBq (10); the maximal activity of  $^{90}\text{Sr}$  measured for an individual was 190 kBq. De-

tailed analyses of the whole-body counter data have been given in refs. (9, 10).

An autopsy program had been under way at the URCRM during the period 1951–1989 (11). This autopsy program included radiochemical measurements of  $^{90}\text{Sr}$  in bone samples from autopsies of Urals residents and was ended only after 21 members of the ETRC were measured *in vivo* with the whole-body counter and their  $^{90}\text{Sr}$  body burdens, derived from whole-body count measurements, were validated by the results of the analysis of *post mortem* samples (11). The consistency of these two methods was confirmed, and this serves as a major quality assurance check for the critically important whole-body counter data.

In addition, to validate the whole-body counter data set, the measurement system was once again calibrated in 1998 using a specially constructed anthropomorphic phantom (12) that contains  $^{90}\text{Sr}$  distributed through simulated bones and another set of phantoms containing uniformly distributed  $^{40}\text{K}$  and  $^{137}\text{Cs}$ . The strontium phantom (FST-06T) is shaped as an anatomical model of ICRP Reference Man (13) and contains an activity of  $44 \pm 2$  kBq of  $^{90}\text{Sr}$  (plus an equal amount of its decay product  $^{90}\text{Y}$ ) distributed uniformly in the skeleton mass. The design of this phantom has been described in detail (12).

The calibration factors obtained in 1973 and in 1998 agreed quite well—the more important ones are within a few percent, and all factors agree within 16%. The results of the repeated calibration with the FST-06T phantom confirmed the reliability and credibility of the data set of multiple whole-body counter measurements.

The condition in 1998 of the original SICH-9.1 detectors and electronic equipment was poor. To provide for the continuation of the individual body-burden monitoring program, a new set of detectors and a new electronic system for spectrum analysis were specified and purchased. It was decided to use the same shielding room and the same geometry of measurements (scanning bed) as well as the same type of detectors (phoswich). Figure 2 demonstrates several views of the new set of equipment with the FST-06T phantom placed as a “subject” undergoing measurement.

### *The URCRM Databases*

There are several databases located at the URCRM that are used jointly by dosimetrists and epidemiologists working together on population risk assessment projects.

*Database MAN.* One of the more important URCRM databases is database MAN; the details are indicated in Fig. 3. The purpose of database MAN is to be the central repository of all “input” data pertaining to a member of the Techa River Cohort. This information includes all identification data; pedigree or family information; data on migration from location to location; all known addresses; information on the deceased at time of death, etc.; the cause(s) of death; the diagnoses in addition to and including the cause(s) of death; and available information on measurements of body burdens of radionuclides and  $\beta$ -particle counts of teeth. All information pertaining to a particular member of the registry is accessed through an identification code or IC.

*Database ENVIRONMENT.* This database contains available data on source terms, measurements of radionuclides in river water and sediment, and external  $\gamma$ -ray exposure rates in the environment. In addition, hydrological data pertaining to the Techa River are included. Much of the material that has served as the basis of the derivation of this database has been described in ref. (6). This database is the responsibility of the URCRM Environmental Department and the Biophysics Laboratory and is available to the other groups. The link between databases MAN and ENVIRONMENT is through a “settlement code,” which is the same identifier both for the residence place of exposed persons and for all environmental measurements in this site.

*Other databases.* There are several other databases that contain primary data and that can be used for risk analysis. The more important are the Tumor and Autopsy Registries. The Tumor Registry contains about 25,500 copies of Regional Cancer Dispensary notifications for the residents of the catchment area, and the Autopsy Registry contains *post mor-*

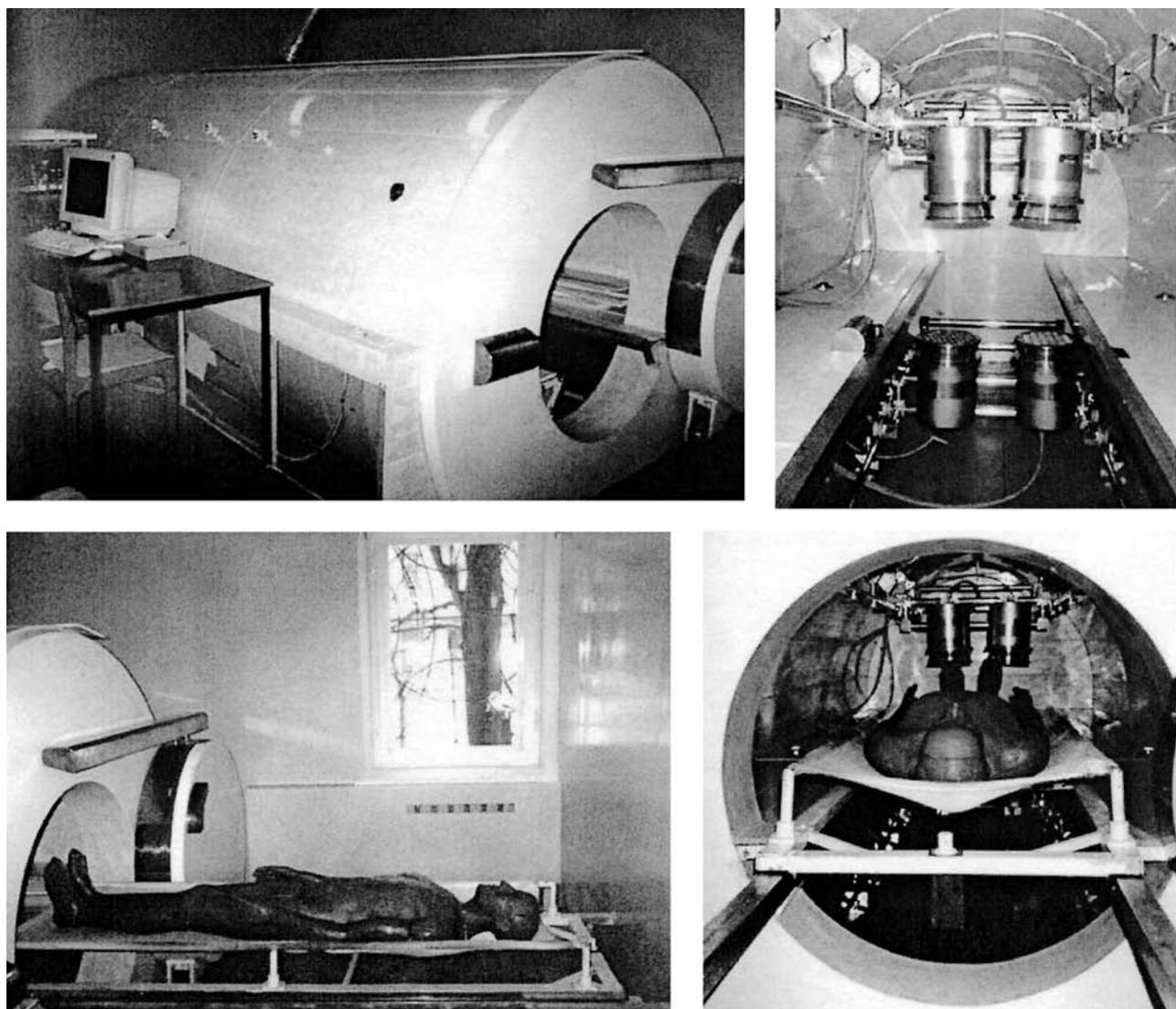


FIG. 2. Several views of the updated whole-body counter with the new phantom placed as a "subject" to be measured.

tem diagnoses and  $^{90}\text{Sr}$  measurements in bone samples for 6,024 subjects who lived in the Urals. Both registries have been matched to the Techa River Registry. These two registries were found to include data for members of the ETRC concerning about 4,000 tumors and 1,097 measured samples of bones.

#### *Freezing of the Cohorts and Databases for Analysis*

Personal data and residence-history data for subjects under observation are occasionally updated and corrected in accordance with newly received archival documents, interviews and other data. On the basis of such new information, subjects are sometimes moved from one cohort to another within database MAN. Also, status changes through a variety of processes such as death, marriage or migration; newly born persons are added to the Offspring Cohort. Updated information of these and other types is occasionally entered into the appropriate databases.

At various times in the past, the ETRC and its associated databases have been "frozen" for analysis. Thus, while work continues on following up members of the cohort and in improving the dosimetry, these changes are not implemented on a piecemeal approach. Rather, at selected dates of "freezing" the cohort and its databases for analysis, the changes that have progressed incrementally over several years are implemented

at once for future analysis. The dates of the "freezings" are mutually agreed upon by the epidemiologists and dosimetrists involved in joint study on radiation risk analysis. The most recent freeze occurred on September 2004 with updates on the epidemiological follow-up as of that date and with the previously planned 2001 update of the dosimetry system; data given in this paper refer to the September 2004 freeze. Future plans include a freeze for about 2006.

The current dosimetry system is referred to as TRDS-2000, although the actual date of the implementation was delayed until 2001. Major activities leading to improvements in the TRDS-2000, in comparison to the previous dosimetry systems (1, 14), include:

1. A comprehensive, analytical review (6) of historical data on radionuclide releases to the Techa River, measured concentrations of radionuclides in water and in sediments of the Techa River, hydrological data, and measured external  $\gamma$ -ray exposure rates at and near the river.
2. The development (15) of a river model to describe the time- and distance-dependent radionuclide concentrations and exposure rates along the Techa River.
3. Use of the river model and other data to compute individual body-burden histories and resulting internal doses (16) from all radionuclides, including short-lived radionuclides that had not been included in previous dose estimates.

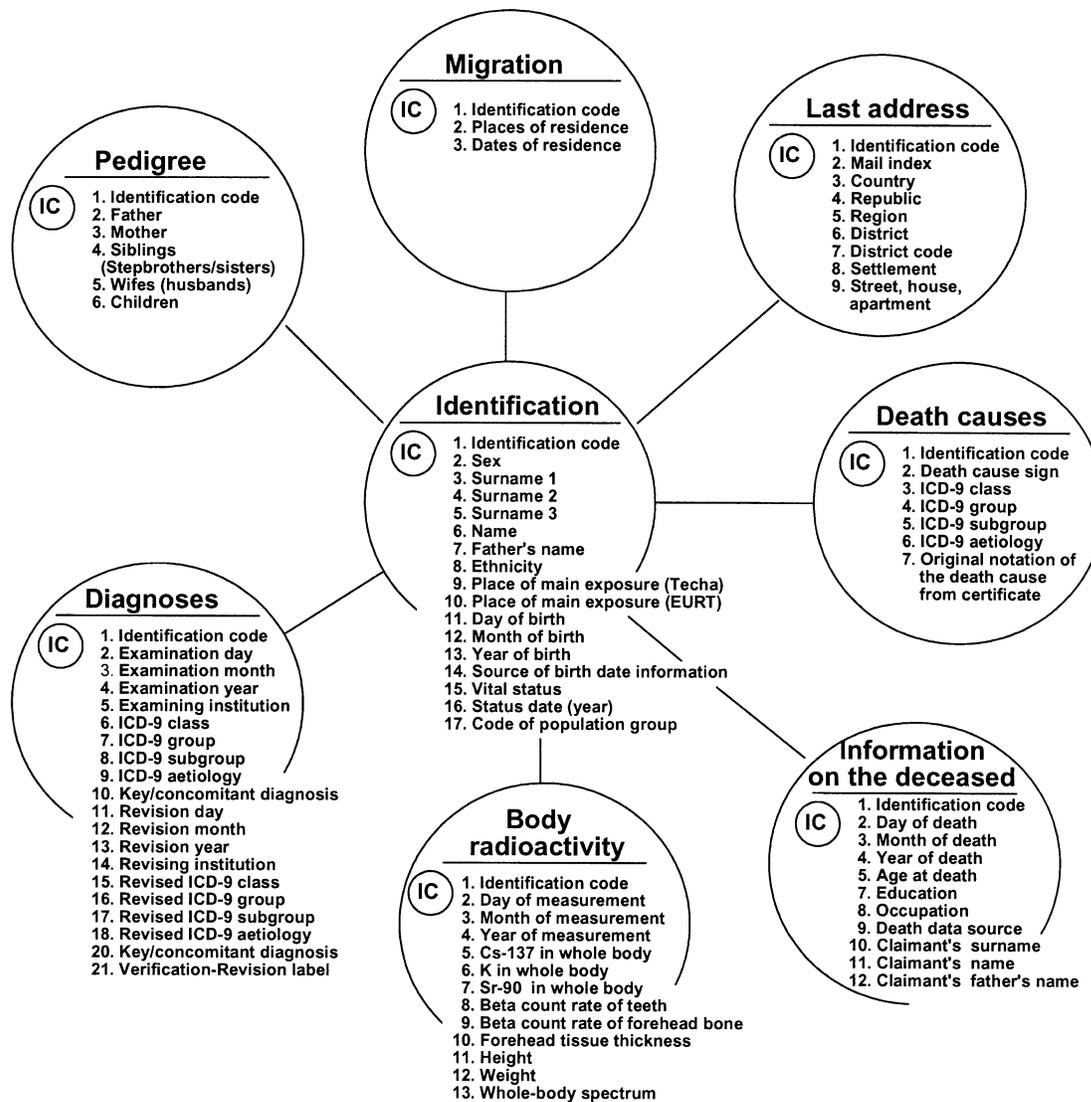


FIG. 3. Information contained in database MAN.

4. A major revision (17) in the computation of external dose based on the upgraded TRDS approach, the river model, a re-evaluation of all measurements of external  $\gamma$ -ray exposure rates near the shoreline and in the living areas, and a re-examination of data pertaining to the amounts of time spent near the river and in other locations.
5. Evaluation for the first time of the uncertainty in the calculated doses for members of the ETRC (18).

A preliminary description of the general approaches and initial data sets used for the creation of the TRDS was provided by Degteva *et al.* (19). The TRDS is designed as a modular database processor. That is, depending on the input data for an individual, various elements of several TRDS databases are combined to provide the dosimetric variables requested by the user. The input data include the following information for each member of the ETRC: identification code, year of birth, year of entry to the catchment area, year of migration from the catchment area, year of vital status determination, and residence history within the contaminated areas. These data are prepared and updated by members of the Registry Department who are working on companion epidemiological studies.

#### Basic Equations for Dose Calculations

The method being used for the TRDS-2000 basic dose calculations is relatively simple and can be written as a single equation:

$$D_{o,Y} = \sum_{y=1}^E \sum_L M_{y,L} \left\{ \sum_r I_{y,r,L} \cdot DF_{r,o,Y-y} + A_o \cdot P_{Riv,y}^L \right\} \times \left[ T_1 + S(k_{Out/Riv}^L \cdot T_2 + k_{In/Out} \cdot k_{Out/Riv}^L \cdot T_3) \right], \quad (1)$$

where  $D_{o,Y}$  is the absorbed dose (Gy) in organ  $o$  accumulated to calendar year  $Y$ ;  $Y$  is the calculational end point for a particular individual (can vary within the range 1950–2005);  $y$  is the year of environmental exposure (external irradiation and intake of radionuclides);  $E$  is the end point of external exposure and intake of radionuclides for a particular individual (can vary within the range 1950–1959);  $L$  is the river-location (village) identifier;  $M_{y,L}$  is the fraction of year  $y$  spent in location  $L$ ;  $r$  is the identifier of ingested radionuclide ( $^{89}\text{Sr}$ ,  $^{90}\text{Sr}$ ,  $^{95}\text{Zr}$ ,  $^{95}\text{Nb}$ ,  $^{103}\text{Ru}$ ,  $^{106}\text{Ru}$ ,  $^{137}\text{Cs}$ ,  $^{141}\text{Ce}$  and  $^{144}\text{Ce}$ );  $I_{y,r,L}$  is the intake function (Bq year $^{-1}$ ) for year  $y$ , radionuclide  $r$ , and location  $L$  (function of age, related to  $y$ ), further described below;  $DF_{r,o,Y-y}$  is the conversion factor (Gy Bq $^{-1}$ ) for dose ac-

**TABLE 2**  
**TRDS System Databases**

System database	Form	Content	Model used	Source of data
TECHLIST	File	List of Techa settlements and codes ( $L$ )	—	URCRM archives
TECHEXT	Library of 39 files	For each of 39 settlements annual dose rates near the river ( $P_{Riv,y}^L$ ), ratios of dose rates outside residence areas to near the river ( $k_{Out/Riv}^L$ ) and ratios of dose rates inside residence areas to outside residence areas ( $k_{In/Out}$ )	Techa River Model	Database ENVIRONMENT
REGIME	File	$T_1, T_2, T_3$ for age groups	Behavioral model	URCRM Reports
DOS.F	Library of nine files	For each of 9 organs, age-dependent dose conversion factors ( $A_o$ )	Monte Carlo calculations	Literature
REPER	File	Annual $^{90}\text{Sr}$ intakes for adult residents of the reference settlement	Strontium-90 intake model	Database MAN
CHILD	File	Annual relative $^{90}\text{Sr}$ intakes for children who lived in the reference settlement	Strontium-90 intake model	Database MAN
NUCL - STC	Library of 39 files	Annual ratios of intake of $^{90}\text{Sr}$ for each of 38 settlements to that for reference settlement; and intake of nuclide to $^{90}\text{Sr}$ for each of 39 settlements	Techa River Model	Database MAN
SR90, SR89	Two libraries, each of 31 files	Age- and time-dependent dose conversion factors for different organs ( $DF_{r,o,y,y}$ )	URCRM model for Sr metabolism	Database MAN
CS137, RU103, RU106, ZR95, NB95, CE141, CE144	7 libraries, each of 9 files	Age- and time-dependent dose conversion factors for different organs ( $DF_{r,o,y,y}$ )	ICRP-67 models	Literature

accumulated in organ  $o$  in year  $Y-y$  from intake of radionuclide  $r$  in year  $y$  (function of age, related to  $y$ );  $Y-y$  is the time since intake in years;  $A_o$  is the conversion factor from absorbed dose in air to absorbed dose in organ  $o$  (function of age, related to  $y$ );  $P_{Riv,y}^L$  is the dose rate in air ( $\text{Gy year}^{-1}$ ) near river shoreline at location  $L$  in the summer of year  $y$ ;  $k_{Out/Riv}^L$  is the average ratio of dose rate in air outdoors within residence area to dose rate near river shoreline at location  $L$ ;  $k_{In/Out}$  is the ratio of dose rate in air indoors to dose rate outdoors;  $S$  is the snow-shielding factor equal to 0.85;  $T_1$  is the time spent on riverbank (relative to whole year) (function of age, related to  $y$ );  $T_2$  is the time spent outdoors (relative to whole year) (function of age, related to  $y$ ); and  $T_3$  is the time spent indoors (relative to whole year) (function of age, related to  $y$ ).

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

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

where  $I_R^{Sr90}$  is the annual  $^{90}\text{Sr}$  intake for adult residents of the reference settlement (Muslyumovo);  $\alpha_{Age,R}^{Sr90}$  is the annual  $^{90}\text{Sr}$  intake for other age

groups relative to that for adults living in the reference settlement;  $f_L^{Sr90}$  is the annual ratio of  $^{90}\text{Sr}$  intake for location  $L$  to  $^{90}\text{Sr}$  intake for residents of the reference settlement; and  $f_L^r$  is the annual ratio of nuclide to  $^{90}\text{Sr}$  in the intake for location  $L$ .

#### TRDS Databases

The TRDS relies on a number of system databases to compute doses for each cohort member. A summary of the system databases is presented in Table 2. These databases were prepared during the course of research performed in the framework of the current project. A full description of the models and data sets used for production of the TRDS databases is provided in refs. (16, 17, 20).

To reconstruct annual dose rates near the river and within residence areas [ $P_{Riv,y}^L, k_{Out/Riv}^L, k_{In/Out}$  (database TECHEXT)], all available results of exposure-rate measurements near the Techa River were retrieved from the URCRM archives and databases (17). To fill the gaps in measured data the Techa River Model (15) that describes radionuclide transport from the site of release along the river and accumulation of radionuclides by bottom sediments was used. Dose rates in air on the riverbanks were calculated on the basis of modeled radionuclide concentrations in bottom sediments; for this purpose, coefficients (21) obtained by Monte Carlo

**TABLE 3**  
**Dose Rate in Air near the Techa River Shoreline for Sites in the Upper and Middle Reaches of the River**

Calendar year	Dose rate in air, $\mu\text{Gy h}^{-1}$	
	Metlino site (7 km from the site of release)	Muslyumovo site (78 km from the site of release)
1950	310	3.4
1951	1380	17.5
1952	470	5.5
1953	465	11
1954	250	9.9
1955	80	4.2
1956	80	4.2
Background	0.09–0.14	

Notes. More details on dose rates for these and other sites are available in ref. (22). Values for 1950 and 1951 are calculated; others are measured.

**TABLE 4**  
**Typical Life Patterns for Different Age Groups of the Techa Riverside Residents (17, 22)**

Age group, years	Time spent at specified site, hours per year			
	Shoreline (summer time)	Residence area (outdoors)	Residence area (indoors)	Far from the river (uncontaminated territory)
<7	45	2235	6480	0
7–15	150	2130	5760	720
16–59	150	1410	3960	3240
$\geq 60$	150	2490	6120	0



**TABLE 7**  
**Relative Annual  $^{90}\text{Sr}$  Intake (Relative to Muslyumovo) for Several Settlements**

Settlement	Distance from the site of release, km	Main sources of drinking water listed in order of importance	Location factor, $f_L^{90\text{Sr}}$
Metlino	7	Techa River and wells	0.72
Asanovo	33	Techa River and wells	0.76
Nadyrov Most	48	Wells and Techa River	0.51
Ibragimovo	54	Techa River	1.5
Isaev	60	Techa River and wells	0.66
Muslyumovo	78	Techa River	1.0
Kurmanovo	88	Techa River	0.72
Brodokalmak	109	Wells and Techa River	0.29
Russkaya Techa	138	Wells and Techa River	0.32
N. Petropavlovskoye	148	Techa River and wells	0.54
Lobanovo	163	Techa River and wells	0.41
Anchugovo	174	Techa River and wells	0.42
V. Techa	176	Techa River and wells	0.50
Pershinskoye	212	Wells and Techa River	0.28
Klyuchevskoye	223	Wells and Techa River	0.20
Zatechenskoye	237	Techa River and wells	0.32

Carlo simulations. The required inputs for these analyses have been developed during the course of Project 1.1. The actual results vary depending on the analysis being undertaken, i.e., the specific individual, the calculational end point year  $Y$ , organ of interest  $o$ , and route of exposure (internal or external).

The preliminary results for the evaluation of uncertainty in individual doses are not currently being used for risk derivation purposes, and the results will not be described here. A more complete discussion of the evaluation of uncertainty in doses calculated with TRDS-2000 has been given in ref. (18).

## RESULTS AND DISCUSSION

The organs for which doses are calculated are red bone marrow, bone surface, stomach wall, small intestinal wall, upper large intestinal wall, lower large intestinal wall, testes, ovaries and uterus. It is possible to include other organs for which dose coefficients have been tabulated by the

ICRP. In general, the criterion for the calculation of dose to a specific organ is whether the dose to that organ is significantly different from the average dose to the other organs.

Cumulative doses are provided for each person on a year-by-year basis starting from the first year of exposure (1950 for those who lived on the Techa River at the onset of contamination or the year of migration to Techa Riverside communities). The calculational end point,  $Y$ , can vary according to the analyst's wishes; for a particular individual, it might be the year of death, the year of exit from the cohort due to migration, the year of vital status determination, or the date of "fixing" the cohort for analysis.  $Y$  could also be any or all of the above minus some presumed latent period for cancer induction. Also, it is possible to perform specific calculations, if desired by the analyst, for

**TABLE 8**  
**Relative Intake of Radionuclides at Various Distances from the Site of Release<sup>a</sup>**

Settlement (distance)	Calendar years	Radionuclide intake relative to local $^{90}\text{Sr}$						
		$^{89}\text{Sr}$	$^{95}\text{Zr}$	$^{95}\text{Nb}$	$^{103}\text{Ru}$	$^{106}\text{Ru}$	$^{137}\text{Cs}$	$^{141,144}\text{Ce}$
Metlino (7 km)	1950–1951	$7.1 \times 10^{-1}$	$2.0 \times 10^{-1}$	$4.0 \times 10^{-1}$	$1.7 \times 10^{-1}$	$8.0 \times 10^{-1}$	1.4	$6.2 \times 10^{-2}$
	1952	$4.9 \times 10^{-3}$	$4.0 \times 10^{-3}$	$5.0 \times 10^{-3}$	$2.9 \times 10^{-4}$	$4.1 \times 10^{-1}$	1.4	$2.7 \times 10^{-2}$
	1953	$3.4 \times 10^{-5}$	$8.0 \times 10^{-5}$	$9.6 \times 10^{-5}$	$4.8 \times 10^{-7}$	$2.1 \times 10^{-1}$	1.4	$1.1 \times 10^{-2}$
Muslyumovo (78 km)	1950–1951	$6.8 \times 10^{-1}$	$7.8 \times 10^{-2}$	$2.1 \times 10^{-1}$	$1.3 \times 10^{-1}$	$6.4 \times 10^{-1}$	$2.8 \times 10^{-1}$	$3.2 \times 10^{-2}$
	1952	$4.7 \times 10^{-3}$	$1.6 \times 10^{-3}$	$2.0 \times 10^{-3}$	$2.2 \times 10^{-4}$	$3.3 \times 10^{-1}$	$2.8 \times 10^{-1}$	$1.3 \times 10^{-2}$
	1953	$3.2 \times 10^{-5}$	$3.1 \times 10^{-5}$	$3.7 \times 10^{-5}$	$3.7 \times 10^{-7}$	$1.7 \times 10^{-1}$	$2.8 \times 10^{-1}$	$5.7 \times 10^{-3}$
Brodokalmak (109 km)	1950–1951	$6.7 \times 10^{-1}$	$5.2 \times 10^{-2}$	$1.6 \times 10^{-1}$	$1.2 \times 10^{-1}$	$5.8 \times 10^{-1}$	$1.4 \times 10^{-1}$	$2.4 \times 10^{-2}$
	1952	$4.6 \times 10^{-3}$	$1.0 \times 10^{-3}$	$1.3 \times 10^{-3}$	$2.0 \times 10^{-4}$	$3.0 \times 10^{-1}$	$1.4 \times 10^{-1}$	$1.0 \times 10^{-2}$
	1953	$3.2 \times 10^{-5}$	$2.0 \times 10^{-5}$	$2.5 \times 10^{-5}$	$3.3 \times 10^{-7}$	$1.5 \times 10^{-1}$	$1.4 \times 10^{-1}$	$4.3 \times 10^{-3}$
Zatechenskoye (237 km)	1950–1951	$6.3 \times 10^{-1}$	$9.4 \times 10^{-3}$	$4.7 \times 10^{-2}$	$7.3 \times 10^{-2}$	$3.9 \times 10^{-1}$	$7.6 \times 10^{-3}$	$6.9 \times 10^{-3}$
	1952	$4.3 \times 10^{-3}$	$1.9 \times 10^{-4}$	$2.5 \times 10^{-4}$	$1.2 \times 10^{-4}$	$2.0 \times 10^{-1}$	$7.6 \times 10^{-3}$	$2.9 \times 10^{-3}$
	1953	$3.0 \times 10^{-5}$	$3.7 \times 10^{-6}$	$4.5 \times 10^{-6}$	$2.0 \times 10^{-7}$	$1.0 \times 10^{-1}$	$7.6 \times 10^{-3}$	$1.2 \times 10^{-3}$

Note. Examples are shown for the years of major intake.

<sup>a</sup> Values relative to corresponding  $^{90}\text{Sr}$  intake.

**TABLE 9**  
**Red Bone Marrow Dose Conversion Factors (Gy Bq<sup>-1</sup>) for the Ingestion of <sup>90</sup>Sr (16)**

Time (Y - y) since intake, years	Age at intake, years				
	1	5	15	20	30
1	$1.83 \times 10^{-7}$	$8.04 \times 10^{-8}$	$6.25 \times 10^{-8}$	$4.00 \times 10^{-8}$	$3.49 \times 10^{-8}$
2	$2.59 \times 10^{-7}$	$1.27 \times 10^{-7}$	$1.07 \times 10^{-7}$	$6.75 \times 10^{-8}$	$5.84 \times 10^{-8}$
3	$3.09 \times 10^{-7}$	$1.59 \times 10^{-7}$	$1.42 \times 10^{-7}$	$8.99 \times 10^{-8}$	$7.74 \times 10^{-8}$
4	$3.45 \times 10^{-7}$	$1.83 \times 10^{-7}$	$1.72 \times 10^{-7}$	$1.09 \times 10^{-7}$	$9.34 \times 10^{-8}$
5	$3.72 \times 10^{-7}$	$2.01 \times 10^{-7}$	$1.98 \times 10^{-7}$	$1.25 \times 10^{-7}$	$1.07 \times 10^{-7}$
10	$4.33 \times 10^{-7}$	$2.40 \times 10^{-7}$	$2.88 \times 10^{-7}$	$1.79 \times 10^{-7}$	$1.52 \times 10^{-7}$
20	$4.53 \times 10^{-7}$	$2.60 \times 10^{-7}$	$3.69 \times 10^{-7}$	$2.23 \times 10^{-7}$	$1.89 \times 10^{-7}$
30	$4.58 \times 10^{-7}$	$2.66 \times 10^{-7}$	$3.99 \times 10^{-7}$	$2.38 \times 10^{-7}$	$2.00 \times 10^{-7}$
40	$4.60 \times 10^{-7}$	$2.69 \times 10^{-7}$	$4.12 \times 10^{-7}$	$2.44 \times 10^{-7}$	$2.04 \times 10^{-7}$
50	$4.61 \times 10^{-7}$	$2.71 \times 10^{-7}$	$4.18 \times 10^{-7}$	$2.46 \times 10^{-7}$	$2.06 \times 10^{-7}$

example, to examine the association of risk with only external dose or only internal dose from one or more radionuclides.

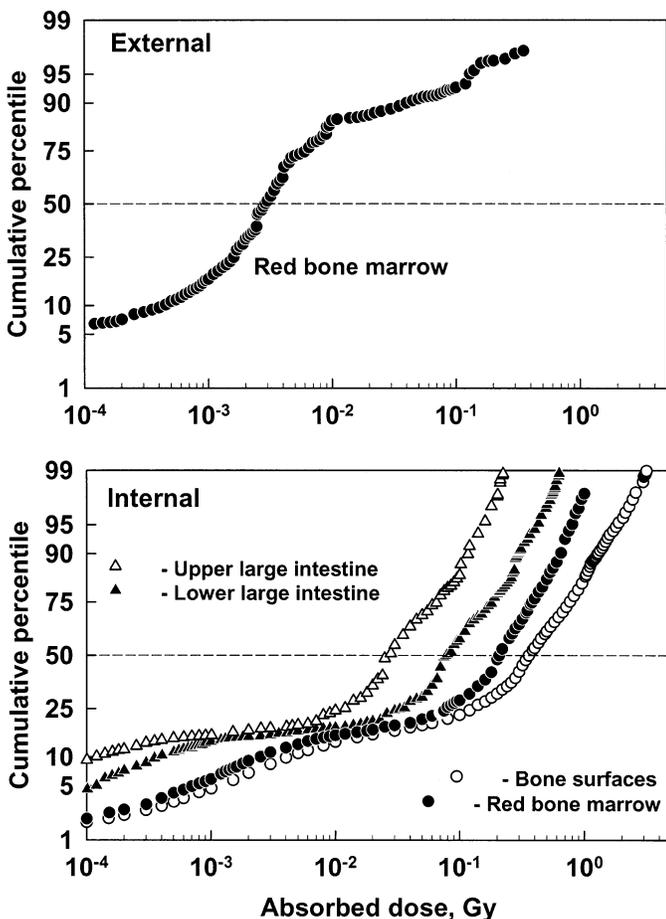
As described above, internal doses for members of the ETRC are calculated on the basis of age- and location-specific mean annual intake levels of radionuclides, age-

dependent biokinetic models for radionuclides, and individual residence histories for each subject. Figure 4 (lower) presents the distributions of internal dose in red bone marrow, bone surface, upper large intestine, and lower large intestine among the members of the ETRC. More than half of the people have internal red bone marrow doses between 0.1 and 0.5 Gy. Absorbed doses in cells on the bone surface have distributions similar to those for the red bone marrow, but the values are about two times higher. Most of these doses are due to <sup>90</sup>Sr, but the new (TRDS-2000) values include contributions from additional radionuclides. For the four organs shown, doses for the upper large intestine are the lowest, with 50% of the doses between 0.009 and 0.06 Gy; doses to the lower large intestine are two to three times higher than the doses for the upper large intestine. The primary radionuclide contributing to doses to tissues other than bone is <sup>137</sup>Cs.

Calculations of external dose show that the new assessments are significantly lower than those published in 1994 (14). Figure 4 (upper) shows the new distribution of external dose; about half of the doses are between 0.0017 and 0.0062 Gy.

The distributions of total dose accumulated through 1990 for 29,873 members of the ETRC are shown in Table 10. The majority of persons received soft-tissue doses within the range of 1–10 mGy, 10–100 mGy for the colon and 100–1000 mGy for the red bone marrow and bone surface. The maximum dose was 5.2 Gy to the bone surface.

Estimates of dose to the red bone marrow are as large as 2 Gy, with mean and median values of 0.30 and 0.21 Gy, respectively. On average, 92% of the red bone marrow dose is due to internal β-particle emitters, and <sup>90</sup>Sr alone contributes 89% of the total red bone marrow dose. In contrast, about 70% of the dose to the stomach and most other soft tissues is on average due to external exposure, with the remainder due mainly to the ingestion of <sup>137</sup>Cs. However, the dose to the lower large intestine is higher and ranges up to 1.1 Gy; most of the lower large intestine dose is due to the ingestion of radiostrontium and other radionuclides with poor intestinal absorption. On average, 95% of the



**FIG. 4.** Distribution of doses to (upper panel) the red bone marrow due to external dose and (lower panel) internal doses from radionuclide intake to the red bone marrow, the bone surface, the upper large intestine, and the lower large intestine.

**TABLE 10**  
**Distribution of Total Dose Accumulated through 1990 for about 30,000 Members of the ETRC**

Organ	Total dose, Gy					
	10%	25%	50%	75%	90%	Maximal
Red bone marrow	0.0037	0.082	0.21	0.40	0.71	2.0
Bone surface	0.0062	0.13	0.37	0.83	1.4	5.2
Lower large intestinal wall	0.0014	0.040	0.081	0.19	0.38	1.1
Upper large intestinal wall	0.0011	0.015	0.030	0.072	0.18	0.60
Small intestinal wall	0.00092	0.0047	0.0095	0.024	0.059	0.45
Stomach wall	0.00090	0.0036	0.0064	0.018	0.051	0.46
Testes	0.0011	0.0040	0.0068	0.018	0.057	0.53
Ovaries	0.00080	0.0031	0.0053	0.015	0.046	0.42
Uterus	0.00081	0.0030	0.0052	0.015	0.046	0.42

Organ	Percentage of population with the indicated range of dose				
	≤1 mGy	1–10 mGy	10–100 mGy	100 mGy–1 Gy	>1 Gy
Red bone marrow	4.1	10.4	13.4	<b>68.9</b>	3.2
Bone surface	3.0	8.2	13.6	<b>58.6</b>	16.6
Lower large intestinal wall	7.7	9.1	40.4	<b>42.7</b>	0.1
Upper large intestinal wall	9.6	10.7	<b>59.6</b>	20.1	—
Small intestinal wall	10.8	<b>45.6</b>	35.7	7.9	—
Stomach wall	11.1	<b>57.8</b>	23.5	7.6	—
Testes	9.4	<b>57.8</b>	24.8	8.0	—
Ovaries	12.2	<b>60.1</b>	20.2	7.5	—
Uterus	12.1	<b>60.4</b>	20.0	7.5	—

*Notes.* The upper part of the table gives the distributions of dose by percentiles. The lower part of the table gives the percentage of the population within several dose ranges. Values in boldface indicate the dose range received by the majority of the population.

lower large intestine dose is due to internal exposure, and  $^{90}\text{Sr}$  alone contributes 33% of the total dose.

The key factor that determines the level of external dose for a person is the distance of the residence location from the site of the release. This factor is also important for internal dose, but for dose to the red bone marrow, the more important factor is the age of the person during the period of releases. Due to the age dependences of mineral metabolism, persons in their teens during the period of releases received maximal levels of red bone marrow and bone surface exposure.

#### Quality Assurance

Much of the work accomplished as the main part of this project is of the nature of quality control/quality assurance. The models and databases used in TRDS-2000 have been validated by comparison with experimental data (as discussed below). One of the primary aspects of the overall project has been the recalibration of the URCRM whole-body bremsstrahlung counter, which is a critical component of the study in terms of providing primary data for the reconstruction of internal dose. The situation for this dose reconstruction effort is highly unusual in that about half of the individuals making up the original TRC have been counted at least once in the unique URCRM whole-body counter; thus the body burdens of the most significant (in terms of dose) radionuclide,  $^{90}\text{Sr}$ , have been measured directly. The  $^{90}\text{Sr}$  body burdens measured for the TRC members have been used for the development of an age-depen-

dent strontium metabolic model (this model has been used to produce TRDS-2000 databases SR90 and SR89) and for the reconstruction of the relative  $^{90}\text{Sr}$  intakes for the Techa Riverside settlements (TRDS-2000 database NUCLSTC).

#### 1. Validation of the strontium biokinetic model

An age-dependent strontium biokinetic model was elaborated for dose estimation for residents of the villages along the Techa River (16, 28). This model takes into account changes in metabolic parameters throughout the entire life of the subject, beginning with bone formation and growth in childhood and including loss of skeletal calcium in old age. Age dependences for the model parameters were obtained by fits to available data sets of  $^{90}\text{Sr}$  measurements in humans. Data with different schedules of intake were used for parameter evaluation: (1) the age dependence of long-term  $^{90}\text{Sr}$  body burdens as measured by the whole-body counter of the residents of Muslyumovo on the Techa River in 1976 (28); (2) United Kingdom (national survey) and United States (New York and San Francisco) data on  $^{90}\text{Sr}$  from global fallout as reported in refs. (29, 30); and (3) experimental data for a single intake of  $^{85}\text{Sr}$  in volunteers (31).

To validate the age-dependent biokinetic model for strontium, model predictions were compared with experimental data other than those used for the evaluation of model parameters (28, 32). It has been found that model predictions are in reasonable agreement with the measurements of global  $^{90}\text{Sr}$  in children's bones from the Glasgow survey

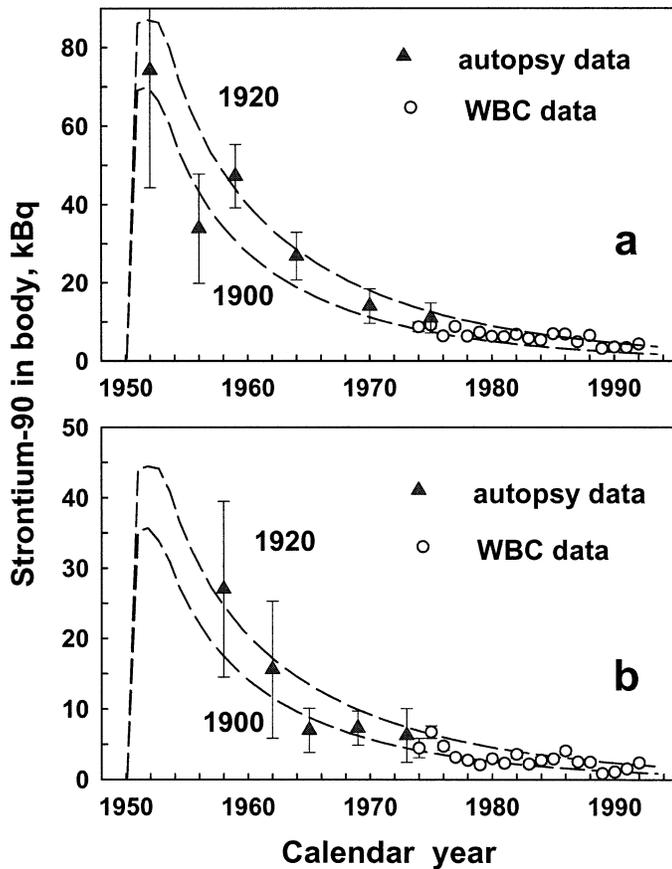


FIG. 5. Mean levels of  $^{90}\text{Sr}$  in adult humans (birth cohort between 1900 and 1920) for the Techa Riverside settlements (panel a) up to 80 km from the site of release and (panel b) for distances of 90–150 km. The model curves outline the corridor of values between age cohorts born in 1900 and in 1920. WBC, whole-body counter.

(33) and also with data from the Czech Republic (34). In addition, model calculations were compared with measured levels for adults (autopsy data plus whole-body counter data obtained after 1976) obtained from 40 years of observation on the Techa River. Figure 5a shows the mean levels for the upper- and mid-Techa region, where the measurements were started in 1951, and Fig. 5b shows the measurements for the lower reaches, which were started after 1956. Two model curves outline the corridor of values for age cohorts included in the measurements. The consistency of model calculations and measured values is obvious.

In addition, predictions of  $^{90}\text{Sr}$  body burden were performed using URCRM and ICRP67 (25) biokinetic models for the area contaminated as a result of the Chernobyl accident (7–12 years after the accident) and for Muslyumovo on the Techa River (30–45 years after the onset of contamination). The comparison of these calculations with the results of actual measurements (autopsy data obtained in 1993–1998 for the Zhitomir Oblast contaminated as a result of the Chernobyl accident and whole-body counter measurements obtained in 1978–1994 for the residents of Muslyumovo) has been described (26). This comparison has

demonstrated that both biokinetic models (URCRM and ICRP 67) satisfactorily describe the measurements for adults in the case of the Chernobyl accident. Applied to other ages, the URCRM model curves are in good agreement with  $^{90}\text{Sr}$  body burdens measured with the SICH-9.1 whole-body counter between 1978 and 1994 for all age cohorts of the Muslyumovo residents. (Recall that whole-body counter data obtained in 1974–1978 only have been used for model parameter evaluation.) The ICRP 67 model predictions were found to be higher than the whole-body counter data for people aged 10–20 years at the onset of intake and lower by a factor about 1.5–1.8 for children aged 1–5 years at the onset of intake (26).

The consistency between the URCRM strontium biokinetic model calculations and the results of actual measurements in humans of different ages for different schedules of intake and for periods as long as 45 years after intake assures the reliability of this model used in TRDS-2000 for the calculation of internal doses due to  $^{90}\text{Sr}$ .

## 2. Validation of the Techa River Model

The Techa River Model was developed to reconstruct radionuclide concentrations in water and sediments for the early period of contamination between 1949 and 1951. This model is used in TRDS-2000 for the calculation of relative intakes of  $^{137}\text{Cs}$  and short-lived radionuclides (database NUCLSTC) and for the reconstruction of exposure rates on the riverbank (database TECHEXT) for the period 1949–1951, when there were no appropriate measurements.

As demonstrated in ref. (15), this model successfully correlates the rates of releases as reconstructed by the Mayak experts, hydrological data, and available environmental monitoring data. Two data sets have been used to evaluate model parameters:

1. Results of experiments on physical modeling of radionuclide behavior in different kinds of artificial reservoirs carried out in 1953–1954 in the Urals.
2. Measurements of specific  $\beta$ -particle activity in the water of the Techa River along the distance from the site of release for 1951.

Parameter estimates obtained for the Techa River are compatible with values published in the literature for a similar watercourse (35). Also, the calculated rates of change of  $^{90}\text{Sr}$  and  $^{137}\text{Cs}$  concentrations in water for the period of massive releases are in reasonable agreement with the results of measurements of these long-lived radionuclides performed in the 1960s and 1970s for flood-plain soils extensively contaminated in 1951 (15). The Techa River Model predictions are also validated by experimental data on radionuclide concentration in bottom sediments (these data have not been used for the evaluation of model parameters).

An important result of the modeling was the ability to reconstruct external  $\gamma$ -ray dose rates in air near the riverbank. These dose rates were calculated for 1950–1951 on

the basis of modeled and measured radionuclide concentrations in bottom sediments using two different methods, and the results showed reasonable agreement with each other (15). The results of analogous calculations performed for 1952 were validated by actual measurements. The close agreement of the values calculated using both approaches and measurement results provides assurance that the levels of river-system contamination in 1949–1950 and the external  $\gamma$ -ray dose rates reconstructed using this model are reliable.

### 3. Possibilities for the validation of external doses

Because substantial uncertainty is attached to the estimates of external dose, validation of the new assessments of external dose is an issue of major importance. There is an unsubstantiated allegation (36) that the current calculations of external dose are low by a factor of three to five. The more useful, accepted methods of validation are measurements of luminescence of quartz extracted from bricks and, more importantly, the measurement of dose in teeth of members of the ETRC through the technique of electron paramagnetic resonance (EPR). Fluorescence *in situ* hybridization (FISH) is also a possible technique for validation of external dose.

The applicability of the use of “natural” solid-state dosimeters such as quartz (a component of bricks) and hydroxyapatite (a component of tooth and bone tissue) has been investigated within the framework of this JCCRER Project and a separate project supported by the European Commission (the Coordinator is Dr. Peter Jacob, GSF, Germany). Samples of bricks from abandoned (but still standing) buildings located near the Techa shoreline were collected, the quartz was extracted from the bricks, and doses were assessed using luminescence methods (37, 38). Monte Carlo simulations of doses accrued in bricks were performed for the geometries of exposure specific to the sample sites on the basis of the dose rates in air near the shoreline as reconstructed with the Techa River Model. It was found that the calculated and measured doses in bricks are in reasonable agreement (37, 38). This early study demonstrated the potential of the luminescence method in combination with Monte Carlo simulations of radiation transport at sampling sites for the validation of environmental doses in the upper and middle Techa region. More advanced studies have been reported recently by Jacob and colleagues (39, 40) for samples taken in Metlino; the results again show that the calculational approach used in the TRDS-2000 is confirmed by the analysis of quartz taken from fixed locations.

An initial pilot study (41, 42) was performed to measure dose received by teeth as determined by EPR analysis. The applicability of EPR for retrospective individual dose evaluation was confirmed. This method, based on measurements of samples collected for dental health reasons, also provides the capability for validation of estimates of un-

certainty in assessment of external dose. An analysis of the territorial distribution of living subjects included in the ETRC has been performed to show that it is feasible to arrange a special system for obtaining sufficient numbers of tooth samples for EPR analyses. Some studies were also carried out for the purpose of improving the experimental technique (43–45). A comparison (46) of EPR-based individual results for 13 residents of Metlino with mature teeth at the time of the releases showed excellent agreement with the calculated estimates derived from use of the TRDS-2000 approach. Also, it has been shown (27) that, for the middle Techa region, EPR doses are comparable with the sum of the background dose plus the dose from incorporated  $^{90}\text{Sr}$  (the latter has been calculated using Monte Carlo simulation of electron transport in tooth tissues). This finding confirms that the external component of total dose for the middle and lower Techa region was relatively low. In general, these studies have demonstrated the potential of EPR methods for the validation of individual external doses for members of the ETRC.

A careful analysis (46) of FISH results (presumed to represent primarily external dose) for 28 permanent residents of Metlino, some of which were reported previously by Bauchinger *et al.* (47), indicated a FISH-based sample-average value of  $0.38 \pm 0.10$  (mean  $\pm$  standard error of mean) Gy, whereas the estimated sample average from use of the TRDS-2000 was  $0.31 \pm 0.03$  Gy.

The comparative analysis of the applications of the above three retrospective dosimetry methods (luminescence, EPR and FISH) for the first validation of external doses for the Metlino site indicates that it is feasible to validate TRDS-2000 external dose estimates in the future.

### *Possibilities of Additional Improvements in Dosimetry (TRDS-2006)*

The substantial improvements in the TRDS-2000 have led to significant changes in the estimates of dose for members of the ETRC. Further major improvements in the dosimetry system to support epidemiological studies can be made by:

1. Further study of uncertainty with the goal of reducing uncertainty in the final dose estimates.
2. Study of other sources of dose that could confound the analysis of the epidemiological data for the members of the ETRC.
3. Validation of the dose estimates, particularly of the revised estimates of external dose.

Work will continue to focus on analysis of uncertainty, and how these results can be used to direct work on the major sources of uncertainty that can be reduced. The analysis of uncertainty has not yet been formalized into the TRDS-2000 through the creation of a Monte Carlo version of the entire TRDS code. This is a major task that is of high priority. It is evident that there are two relatively large sources of uncertainty that can be reduced. One is the as-

sociation of a particular individual with the location of the house within which he/she lived. This is an important variable affecting external dose. At present a household-weighted distance of homes from the river in each village is being assumed with attendant large uncertainty in the estimated dose. Another major source of uncertainty relates to the source of drinking water (water taken from the river or from wells). Based on data on direct measurements of body burdens, it seems clear that this source of uncertainty might be reduced in a variety of ways. The preferred way would be to use the measured body burdens directly as individual input data. This is not being done at present because about half of the members of the original cohort do not have such measurements. However, it is possible to associate family members into households wherein one or more other persons did have such measurements. The assumption could then be made that all members of the household had the same source of drinking water. Another helpful aspect will be the continuation of counting of additional members of the cohort with the SICH-9.1 whole-body counter.

In terms of confounding sources of dose to the members of the ETRC, there are three known sources. One is the East Urals Radioactive Trace (EURT), or the Kyshtym explosion in 1957. This source of radioactive material is known to have affected a few thousand members of the ETRC who had been relocated away from the Techa River and into the path of the future EURT. The ability to calculate doses from the EURT for this subset of the ETRC already exists in the TRDS-2000 code. However, there has not been an evaluation of the existing data to support the necessary input parameters on time- and location-dependent intake rates of radionuclides and on external  $\gamma$ -ray exposure rates.

Another potentially major source of confounding exposure is the gaseous releases through the radiochemical plant stacks at the MPA. Large releases of  $^{131}\text{I}$  and other radionuclides are known to have occurred (48). And finally and as discussed above, there is reason to believe that the members of the ETRC who were more heavily exposed were examined medically rather frequently. Such examinations included a full battery of radiological diagnostic examinations.

Validation of the internal doses calculated with use of the TRDS-2000 continues. One recent success has been the rederivation of the  $^{90}\text{Sr}$  intake function by a method that is more rigorous and that produces continuous, rather than point, estimates (49). Work also continues to formalize completely an age- and gender-dependent biokinetic model for strontium developed specifically for the Techa River population—the Techa Biokinetic Model (50).

Finally, the validation of the new estimates of external dose is considered to be a critical factor in the continuing credibility of the TRDS-2000 results and the companion epidemiological studies they support. Recent successes in the measurement of doses by luminescence of natural ma-

terials, by EPR of tooth enamel, and by FISH of circulating lymphocytes have demonstrated that these measurements can be applied to the Techa River situation. However, the measurements can be difficult and must be supported by extensive modeling to help in the interpretation of the measured results. For example, the time-dependent, complicated source geometries must be modeled to interpret the results of luminescence measurements. The EPR measurements are also complicated by the fact that the measurements of external dose are affected by the presence of  $^{90}\text{Sr}$  in dental tissues. Thus an EPR measurement by itself is not sufficient as a validating measurement without some accompanying knowledge of the contribution of  $^{90}\text{Sr}$  and perhaps other radionuclides. Fortunately, there have been recent advances in the understanding of the tooth as a complex dosimeter (51–53). The FISH-based measurements can be complicated to an unknown extent by the presence of  $^{90}\text{Sr}$  in bone tissue, and the interpretation of FISH measurements must rely on adequate calibration curves that are convincingly suitable for complex exposure situations.

## CONCLUSIONS

Substantial improvements have been made in the Techa River Dosimetry System (TRDS-2000). These improvements have brought substantial changes in the estimates of dose for the members of the ETRC.

Limited data on validation generally support the new estimates, but validation work is considered as an important, continuing task.

The first preliminary results of the analysis of uncertainty in the TRDS doses have provided valuable insight into how work can be directed to reduce uncertainty in dose estimates. The further study of uncertainty, effective implementation of a Monte Carlo version of the TRDS-2000 code, and work on reducing uncertainty are important aspects of future plans.

There are confounding sources of dose for some members of the ETRC, such as the EURT, the gaseous emissions from the MPA, and a potential bias in medical exposure toward those more highly exposed on the Techa River. Better means of estimating these confounding sources of dose will be part of future investigations of this cohort.

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