DESCRIPTION OF THE COMPUTER DATABASE "TOOTH" AND DISCUSSION OF REQUIREMENTS FOR EPR MEASUREMENTS TO SUPPORT A VALIDATION STUDY OF EXTERNAL DOSES CALCULATED BY USE OF THE TECHA RIVER DOSIMETRY SYSTEM-2000

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1. INTRODUCTION

The Mayak Production Association (MPA) was the first Russian site for the production and separation of plutonium. The extensive increase in plutonium production during 1948–1955, as well as the absence of reliable waste-management technology, resulted in significant releases of liquid radioactive effluent into the rather small Techa River. This resulted in chronic external and internal exposure of about 30,000 residents of riverside communities. The major ^{90}Sr intake by inhabitants of the area occurred in 1950–1951. About 3,000 kBq of ^{90}Sr were ingested with river water by the residents of the upper and mid-Techa region. The "Extended Techa River Cohort" (ETRC) has been studied for several decades by scientists from the Urals Research Center for Radiation Medicine (URCRM). A special database was established for the follow-up of the exposed population. This database contains the roster of exposed persons, their residence histories, and the results of medical and dosimetric examinations. A long-term dosimetric study has produced a unique database on the content of ^{90}Sr in the human body, including measurements of the radionuclide in bones, teeth and whole body for more than 15,000 exposed persons for a period of more than 45 years.

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 the releases from the MPA (Degteva et al. 2000). As a result of the recent completion of the first phase of Project 1.1 (1996–2000), many improvements have been accomplished in the derivation and implementation of Techa River Dosimetry System-2000 (TRDS-2000[*]); these improvements resulted in major changes in doses calculated for members of the ETRC. For example, external doses were re-evaluated on the basis of more complete examination of the existing data and on more realistic (rather than radiation-protection) assumptions, and the currently estimated doses from external exposure decreased by as much as a factor of ten compared to earlier estimates (Vorobiova et al. 1999; Degteva et al. 2000). And finally, the uncertainty in both the internal and external doses was evaluated for the first time (Napier et al. 2000; Shagina et al. 2000).

Validation of the new estimates of external dose is considered to be a critical factor in establishing the continuing credibility of the TRDS-2000 results and of the companion epidemiologic studies they support. Recent successes in the measurement of doses by thermoluminescence of natural materials and by electron paramagnetic resonance (EPR) of tooth enamel have demonstrated that these measurements can be applied to the Techa River situation. The validation task of the current project is planned as the combined analysis of the entire pool of EPR measured samples. This combined analysis and the supportive modeling necessary for the interpretation of the EPR results will be used for the purpose of validation of estimates of external dose and further evaluation of associated uncertainties.

It is planned to work in close cooperation with other institutions to study and analyze the results of several groups of methods and data sets:

[*] The TRDS-2000 is a codified database processor that is used to calculate doses for members of the ETRC.

- EPR spectrometry (including intercomparison among the different laboratories involved and the different techniques used for sample preparation, EPR measurement, and spectrum analysis);
- Determination of the concentration of ^{90}Sr in tooth tissues (enamel, dentin) by low-level beta counting, radiochemistry or other methods;
- Modeling of strontium metabolism in teeth (necessary to reconstruct the complete time pattern of ^{90}Sr retention in tooth tissues since the onset of intake); and
- Monte Carlo modeling of electron and photon transport and absorbed dose distribution through human tissues (including geometric models of teeth).

Also, it is planned to improve and expand the special data base that has been established for this purpose in order to include all information pertinent for each tooth sample: Identification Code (IC) of the donor; his/her residence history and house location; medical exposure; date and place of tooth extraction; tooth position and odontometric measurements (which will be used as input parameters for geometric models of teeth); date and laboratory of EPR measurements; and date, method and laboratory for ^{90}Sr measurements (these ^{90}Sr measurements are very important for correct evaluation of the contribution of ^{90}Sr to the total dose measured by EPR).

The purposes of this document are the following:

1. To describe the database "TOOTH," which contains data on tooth samples and tooth donors for the members of the ETRC and for residents of background areas and available data on EPR and ^{90}Sr measurements in tooth tissues;
2. To evaluate the uncertainty of EPR-tooth-dosimetry methods used for dose reconstruction in the Southern Urals;
3. To analyze background levels of the EPR signal from tooth enamel for residents of non-contaminated areas of the Urals region;
4. To present a preliminary analysis of the different contributions to EPR signals for the members of the ETRC; and
5. To summarize the requirements for the TRDS-2000 external dose-validation study.

2. BACKGROUND: PILOT EPR STUDIES IN THE URALS REGION

Preliminary EPR studies of the Techa River population (Romanyukha et al. 1996a,b; Wieser et al. 1996) have shown that the absorbed dose in tooth enamel consists of three main contributions: external exposure; internal exposure mainly due to ^{90}Sr; and background radiation including all other sources of exposure, except that arising from the Techa River. Thus, an EPR measurement by itself is not sufficient as a validation without some accompanying knowledge of the contribution of ^{90}Sr and background exposure to the resulting EPR signal.[†] Therefore, EPR

[†] In addition, as experience is gained with EPR as a dose-reconstruction tool, it is becoming apparent that some teeth exhibit large EPR signals that are inexplicable. Either some agent other than radiation is causing these signals, or a small, but significant fraction of persons has received large unknown or unremembered radiation exposure. For this reason, only a few EPR measurements are not an adequate basis for establishing conclusions.

measurements must be supported by an evaluation of the EPR-background signal, extensive modeling, and the determination of ^{90}Sr in tooth tissues in order to support interpretation of the EPR measurements (Tolstykh et al. 2000).

The issues of human-tissue-dose assessment on the basis of EPR measurements have once again attracted attention to the unique URCRM data base on the measurements of ^{90}Sr in teeth, bones and whole body for those exposed on the Techa River (Table 1).

The following tasks devoted to determining the contribution of ingested ^{90}Sr to the absorbed dose in enamel of teeth from Techa Riverside residents that can be performed on the basis of the data sets shown in Table 1 were described by Tolstykh et al. (2000):

- Analysis of ^{90}Sr measurements in teeth available in the URCRM data base in order to develop a model for retention of this nuclide in human teeth;
- Investigation of the correlation between ^{90}Sr content in teeth and in the skeleton and determination of the feasibility of the prediction of ^{90}Sr concentration in teeth on the basis of WBC measurements;
- Development of approaches to the evaluation of absorbed dose in enamel from the ^{90}Sr incorporated in tooth tissues using Monte Carlo simulation; and
- Preliminary comparison of enamel-dose estimates obtained by Monte Carlo simulations with the results of EPR measurements.

The findings of this study have outlined future tasks for the development of a dose-reconstruction methodology for members of the Techa River Cohort, who have combined external exposure and internal exposure due to ^{90}Sr intake: Combined measurements of ^{90}Sr concentrations and absorbed doses (measurable by the EPR method) in different tooth tissues should allow the determination of the ^{90}Sr contribution to absorbed dose to teeth. If the ^{90}Sr concentration can be measured with sufficient accuracy, it should be possible to determine the external exposure by subtraction of the ^{90}Sr component and the background component from the total absorbed dose in enamel.

Table 1. URCRM database on ^{90}Sr in humans.

Name of registry	Method of measurement	Number of samples or measurements	Period of measurement	Number of Techa River residents examined
Autopsy Registry (AR)	Radiometry and/or radiochemistry of autopsy samples (bones and teeth)	921 bones and 66 teeth	1951–1993	260
Tooth Registry (TR)	Radiochemistry of extracted teeth	342 teeth	1959–1964	270
Tooth-beta count (TBC)	In vivo measurement of surface beta activity of the four anterior teeth	29,720 measurements	1959–1995	15,255
Whole-body count (WBC)	In vivo measuring the bremsstrahlung of ^{90}Y-beta rays with a phoswich detector in a specially shielded room	31,800 measurements	1974–1995	15,250

Preliminary EPR studies also led to the development of a strategy for tooth sampling (Degteva et al. 1997) as follows. It is necessary to collect enough teeth for three groups in the population with different kinds of exposure: 1) Exposure only to background sources [people who did not live near the Techa River after the onset of radioactive contamination]; 2) Exposure due to background plus ^{90}Sr ingestion with water from the Techa River (residents of the middle and lower Techa Riverside); and 3) External exposure from the Techa River bottom sediments plus internal exposure due to ^{90}Sr plus background radiation (residents of the upper Techa Riverside).

These pilot studies have demonstrated the applicability and importance of EPR measurements of teeth to population-dose reconstruction in the Urals region. However, the additional source of exposure of teeth to ^{90}Sr incorporated within the tooth adds a complicating factor. Adequate resolution of this complicating factor will not be trivial.

3. DESCRIPTION OF DATABASE "TOOTH"

Measurements of ^{90}Sr in extracted permanent teeth from the Urals residents were performed at the URCRM during 1959–1964 (Table 1). The teeth under investigation were extracted for reasons of dental health, and ^{90}Sr in the teeth was measured by radiochemical separation and counting. Later, these results (342 teeth in total) were matched with the roster of exposed persons and arranged as the so-called Tooth Registry (Tolstykh et al. 2000).

At the end of 1991 the collection of tooth samples in the Urals was started again (Table 2) with the purpose of providing validation using the EPR method of dose reconstruction. Tooth collection has continued during a 10-y period, but the source of financial support has changed several times (EMERCOM and Ministry of Health of the Russian Federation; the U.S.

Table 2. The dynamics of tooth collection.

Calendar year	Number of teeth from exposed donors	Number of teeth from background donors	Total number per year
1992	37	1	38
1993	41	1	42
1994	22	0	22
1995	36	1	37
1996	25	0	25
1997	66	159	225
1998	105	222	327
1999	171	303	474
2000	57	416	473
2001[a]	2	63	65
Sum	562	1168	1728

[a] Status as of February.

Department of Energy's Office of Health Studies; the European Commission via an INCO-COPERNICUS project; and finally through a grant from the International Science and Technology Center [ISTC]). During the first five years (1992–1996) the majority of tooth samples were collected in the URCRM clinic; about 30 teeth were collected per year, and almost all of the teeth were from exposed persons. During the second five years (1997–2001) the majority of samples has been received from dentists from rural clinics of Chelyabinsk Oblast (Kunashaksky, Sosnovsky and Krasnoarmejsky Raions) and Kurgan Oblast (Dalmatovsky and Katajsky Raions). It should be noted that the majority of the members of the ETRC now live in these five raions; also, the "unexposed" part of the population in these raions is now being considered as a comparison or control group in the companion epidemiologic studies.

In addition, during the last three years an exchange of information on tooth donors and tooth samples has been arranged with dosimetrists at the Mayak Production Association (MPA) within the framework of a joint ISTC contract. The reason for such an exchange is that the system for the collection of teeth from Mayak workers and Ozyorsk residents (established by the MPA) has received some samples from former Techa Riverside residents and persons exposed due to the Kyshtym Accident (who now live in Ozyorsk). It is possible to identify such persons (and then to select appropriate subpopulations for common analysis) only by matching the MPA tooth-donors list with the URCRM roster of the population exposed on the Techa Riverside.

As a result of these activities, for the last five-y period more than 300 teeth per year have been collected, but only 27% of them were received from exposed donors. Over the 10-y period more than 1700 teeth have been collected, and 562 teeth have come from exposed persons (Table 2).

Because the URCRM does not have an EPR spectrometer, it has been necessary to make special agreements with other institutions to measure the collected samples. Since 1992 the URCRM has supplied tooth samples (Table 3) to the following institutions performing EPR measurements:

- Institute of Chemical Physics (ICP), Moscow, Russia;
- GSF-National Research Center for Environmental and Health (GSF), Neuherberg, Germany;
- Institute of Metal Physics (IMP), Ekaterinburg, Russia;
- Center for Applied Dosimetry (CAD), University of Utah, Salt Lake City, USA;
- National Institute of Standards and Technology (NIST), Gaithersburg, USA; and
- Medical Radiobiological Research Center (MRRC), Obninsk, Russia.

The fate of a whole tooth sent to an EPR laboratory could be quite different depending upon a variety of conditions. Typically, for EPR measurements it is necessary to separate tooth tissues (enamel, crown dentin and root), then to crush these tissues into grains, and to treat the grains with chemicals. There were some cases when after such treatment the mass of the sample became too low for EPR analysis (<20 mg). Also, there were some cases when all three types of tooth tissue (enamel, crown dentin and root) from a single tooth were measured; and there were

Table 3. The dynamics of teeth sent for analysis to EPR laboratories.

Calendar year	Number of teeth	Laboratories
1992	20	ICP
1993	26	ICP, GSF
1994	22	GSF
1995	14	GSF
1996	9	IMP
1997	21	IMP, GSF
1998	115	IMP, CAD, NIST
1999	57	IMP, GSF, NIST
2000	65	IMP, GSF, MRRC
2001[a]	16	IMP, MRRC
Sum	310	

[a] Status on February

some cases of repeated measurements of the same samples, but in different laboratories. Therefore, the number of EPR measurements received (Table 4) is not equal to the number of teeth sent for analysis.

In addition, some EPR laboratories, such as the IMP, the ICP and the Moscow Institute of Biophysics (IBP), made direct arrangements in 1992–1994 with Urals dentists for collection of teeth for independent EPR studies. Then, the technical reports on these studies were sent to the URCRM in order to match the lists of tooth donors (investigated by EPR and/or other methods) with the roster of exposed persons. In such a way the individual-exposure histories (available at the URCRM) and the results of EPR measurements from other laboratories became available for further common analysis.

Table 4. The dynamics of EPR measurements of teeth received from EPR laboratories.

Calendar year	Number of EPR measurements	Laboratories
1992	22	ICP, IMP
1993	17	ICP, GSF
1994	35	GSF, IBP
1995	10	GSF
1996	9	IMP
1997	19	IMP, GSF
1998	117	IMP, CAD
1999	53	IMP, GSF
2000	108	IMP, GSF
2001[a]	14	IMP
Sum	404	

[a] Status on February

The involvement of so many organizations in this process over the years has led to a situation where teeth and data have been disseminated over many organizations and countries. The current goal is to bring under control these multiple processes of tooth sampling, tooth sharing, and EPR measurements that have been performed by different institutions within the frameworks of different projects. This is being done in order to arrange for a common analysis of the entire pool of EPR data. Thus, within the framework of the current project (JCCRER Project 1.1) it has been decided to establish a standard procedure for tooth collection and registration, and to improve and expand the special data base that has been established for this purpose.

3.1. Sample collection and registration

The first task of sample registration is to arrange the matching of tooth donors with the roster of exposed persons. It is possible to use special tools developed in the framework of Data Management System MAN (Vyushkova et al. 1996), which is available at the URCRM for this purpose. The experience of a pilot study shows that proper matching can be performed by URCRM staff members, and that such matching permits extraction of supplemental information for ETRC members from database "MAN" and the URCRM archive (exposure history, whole body count, x-ray examinations, etc.). Each tooth sample must be packed in a plastic bag together with a completed questionnaire. Each questionnaire must include the following information about the tooth donor: surname, name, patronymic name, date of birth, place of birth, current place of residence, other places of residence since 1949, date of tooth extraction, and tooth position. Experience has shown that such information is enough for exact matching with the roster of exposed persons (Fig. 1). There is no current practice of x-ray examination of teeth in rural dental clinics. Information on other x-ray examinations for ETRC subjects can be abstracted from their out-patient cards kept in the URCRM archive. After matching, all data on

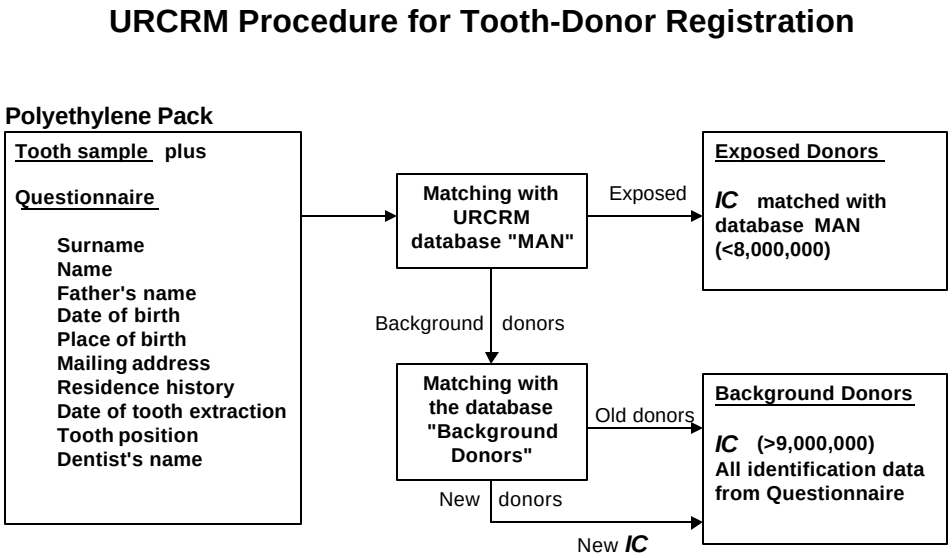

Fig. 1. URCRM procedure for tooth-donor registration.

extracted teeth must be registered in a special computer file of data base "TOOTH," and all tooth samples must be kept in a refrigerator in special containers marked with identification codes.

As noted above, the collection of teeth has been made only if teeth are being removed for purposes of dental health. Such conditions are confirmed by dentists' signatures. The confidentiality of all information is assured by restricting access to identifying personal information to only a few persons at the URCRM.

3.2. Structure of computer database

The electronic database "TOOTH" is supported by Microsoft Access software and consists of five related computer files described below.

3.2.1. File "Donors"

File "Donors" contains basic information about the donor that is taken from the questionnaire accompanying the tooth. When a match is made of the donor to a person in the register of exposed persons, information from the questionnaire is checked with information from database "MAN;" data about places and times of exposure are added to the "Donor" file. The names and descriptions of the fields in computer file "Donors" are presented in Table 5.

Field "Identification_code" is a primary key index and no duplicates are allowed. Each donor in database "TOOTH" has a unique identification code. Detailed information about the donor is necessary in order to search for the presence of the donor in database "MAN" or in the

Table 5. Structure of the file "Donors."

Field Name	Data Type	Field Size	Indexed?	Description
Identification_code	Number	Long Integer	Yes (No duplicates)	Donor's unique identification code
Surname	Text	20	No	Donor's surname
Name	Text	20	No	Donor's name
Father's_name	Text	20	No	Name of donor's father
Day_birth	Number	Byte	No	Day of donor's birth
Month_birth	Number	Byte	Yes (Duplicates OK)	Month of donor's birth
Year_birth	Number	Integer	Yes (Duplicates OK)	Year of donor's birth
Place_birth	Text	100	No	Place of donor's birth: country, region, district, settlement
Address	Text	100	No	Last address
Residency	Text	100	No	Residence history since 1949
Notes	Text	100	No	Additional data about donor

file “Donors.” It should be noted that dentists do make mistakes while filling out the questionnaire. In addition, the donor may have changed surname and address.

3.2.2. File “Teeth”

File “Teeth” is filled in with information from the questionnaire and includes data on tooth position and date of extraction. The names and descriptions of the fields for file “Teeth” are presented in Table 6. The dentist’s name and the name of the dental clinic or settlement are recorded in the fields “Dentist’s_name” and “Dental_clinic,” respectively. The place of tooth storage is written in the field “Place_storage.” Typically, the tooth sample would be kept in the tissue bank at the URCRM or would have been sent to a research laboratory for EPR measurement. In the field ”Date_delivery” is recorded the date that the tooth might have been delivered to an EPR-measurement laboratory. If a tooth or its tissues was returned to the URCRM or was sent on to another laboratory, such information is recorded in the field ”Place_storage.” The field “Identification_code” joins the files “Teeth” and “Donor” with a type of relationship of “one-to-many.” File “Teeth” is related to other files using the field “Tooth_code.” This field is of the number-data type, and it is an index field without duplicates.

Table 6. Structure of the file “Teeth.”

Field Name	Data Type	Field Size	Indexed	Description
Identification_code	Number	Long Integer	Yes (Duplicates OK)	Donor’s unique identification code
Tooth_code	Number	Integer	Yes (No Duplicates)	Tooth’s unique registration code
Quadrant	Number	Byte	Yes (Duplicates OK)	Tooth position: quadrant
Tooth_number	Number	Byte	Yes (Duplicates OK)	Tooth position: tooth number in the dentition
Month_extraction	Number	Byte	No	Month of tooth extraction
Year_extraction	Number	Integer	Yes (Duplicates OK)	Year of tooth extraction
Dental_clinic	Text	45	Yes (Duplicates OK)	Name of dental clinic or settlement where tooth was extracted
Dentist_name	Text	20	Yes (Duplicates OK)	Name of dentist
Place_storage	Text	50	Yes (Duplicates OK)	Where tooth is stored (URCRM or EPR laboratory)
Date_delivery	Date/ Time	Short Date	Yes (Duplicates OK)	Date of delivery of tooth for measurement
Notes	Text	50	No	Notes about tooth

3.2.3. File “Odontometrics”

Computer file “Odontometrics” consists of results of odontometric measurements and a description of tooth conditions (Table 7). Odontometric measurements include the measurements of height, mesiodistal (MD) and buccolingual (BL) diameters of the crown, and length and maximal diameter of the roots. The field “Tooth_code” has a relation of “one-to-one” and connects files “Odontometrics” and “Teeth.”

3.2.4. File “EPR measurements”

The file “EPR-measurements” contains information on EPR dosimetric measurements (Table 8). It is important to have complete information, including not only that for the fields “EPR_dose” and “Error,” but also for fields “Date_measurements,” “Tooth_tissue,” and “Laboratory.” Entry of the field “Sample_mass” is dependent on available information. The field “Notes” is filled if it is necessary to explain the results obtained or in the case of missing results (for example, the tooth sample was prepared for EPR measurements but not measured because of small sample mass). As can be seen from Table 8, the field “Tooth_code” is of the “number” data type as in previous cases. This index field allows for duplicates, because many samples can be prepared for dosimetric measurements from a single tooth, or the same tooth sample can be measured many times in different years or in different laboratories. The field “Tooth_code” has the relation of “one-to-many” and connects the file “EPR measurements” with the file “Teeth.” This connection among files provides for the integrity of the database.

Table 7. Structure of the file “Odontometrics.”

Field Name	Data Type	Field Size	Indexed	Description
Tooth_code	Number	Integer	Yes (Duplicates OK)	Tooth’s unique registration code
MD_diameter	Number	Single	No	Mesiodistal diameter of crown, mm
VL_diameter	Number	Single	No	Buccolingual diameter of crown, mm
Height_crown	Number	Single	No	Height of crown, mm
Length_1_root	Number	Single	No	Length of 1st root, mm
Width_1_root	Number	Single	No	Width of 1st root, mm
Length_2_root	Number	Single	No	Length of 2nd root, mm
Width_2_root	Number	Single	No	Width of 2nd root, mm
Length_3_root	Number	Single	No	Length of 3rd root, mm
Width_3_root	Number	Single	No	Width of 3rd root, mm
Length_4_root	Number	Single	No	Length of 4th root, mm
Width_4_root	Number	Single	No	Width of 4th root, mm
Crown condition	Text	150	No	Description of crown condition
Enamel condition	Text	100	No	Description of enamel condition
Roots_condition	Text	100	No	Description of roots condition

Table 8. Structure of the file "EPR measurements."

Field Name	Data Type	Field Size	Indexed	Description
Tooth_code	Number	Integer	Yes (Duplicates OK)	Tooth unique registration code
Tooth_tissue	Text	50	Yes (Duplicates OK)	Tooth tissue used in EPR measurements
EPR_dose	Number	Long integer	No	Results of EPR measurements, mGy
Error	Number	Integer	No	Error of EPR measurements, mGy
Sample_mass	Number	Integer	No	Sample mass, mg
Date_measurement	Number	Integer	Yes (Duplicates OK)	Date of EPR measurement
Laboratory	Text	15	Yes (Duplicates OK)	Laboratory of EPR measurements
Notes	Text	100	No	Notes

3.2.5. File "^{90}Sr concentration"

File "^{90}Sr concentration" contains information on measured concentrations of ^{90}Sr in tooth samples (Table 9). The field "Tooth_code" is of "number" data type as used previously. This index field allows duplicates, because several samples from the same tooth can be prepared for measurements or the same tooth sample can be measured many times in different years or in

Table 9. Structure of the file "^{90}Sr concentration."

Field Name	Data Type	Field Size	Indexed	Description
Tooth_code	Number	Integer	Yes (Duplicates OK)	Tooth's unique registration code
Tooth_tissue	Text	50	Yes (Duplicates OK)	Tooth tissue used for the measurements of ^{90}Sr concentration
Concentration_Sr	Number	Single	No	^{90}Sr concentration, Bq/g
Error_Sr	Number	Single	No	Error of measurements, Bq/g
Sample_mass	Number	Integer	No	Sample mass, mg
Date_measurement	Number	Integer	Yes (Duplicates OK)	Date of ^{90}Sr measurements
Laboratory	Text	15	Yes (Duplicates OK)	Method used for the measurement of ^{90}Sr
Method	Text	25	Yes (Duplicates OK)	Laboratory making ^{90}Sr measurements
Notes	Text	50	No	Notes

different laboratories. The field "Tooth_code" has the relation of "one-to-many" and connects the file "^{90}Sr concentration" with the file "Teeth."

3.2.6. Relationships among the files

All files are joined with enforced referential integrity by means of cascade update of related fields. File "Donors" joins with file "Teeth" through the field "Identification_code," -to-many." The field "Tooth_code" also has the relation of "one-to-many" and connects the files "Concentration ^{90}Sr," "EPR measurements," and "Odontometrics" to the file "Teeth." Fig. 2 shows the relationships among the files.

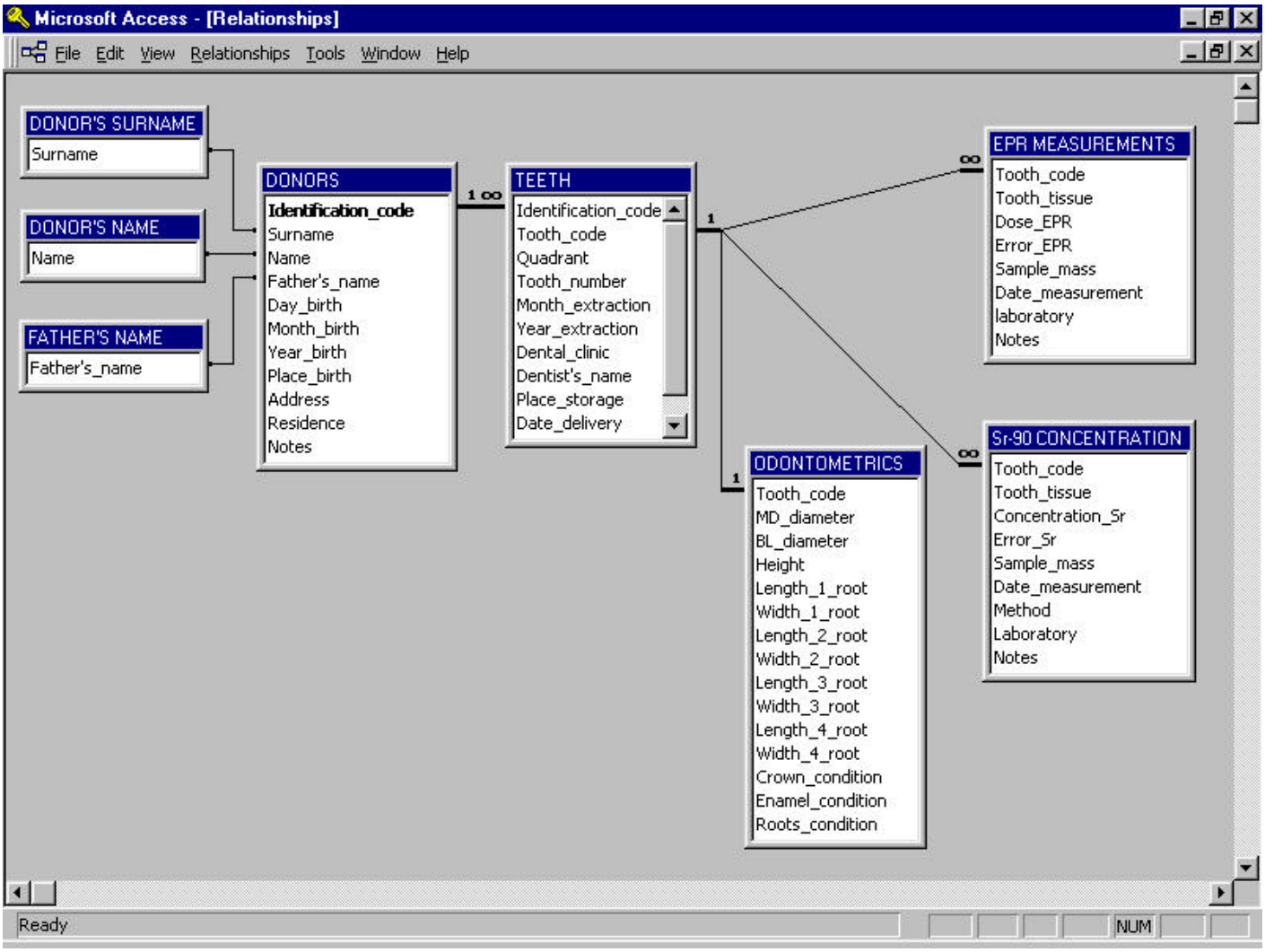

Fig. 2. Relationships among the files.

Three subsidiary files in addition to the five main files are shown in Fig. 2: "Donor's surname," "Donor's name," and "Donor's father name." These subsidiary files join with file "Donor." These subsidiary files are designed to reduce the number of mistakes during data input. The structure of database "TOOTH" facilitates the easy preparation of reports, the composition of queries for selection of teeth for measurement, and the analysis of measurement results.

Methods of data input and editing of the database files are explained in detail in Appendix 1.

3.3. Content of database

The main purpose of creating database "TOOTH" was to provide an objective basis for the validation study by EPR measurements of TRDS-2000 external dose estimates. Below information is briefly described concerning the exposure histories of tooth donors, as well as the data on EPR measurements currently available in this database.

At the end of February 2001 data base "TOOTH" contained information on 1,728 teeth collected from 1,358 donors. There is a distinct difference between the amount of data pertaining to members of the background and the exposed groups (there are 562 teeth collected from 404 exposed donors). For donors from the background group only information from the questionnaires is available, although the opportunity exists to collect additional information by querying a person directly. All exposed donors have been matched (via their IC) to data base "MAN," so for them detailed exposure histories, pedigrees, diagnoses, and the results of all WBC and TBC measurements are available in the URCRM database. In some cases cytogenetic data (FISH) are available, as well. The URCRM roster for exposed populations includes data for the following cohorts:

- The Extended Techa River Cohort (ETRC);
- The Techa River Offspring Cohort (TROC);
- The East Urals Radioactive Trace (EURT) residents; and
- The so-called Urals Liquidators (UL), the persons who did not live in contaminated areas, but who could be exposed as a result of their occupational work on these territories.

For our study it is necessary to identify individuals of "pure background;" therefore, donors are matched against all of these cohorts. The result of such matching is that ETRC members represent 78% of the exposed tooth donors; TROC and EURT members represent 10% each of the exposed group, and the remaining 2% are liquidators (UL).

The statistics of EPR measurements available in database "TOOTH" are presented in Table 10. As seen, the majority of measurements have been performed at the IMP, Ekaterinburg, and the GSF, Munich, Germany. It can be noted that the URCRM sent tooth samples (Table 3) for EPR measurements initially to the ICP (1992–1993) and then to the GSF (since 1993). In the early period the IBP and the IMP arranged an independent collection of teeth in the Kurgan and Sverdlovsk Oblasts. Matching of the donors of teeth for which they have EPR results with the

Table 10. The number of EPR measurements of Urals samples performed in different laboratories.

Laboratory	Number of EPR measurements by category		
	Exposed samples	Background samples	Total
IPM	169	30	199
GSF	77	36	113
CAD	0	48	48
ICP	27	1	28
IBP	14	2	16
Total	287	117	404

URCRM data base showed that some of these samples (18 in total) were from members of the ETRC. Active collaboration with the IMP started in 1996 (Table 3). During later years collaboration with other EPR laboratories (CAD, NIST, and MRRC) started. Under the auspices of JCCRER Project 1.1, 86 background teeth were sent to the CAD (University of Utah) in 1998. The URCRM has received EPR results for 48 teeth (Table 10), the remaining unmeasured 38 samples (Haskell 1998) have been lost to our study.

Table 11 shows the number of teeth that are now undergoing measurement at the IMP, the NIST and the MRRC. According to agreements with EPR experts, it is anticipated that the results of these measurements will be received before the end of 2001.

As seen from several tables, a number of laboratories have been engaged during the last ten years in retrospective EPR dosimetry by performing measurements on teeth from Urals donors. Also, it should be noted that methods for EPR-tooth dosimetry have developed very rapidly during this period. Therefore, to be able to analyze the entire pool of measured samples it is necessary to describe the EPR methods used and to consider available intercomparison and intercalibration programs to ensure the quality and consistency the results.

4. EVALUATION OF AVAILABLE EPR MEASUREMENTS

A description and a comparison of methods used in EPR dosimetry are included in this section, but only for the methods used for dose reconstruction with teeth from Urals donors. For example, only the methods used at the ICP and the IBP during 1992–1994 are described. Thus,

Table 11. The number of Urals teeth that are now being measured in different laboratories.

Laboratory	Teeth of exposed donors	Teeth of background donors	Total number
IMP	6	58	64
NIST	23	20	43
MRRC	10	7	17
Total	39	85	124

this report is not an attempt to review the entire gamut of procedures that have been and are being used for sample preparation, signal evaluation and dose calibration in EPR dosimetry.

All results presented here are given in terms of absorbed dose in hydroxyapatite. The absorbed dose in tooth enamel, which is 97% hydroxyapatite (Driessens and Verbeeck 1990), is assumed to be equal to the absorbed dose in hydroxyapatite. Results obtained for tooth dentin (containing only about 40% hydroxyapatite) were calculated using conversion factors specific to the mass-energy absorption in tooth dentin.

4.1. Description of methods used for EPR-dose reconstruction

The participants' EPR spectrometers and procedures used for EPR-dose reconstruction in the Urals are listed in Table 12. As seen, the participants used various modifications of procedures for the preparation of a pure enamel sample, evaluation of the dosimetric signal, and dose calibration. The essential features of each procedure are described below.

Sample preparation.

- The *mechanical method* (Serezhenkov 1992; Serezhenkov et al. 1992): Dentin is removed by a dental drill and the enamel is ground into a powder. The powder sample is not etched after grinding.
- The *chemical method* (Romanyukha et al. 1994, 1996a,b): The dentin is softened and removed with NaOH or KOH in an ultrasonic cleaning unit followed by granulating the enamel with optional etching of the ground sample. This method was later modified (Romanyukha et al. 2001). And since 1998, the dentin was removed with NaOH or KOH in an ultrasonic cleaning unit with high temperature (60°C).

Evaluation of the dosimetric signal.

Three categories of signal-evaluation techniques, including several options, have been applied. The techniques are distinguished by the procedures used for elimination of the native background signal and measurement of the intensity of the dosimetric signal.

- The *spectrum-subtraction method* (Haskell 1999): The EPR spectrum of a non-irradiated reference sample is subtracted from the spectrum of the irradiated sample. The reference sample is prepared from homogenized enamel material of several young adults or is selected to have the most symmetric native EPR line. As an option, the EPR signal of a pitch sample is used as a model for the native background EPR signal in tooth enamel. Optionally, the spectrum of the empty sample tube was subtracted. The amplitude of the dosimetric signal is measured in the resulting difference spectrum.
- The *selective saturation method* (Ignatiev et al. 1996): This method makes use of the fact that above a certain level of microwave power the intensity of the dosimetric signal keeps monotonically increasing with power while the intensity of the native background signal is saturated. The native background signal is then virtually eliminated by the difference of spectra recorded at two levels of microwave power above the onset of saturation for

Table 12. Methods and spectrometers used for EPR-dose reconstruction for Urals teeth.

Laboratory	Sample preparation	Spectrometer	Signal evaluation	Dose calibration
IMP	Chemical, etching (0.1–0.6 mm)	ERS231, GDR	Selective saturation (1995–1998) Deconvolution, Gauss (1998–2001)	Individual; Calibration curve (1997–2001)
GSF	Chemical, etching (0.1–0.6 mm)	Bruker ESP 300, ECS 106	Subtraction, Lorentz (1993–1994); Selective saturation (1995–1996); Deconvolution, Gauss (1996–2001)	Individual; Calibration curve (1996–2001)
CAD	Chemical, (0.3–0.9 mm)	Bruker ESP 300E	Subtraction, standard + empty tube	Non destructive
ICP	Mechanical, 0.5–2 mm	Radiopan, Poland	Subtraction, standard	Calibration curve
IBP	Mechanical, 0.5–1 mm	Bruker ER 300D	Subtraction, Lorentz	Individual

the native background signal. The amplitude of the dosimetric signal is determined from the resulting difference spectrum.

- The *deconvolution method* (Egersdörfer et al. 1996; Koshta et al. 2000): The EPR spectrum of tooth enamel is approximated by mathematical realizations of the native background and dosimetric signal. The type of EPR-signal realization and the method of approximation distinguish the methods. The magnitude of the dosimetric signal is derived from an amplitude parameter providing the best fit to the measured spectrum. The measured spectrum is approximated as a linear combination of Gaussian functions.

Dose calibration.

Three methods have been applied to evaluate the absorbed dose from the amplitude of the dosimetric signal (dose calibration):

- The *individual-calibration* method (additive dose method): The sample is exposed in the laboratory to several additional doses. After each additional exposure the amplitude of the dosimetric signal is measured and the originally absorbed dose is obtained from the intercept of the linear regression line with the dose axis.
- The *universal calibration curve* method: A dose-response function of tooth enamel is established by *in vitro* irradiation of teeth from young adults, who are presumed to have had negligible prior external exposures. The method assumes a moderate variation in the radiation sensitivity of tooth enamel from different individuals.
- The *non-destructive calibration* method: The method is non-destructive in the sense that the original dose information of the sample is not destroyed by individually calibrating the radiation sensitivity. Only a small fraction of the sample is exposed to one large dose for determination of its sensitivity (Haskell 1999).

4.2. Intercomparisons on EPR-tooth dosimetry

The programs of intercalibration and intercomparison among the results obtained by five laboratories involved in EPR-dose reconstruction for the Urals samples (since the early 1990s) and the MRRC, Obninsk (which will be involved in the future), are described in this section.

Russian Intercomparison (IBP, IMP, and ICP) of 1993

The first experience of intercomparison of EPR results for three EPR laboratories involved in dose reconstruction in the Urals has been reported by Kleschenko et al. (1992, 1993, 1994). Each participant (IBP, IMP and ICP) prepared a mixture of grains from the enamel of several teeth using their own sample-preparation techniques. Then, each participant separated their mixture into 24 portions. Twelve portions were shared among the three participants (including the host) for the measurement of the background-EPR spectrum, then the sample portions were returned to the host laboratories. After that all portions were irradiated *in vitro* by the host laboratory in four known doses within the range 0–500 mGy and shared again. As a result, each participant evaluated two sets of 12 samples (with or without previous evaluation of

background spectra). For example, Participant #1 had to measure (in addition to the background samples):

- Four samples with known applied doses (own preparation and irradiation);
- Four samples with unknown applied doses (preparation and irradiation performed by Participant #2); and
- Four samples with unknown applied doses (preparation and irradiation performed by Participant #3).

This protocol created several problems for the participants, and as a result not all measurements could be evaluated properly. First of all, the existence of background-EPR signals comparable with the applied doses resulted in the rejection from the analysis of the set of samples irradiated without previous evaluation of background spectra. Secondly, there were significant differences in sample-preparation procedures used in the IBP, the IMP and the ICP. The samples prepared at the ICP were coarse-grained (0.5–2 mm), and this created an anisotropy of the dosimetric EPR signal (especially at the IMP, where measurement conditions were designed for significantly smaller grain size). And vice versa, sample-grain size in the range 0.1–0.6 mm prepared at the IMP (also using chemical treatment in an ultrasonic bath) were not in keeping with the measurement conditions used at the ICP. Only the samples prepared at the IBP (0.5–1 mm) were acceptable for all three participants. The dosimetrists at the IBP were able to measure the samples prepared both at the IMP and the ICP without significant problems.

To illustrate the results of this intercomparison, results are included for the ICP and the IPM measurements of samples prepared at the IBP and the IBP results for samples prepared at the ICP and the IMP. Results are shown in Fig. 3; all of these samples were measured with previous evaluation of background spectra.

As seen from Fig. 3, all three laboratories demonstrated an ability to evaluate applied doses in the range below 500 mGy. Unfortunately, due to the failures in the arrangement of this intercomparison (discussed above) it was not possible to make any conclusion about the uncertainties of dose reconstruction on the basis of such a small number of measurements.

Intercomparison of measurements on teeth from Mayak workers (GSF and IMP) of 1997

The accuracy of the dose-reconstruction technique of EPR spectrometry was evaluated in 1997 using teeth donated by Mayak workers with known occupational radiation-exposure histories (Romanyukha et al. 2000a). The GSF and the IMP participated in this comparison.

The teeth from Mayak nuclear workers were extracted for medical reasons and provided by dental clinics in Ozyorsk. Each donor had an officially recorded film-badge dose. Eight samples were measured at both the GSF and the IMP. Each tooth was cut into halves for measurement by the GSF and the IMP. There were three frontal teeth among the samples, and, according to the GSF protocol, only lingual fragments were used for radiation-dose reconstruction (in order to eliminate the uv component of the EPR signal). Therefore, strictly speaking, the comparison of techniques can be based only on results for the other five samples.

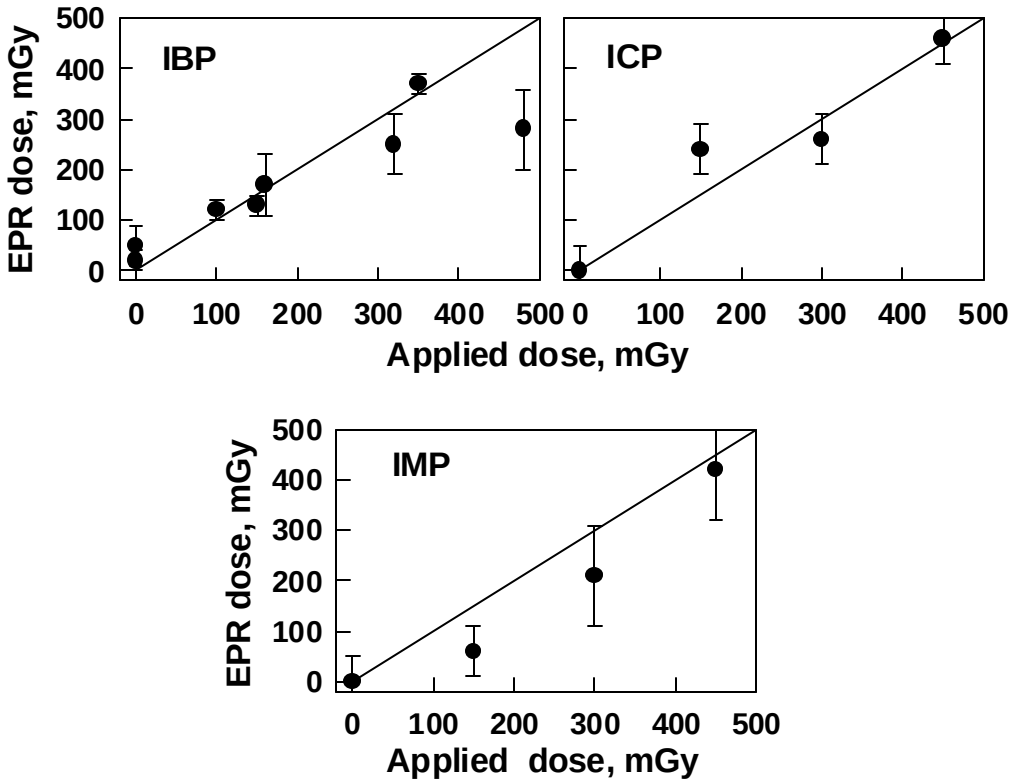

Fig. 3. Results of the IBP-ICP-IMP intercomparison of 1993.

All measurements were performed without prior knowledge of the official film-badge doses. Each group used its own experimental procedures for sample preparation and dose reconstruction. All the EPR reconstructed doses were given in terms of absorbed dose to tooth enamel. The linear correlation coefficients with film-badge doses were estimated as 0.99 for the IMP and 0.97 for the GSF.

Because each tooth was divided into two parts for independent measurements in different laboratories, the results can also demonstrate the relationship between the EPR estimates of the two laboratories. For this purpose, the results obtained by the IMP were compared with those of the GSF. The correlation coefficient for the results obtained by the IMP and the GSF was 0.99. The estimated slope of the GSF results on the IMP results was 0.88±0.05. This demonstrates the high credibility of the EPR method for dose reconstruction in tooth enamel, even though two different EPR techniques, the additive-dose method (IMP) and the calibration-curve method (GSF), were employed. As the GSF results are somewhat lower than those of the IMP, this may be due to a systematic error or may be due to chance due to the small number of shared samples.

2nd International Intercomparison on EPR Tooth Dosimetry (GSF, CAD, IMP, MRRC) of 1998

Eighteen EPR laboratories, including the IMP, the GSF, the MMRC and the CAD, participated in an international intercomparison program. Each participant prepared five enamel samples from molars and evaluated the absorbed dose on the same samples after irradiation *in vitro* in the range 0–1000 mGy at the International Atomic Energy Agency (IAEA). The participants used various procedures for the preparation of pure enamel samples, evaluation of the dosimetric signal, and dose calibration. The objective of the 2nd intercomparison program was to evaluate all methods currently being used by different laboratories for dose reconstruction by EPR and to demonstrate the present state of the technique.

The analysis of the results of the intercomparison (Wieser et al. 2000a,b) demonstrated a consistency of the individual-EPR methods and high precision of the reconstructed doses. The results obtained have a high correlation with the doses applied at the IAEA (for the GSF $r = 0.971$, for the CAD $r = 0.997$, for the MMRC $r = 0.998$, and for the IMP $r = 0.977$). However, due to differences in dose-calibration factors of the individual methods, large differences in accuracy were found. A tendency was recognized that the quality of the EPR spectrometer used influences the quality of the dose reconstruction. This suggests that minimal requirements for sensitivity and stability of EPR spectrometers need to be established, when the intended use of the spectrometers is for dose reconstruction based on measurements of teeth.

Six of the eighteen participating EPR laboratories demonstrated a high reliability of dose reconstruction throughout the range of applied doses. Among them there were the CAD, the MMRC and the GSF. The results from the IMP demonstrated an overshoot for doses at the lower end of the applied dose range (about 100 and 150 mGy).

Simultaneously with the 2nd intercomparison there was a comparison of sample-preparation and signal-evaluation methods for EPR analysis of tooth enamel (Wieser et al. 2000a). The CAD, the GSF, the IMP and the MMRC participated. In this comparison potential influences of sample preparation and EPR-signal evaluation (just the evaluation of the EPR-signal intensity in arbitrary units without calibration in absorbed dose) were investigated. The comparison did not include a check on the agreement of dose calibration, but it did include for each method a check of the EPR-signal response per unit dose (sensitivity) at absorbed doses of 1000 mGy and 100 mGy. Within the framework of this study the IMP used two principles of EPR-signal evaluation: 1) the selective saturation method [Ignatiev et al. 1996] and 2) the spectrum-deconvolution method (Koshta et al. 2000). This intercomparison has demonstrated that all involved methods provide satisfactory results with reproducibility better than 10% for dose reconstruction at the level of 1000 mGy. With the possible exception of the selective saturation method (used at the IMP), the dosimetric signal from samples irradiated at 100 mGy can be reproduced to about ±30%. The microwave-saturation method provided an extraordinarily high sensitivity but poor reproducibility at 100 mGy. These effects are probably due to the high level of noise inherent in this method at low doses combined with the low sensitivity of the EPR spectrometer used at the IMP.

The intensity of the non-vanishing dosimetric signal (intrinsic signal) in unirradiated samples was found to be equivalent to a dose ≤63 mGy. The intrinsic signal is specific for every

sample; its average value depends upon the peculiarities of the methodical approach, especially on the shape of the reference spectrum that is used for simulation and subtraction of the native signal (Ivannikov et al. 2000). The amplitudes of intrinsic signal were equal to 36 mGy for the IMP; 63 mGy for the MRRC, and 52 mGy for the GSF. The intrinsic signal was not determined by the CAD method and was assumed to be zero. The amplitude of the intrinsic signal represents a bias that can be eliminated by subtracting it from the reconstructed dose.

Intercomparison on teeth from Techa River and other Urals residents (GSF and IMP) of 2000

A comparison of EPR results with tooth enamel from exposed members of the ETRC and persons from the Urals with presumed background exposure was performed in 2000; participating laboratories were the GSF and the IMP. Samples were prepared, for the most part, at the IMP (39), and ten additional samples were prepared at the GSF; EPR measurements and dose evaluations were performed at the IMP and at the GSF. As the GSF and the IMP use similar procedures for sample preparation and spectrum processing, this comparison was an opportunity to compare calibration, reproducibility, and dose-reconstruction quality for these institutes. All 49 teeth were measured at both laboratories with use of the calibration-curve method for dose evaluation. A preliminary comparison of calibration curves prepared at the GSF with teeth of German donors and teeth of Urals donors was performed. The average-radiation sensitivity of enamel (slope of calibration curve) for the Urals population essentially coincided with the results obtained for the German population.

The upper panel of Fig. 4 illustrates the comparison of the GSF and IMP results in the dose range from 0 to 5 Gy. A high correlation coefficient of 0.99 is obtained between the results of the two laboratories. The slope of the regression line is very close to unity and indicates that the IMP and the GSF calibrations for radiation sensitivity of the samples agree within 1%. This result also demonstrates the absence of a systematic bias between EPR doses measured by the two laboratories and thus creates a basis for a combined analysis of the entire pool of data available from the two laboratories.

Unfortunately, however, there is a significant spread of the data around the regression curve in the low dose range (lower panel of Fig. 4). The 95% confidence interval of the deviation between the individual IMP and GSF results is ±180 mGy. This is possibly due to unusual additional EPR signals from the samples that are interfering with the dosimetric signal. The signals may have been caused by sample impurities that are not completely removed or introduced by the sample-preparation procedures. The influence of the interfering EPR signals is considerable for low doses and negligible for high doses.

4.3. Evaluation of uncertainty of the EPR method

The uncertainty of measured absorbed dose to enamel is due to uncertainties in calibration, enamel response to ionizing radiation, intrinsic signal, and sensitivity of the EPR spectrometer. The analysis of the results of the intercomparisons demonstrate that the EPR-dosimetry system, when a spectrum-deconvolution procedure and a universal calibration curve are used, can reconstruct doses within ±25 % and ±100 mGy for doses below 400 mGy with a probability of 0.95 (Wieser et al. 2000a,b).

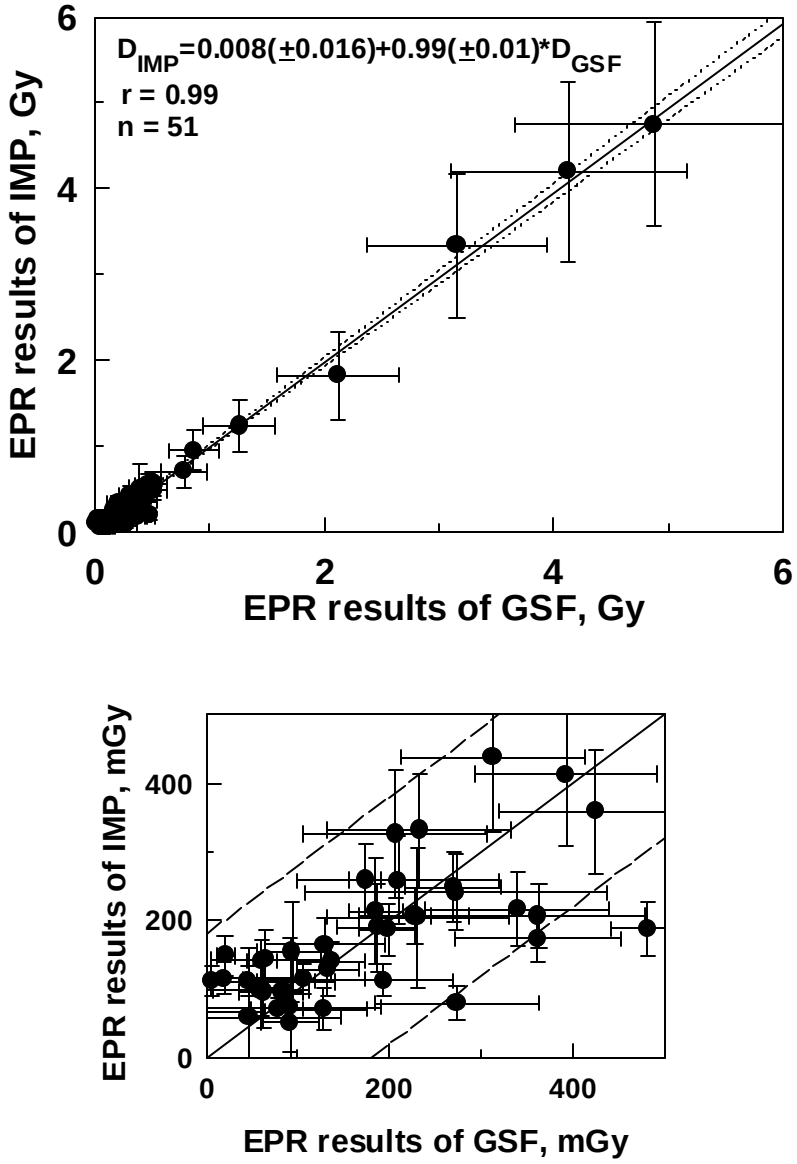

Fig. 4. Results of the intercomparison between measurements at the GSF and the IMP on teeth from Techa River and other Urals residents.

Special attention was given to the comparison of EPR results obtained at the GSF and the IMP (the laboratories where the majority of the Urals samples have been measured). Comparison of the results obtained for teeth from the Mayak workers, persons exposed on the Techa River, and the residents of "background areas of the Urals" demonstrated the consistency of data and the absence of a systematic shift between the measurements from these two laboratories. Nevertheless, the 95% confidence interval of the deviation between the individual IMP and GSF results in the low dose range is equal to ±180 mGy. There are two possible causes for such uncertainty. The first could be the lower sensitivity of the EPR spectrometer used at the

IMP. The second is the presence of impurities interfering with the dosimetric signal recorded in the spectra for some portion of the samples.

When such parasitic signals are observed, the dosimetric evaluation is difficult and in some cases practically not possible. The parasitic signal appears to have been introduced by metal impurities in enamel. The cause of such impurities could be metal dentures and fillings, which for some of the people (especially old persons) could have been in their mouths for many years. According to the literature (Kopeikin et al. 1978) such metals as gold, silver, copper, iron, etc., were widely utilized in the practice of dental prosthetics. Therefore, metal dentures and fillings could be a cause for the presence of metal ions in saliva, which could cause ion exchange between the saliva and hydroxyapatite crystallites.

Some steps are suggested to reduce the uncertainty of EPR measurements for samples that contain metal impurities. The first suggestion is for additional chemical treatment that can dissolve metal impurities that are attached only to the surface of the sample. Another suggestion is for the development of objective criteria for exclusion of some samples from dosimetric analysis due to "bad quality of enamel as a solid state dosimeter." The possible formulation of such a criterion is suggested as the following: If the spectrum contains a parasitic signal lying partly or fully in the range of g-factors of 1.995–2.006 and the amplitude of such a signal is equal to or greater than the amplitude of the dosimetric signal, then dose reconstruction for this sample should be considered as unreliable. At the current moment even operators of limited experience can identify by visual inspection spectra that have problems (strong base line drift or existence of additional EPR lines) that may produce unreliable results. The development of objective criteria, e.g., a numeric quality parameter to judge the acceptance of a given spectrum, is in process.

5. STRUCTURE OF THE EPR SIGNAL FOR URALS RESIDENTS

The uncertainty of EPR-dose reconstruction depends not only on the uncertainty of the measurement of absorbed dose in tooth enamel, but is determined also by the separation of dose due to the exposure event of interest. The total EPR signal measured in tooth enamel of the Techa Riverside residents (*EPRS*) can be evaluated as the sum of a background signal (*BGS*) and an additional signal from the exposure due to the person's contact with the contaminated Techa River (*TRS*):

$$EPRS = BGS + TRS \, .$$

The Techa River signal (*TRS*) consists of two parts:

$$TRS = TRS_{INT} + TRS_{EXT} \, ,$$

where TRS_{INT} is the signal due to the exposure of enamel from radionuclides incorporated within the human body (mainly from beta-emitting ^{90}Sr and its daughter ^{90}Y incorporated in tooth tissues) and TRS_{EXT} is the signal due to the enamel exposure from external sources of gamma-irradiation (mainly arising from the contaminated sediments of the Techa River).

Therefore, for the purposes of *external dose validation* it is necessary to develop procedures for evaluating and subtracting the background (*BGS)* and the $^{90}Sr/^{90}Y$ (TRS_{INT}) contributions from the total EPR signal. A preliminary evaluation of these two contributions is discussed below.

5.1. Evaluation of EPR-background data

The background-EPR signal consists of two parts:

$$BGS = IIS + RSS_{BG} ,$$

where *IIS* is the so-called initial intrinsic signal (Ivannikov et al. 2000) and RSS_{BG} is the age-dependent signal that results from exposure to background levels of radiation exposure.

As discussed above, the intrinsic signal is specific for every sample, but the average *IIS* is a characteristic of the sensitivity limit for a specific EPR-measurement system (Ivannikov et al. 2000). The magnitude of *IIS* is typically equivalent to a dose of about 70 mGy for methods that include the subtraction of a symmetric or modeled native signal. It is recommended that for each method used for dose reconstruction the reconstructed dosimetric signal for unirradiated samples should be reported; also, it should be stated explicitly whether this signal has been subtracted from the reported dose-evaluation results.

The contribution of the background sources of radiation exposure (RSS_{BG}) depends on the radioactive content of the immediate environment (external gamma rays from ^{40}K and members of the ^{232}Th and ^{238}U series in soil and building materials, etc.), gamma and beta rays from ^{40}K incorporated within the body, and cosmic rays. The RSS_{BG} value is proportional to the product of annual dose due to background radiation and the period between tooth-enamel formation and the moment of sample measurement. Tooth-enamel formation is completed prior to tooth eruption, and tooth age depends not only upon the age of the donor but also upon the tooth position. Additional contributions to RSS_{BG} can be introduced by ^{90}Sr from global fallout and by medical exposure.

<u>Evaluation of EPR-background signal for Western Russia</u>

The background levels of the tooth-enamel EPR signals as a function of donor age and of tooth position were investigated for 136 tooth samples from unexposed rural residents of Kaluga Oblast in Russia (Ivannikov et al. 1997, 2000). One significant result of the study was the finding of higher level signals from front teeth that were caused by the induction of paramagnetic centers in these front teeth by the uv component of solar light. Solar light induces in the buccal enamel of the front teeth an EPR signal with the same properties as the radiation-sensitive signal; on average the doses absorbed in front teeth (positions 1–3) are found to be about 200 mGy higher than for inner teeth (positions 1–8). The mean depth of the exponentially distributed solar induced paramagnetic centers was determined to be about 300 μm. Such a thick enamel layer cannot be removed by surface etching. Therefore, it has been recommended to use only enamel from the inner side of the front teeth or to use posterior teeth for dosimetric purposes.

The average value of *IIS* (specific for the currently used methodology at the MRRC) was determined to be 65 mGy (Ivannikov et al. 2000). The *RSS* levels were evaluated by subtraction of 65 mGy from the experimentally determined EPR estimates of dose. Some of the individual values, after subtraction of the *IIS*, become negative. This has no physical meaning from the point of view of ascribing these values to dose, but such negative values should not be rejected as being below the threshold of the method. A typical value of annual dose absorbed by enamel due to background radiation was evaluated to be about 1 mGy.

Evaluation of EPR-background signal for the Urals region

Studies of the background-EPR signal for teeth collected from residents of uncontaminated areas of the Urals were started at the CAD (Haskell 1999) and were continued at the GSF (Table 13). Later, a portion of these samples were measured at the IMP (Table 13). At the current moment only molars (83 teeth in total) have been investigated. The range of ages for tooth donors (45–90 years old) was selected to be the similar to that for members of the ETRC.

The GSF experimental values were corrected by the subtraction of an *ISS* value equal to 60 mGy. The IMP and CAD dose-reconstruction systems did not use the *ISS* correction. Nevertheless, as seen from Table 13, there are no obvious differences in the reported ranges of background-dose range and there are no statistically significant differences among the values of mean doses from the three laboratories. Also, a statistically significant correlation of background-EPR dose with the age of tooth donors was not found (Table 13). A possible reason for this is the substantial variation in the individual measurements (Fig. 5). The uncertainty of the EPR-dose-reconstruction method (±100 mGy for doses below 400 mGy) gives an error of

Table 13. Results of EPR studies of Urals background teeth by three laboratories.

Parameter	CAD	GSF	IMP[a]
Number of samples	48	35	47
Tooth positions	5, 6, 7, 8	6	5, 6, 7, 8
Age range,[b] y	30–90	46–87	44–90
EPR-dose range, mGy	17–410	-15[c]–482	7–303
Dose-age correlation coeff.	0.02	0.26	0.35
Mean dose ± Std. dev., mGy	135 ± 83	130 ± 110	143 ± 69
Median dose, mGy	123	107	129
Quartile range, mGy	96–156	54–191	95–188

[a] - Repeated measurements of samples initially measured at the CAD or the GSF.
[b] - Background samples were collected from persons of the same age range as for the then current age range of members of the ETRC.
[c] - Subtraction of an initial intrinsic signal used in the GSF method sometimes results in negative values of dose.

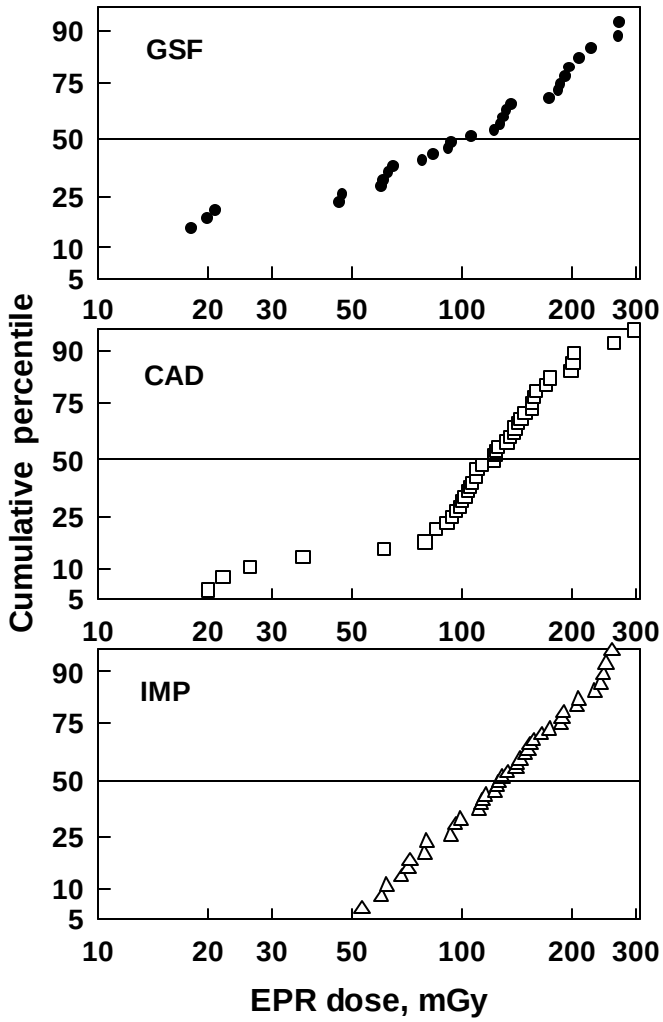

Fig. 5. Distributions of background doses for rural residents of the Urals as measured by three laboratories (the CAD, the IMP and the GSF).

about 100% or more for the majority of the individual-background measurements. Therefore, it is impossible to separate individual variability of background-radiation doses from instrumental uncertainties. The large uncertainty can be decreased only by increasing the number of samples investigated. Also, it is recommended to evaluate "the purity" of each of the EPR spectra and to develop criteria for the rejection from further analysis of samples of poor quality (samples with impurities described above).

The investigation of background levels of the EPR signal for Urals residents is now being continued within the framework of International Science and Technology Center (ISTC) Project No. 509. Samples of front teeth are now being included in the measurement program. The findings that have been presented here must be considered as preliminary results useful for the

planning of a more extensive validation study of external doses for members of the Extended Techa River Cohort.

5.2. Contribution of ^{90}Sr incorporated in dental tissues

Beta particles emitted by ^{90}Sr/^{90}Y incorporated in dental tissues can make a significant contribution to the total EPR signal measured in the teeth of persons exposed on the Techa River (Romanyukha et al. 2000b). Therefore, for the purpose of *external dose validation* it is very important to be able to evaluate or minimize the contribution of ^{90}Sr incorporated in dental tissues.

The URCRM tooth collection contains samples from members of the ETRC of different ages at the onset of ^{90}Sr intake and at the moment of tooth extraction. The concentration of ^{90}Sr in dental tissues has been evaluated using different experimental techniques since the late fifties. This section presents original data on ^{90}Sr in teeth for the Techa River residents. For the analysis of these data it has been necessary to include some general information taken from the literature on dental maturation and mineralization.

The tooth tissues of interest are enamel and dentin. Table 14 presents data on the chemical composition of tooth tissue (Gran and Schwarcz 1987; Driessens and Verbeeck 1990). Tooth enamel, the most mineralized tissue in the human body, has an hydroxyapatite concentration of approximately 97%, while dentin contains no more than 50%.

5.2.1. Strontium metabolism in teeth

The biokinetics of strontium and calcium are very similar due to their similar chemical characteristics. Several studies have shown that incorporation of strontium into bones and teeth takes place during the calcification of these tissues (Driessens and Verbeeck 1990). Incorporation in bone does not end after the period of initial incorporation, but will continue due to the continuous remodeling of bone. Also, incorporation of strontium in adult teeth occurs during life, but it occurs at much slower rates than for bone. Radioactive strontium can be used as a tracer of calcium for studies of mineral transfer among different compartments in the human organism. While the data on internal dosimetry of ^{90}Sr could be evaluated on the basis of calcium biokinetics, the unique data pertaining to members of the ETRC can also be used to investigate calcium metabolism (mineralization and demineralization) in calcified tissues.

Table 14. Composition of human enamel and dentin according to Gran and Schwarcz (1987) and Driessens and Verbeeck (1990).

Tissue	Tissue composition, %				
	Organic compounds	Water	Mineral phase	Mineral phase composition, %	
				Hydroxyapatite crystals	Amorphous phase
Enamel	0.4–0.8	3.2–3.6	96–97	100	-
Dentin	20	10	70	50	50

The morphogenesis, regulation of growth and formation, crystal chemistry, and biochemistry of tooth tissues have been described in the literature. For purposes of the present analysis the general characteristics (such as the age at which different tooth tissues are formed and the schedule of tooth-tissue mineralization) are more important.

Adults. The metabolism of strontium and calcium in *enamel* after completion of mineralization is extremely slow, due to the high level of enamel mineralization and the absence of living cells. The metabolic processes are determined by the turnover of non-organic ions at the enamel and crystal surfaces and ion transport between enamel and fluid (Borovsky and Leontyev 1991).

The calcium (strontium) metabolism in adult *dentin* is affected by two processes: ion exchange on the surface of dentinal tubules and of the pulpar surface and the continuous formation of the peritubular dentin (dentin around the dentinal tubules) and dentinogenesis on the pulpar surface (secondary dentin formation). As a response to varying external stimuli (such as chemical irritants, caries, restorative procedures, attrition, or other trauma), additional portions of dentin (reparative or irritation dentin) may be formed (Ham and Cormack 1979; Linde 1992). The thickness of the walls of the root channels increases by 15–30% in the age period of 20 to 50 years (Klyuev 1976). These processes explain why there is an uptake of strontium by the dentin of adult teeth.

Children. The processes of growth and mineralization determine the accumulation of ^{90}Sr in teeth of young persons. As for the Techa River situation, "children" were residents born in the period after 1935, but before the end of the period of massive releases. The time and age of tooth maturation is dependent on the type of tooth (tooth position). The scheme in Fig. 6 illustrates the development of human dentition (according to Schour et al. 1941). As a whole, permanent tooth formation is a prolonged period that is completed (except for wisdom teeth) by the age of to 12–15 years (Lewis and Garn 1960; Kolesov 1991).

In the period of ^{90}Sr intake different teeth from the same person can be in quite different stages of formation and mineralization. Therefore, individual teeth can accumulate very different quantities of ^{90}Sr. Each tooth has a definite and distinct period of dentition of its own. Table 15 presents this information concerning human teeth.

For strontium accumulation (retention) two factors are very important: 1) the time (age) of the initiation of mineralization and 2) the rate of mineralization during dentition. Data on the first set of parameters are presented in Table 15. The rate of mineralization (rate of formation) is interesting in the context of strontium intake, because the massive radioactive releases into the Techa River occurred during a relatively short period of time (1950–1951). If the crown enamel and dentin are mineralized in a short time period, i.e., there is a period of rapid mineralization, the ^{90}Sr measurements in teeth can provide information about the schedule of strontium intake, because such a period of rapid mineralization effects the appearance of the peak in the age dependence of ^{90}Sr-tooth content.

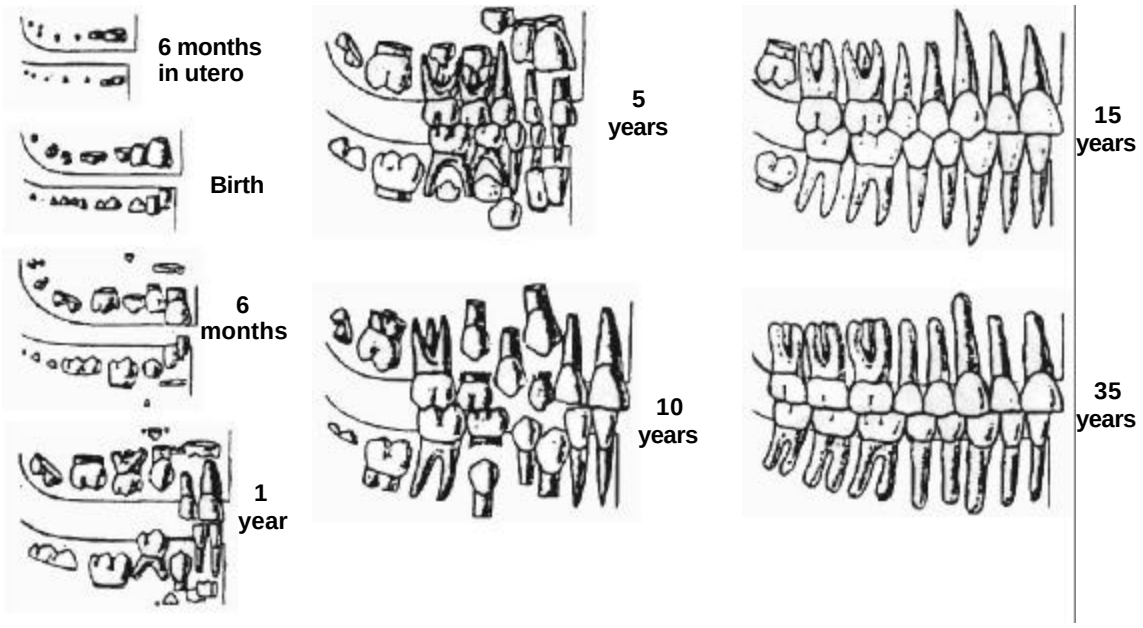

Fig. 6. The development of human dentition (according to Schour et al. 1941).

Table 15. Permanent tooth development
(according to Logan and Kronfeld 1933; Lewis and Garn 1960; Novik 1971; Kolesov 1991).

Tooth	Beginning calcification	Crown completion	Root completion (apical closure)
Central incisor	4–6 mo.	4–5 y	9–10 y
Lateral incisor	9–12 mo.	4–5 y	10–11 y
Canine	4–6 mo.	6–7 y	12–15 y
First premolar[a]	1.6–3 y	6.0–8.1 y	11.2–14.0 y
Second premolar[a]	2.7–4.2 y	6.7–9.3 y	12.1–15.4 y
First molar[a]	At birth	3.1–4.9 y	8.8–11.6 y
Second molar[a]	2.8–4.8 y	7.3–10.2 y	12.8–17.6 y
Third molar[a]	7.5–10.9 y	12.0–17.1 y	18–26 y

[a] For these teeth the variability of timing of maturation reflects the range between the 5th and 95th percentiles.

5.2.2. Analysis data on ^{90}Sr in teeth from residents of the Techa River region

The ^{90}Sr content in teeth from Techa River residents was studied at the URCRM using two methods (Tolstykh et al. 2000): radiochemical analysis for ^{90}Sr content of extracted teeth and *in vivo* measurements of surface-beta activity of the front teeth (tooth-beta counting, TBC). The results are available for more than 400 samples measured by the first method in the period 1959–1964, predominantly, and about 30,000 measurements by the second method for the period 1959–1997 (Table 1).

Fig. 7 presents the age dependencies of ^{90}Sr in teeth evaluated by these two methods in the period 1960–1964 for subjects residing in the upper and mid-Techa region. As seen, a distinct difference is observed between results obtained by the two methods; this difference requires a detailed discussion. First of all, it should be noted that the above two methods were applied to teeth of different positions (TBC to the first incisors only and radiochemistry was applied predominantly to posterior teeth). To understand the reason for the difference of age dependencies it is necessary to compare the periods of mineralization of these two groups of teeth with the calendar period of major ^{90}Sr intake.

According to the Mayak archival data (JNREG 1997; Vorobiova et al. 1999) maximal releases occurred in the period from March 1950 to November 1951. As seen, maximal ^{90}Sr

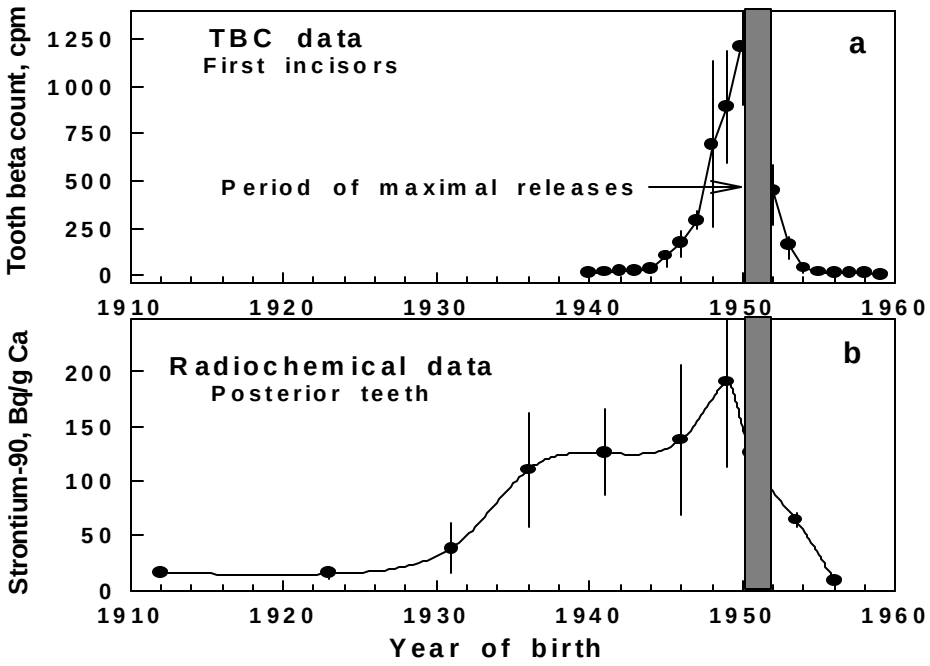

Fig. 7. Age dependencies of ^{90}Sr in teeth obtained by (a) TBC method on front teeth and (b) radiochemical method for posterior teeth. The period of massive radioactive releases into the Techa River is indicated by the shaded area.

contents were observed for persons born just before the period of the massive releases (Fig. 7), but results from the radiochemical method indicated elevated ^{90}Sr concentrations in teeth from persons who were up to 15-y old (born in 1935 and earlier) at the time of the onset of massive releases.

TBC data. The TBC method registers the surface-beta activity of anterior teeth (upper and lower first incisors). The thickness (0.3–0.5 mm) of incisor enamel is shorter than the average path length of 2.1 mm for ^{90}Y-beta particles in enamel (ICRU 1984); thus, beta-particles originating in enamel and partially in dentin are registered by this method. As seen from Fig. 8, TBC data are reliable only for persons within a narrow range of birth cohorts. For other persons the measured TBC values are lower then the TBC-detection limit, which has been evaluated as 9 cpm on the basis of the 95th percentile of the distribution of TBC measurements for persons with "background" exposure (Kozheurov et al. 2000).

Characteristics of the formation of the first incisors are presented in Table 15. The beginning of calcification in the crown occurs at the age of six months. The rapidity of crown formation can be estimated qualitatively on the basis of morphologic data (Massler et al. 1941).

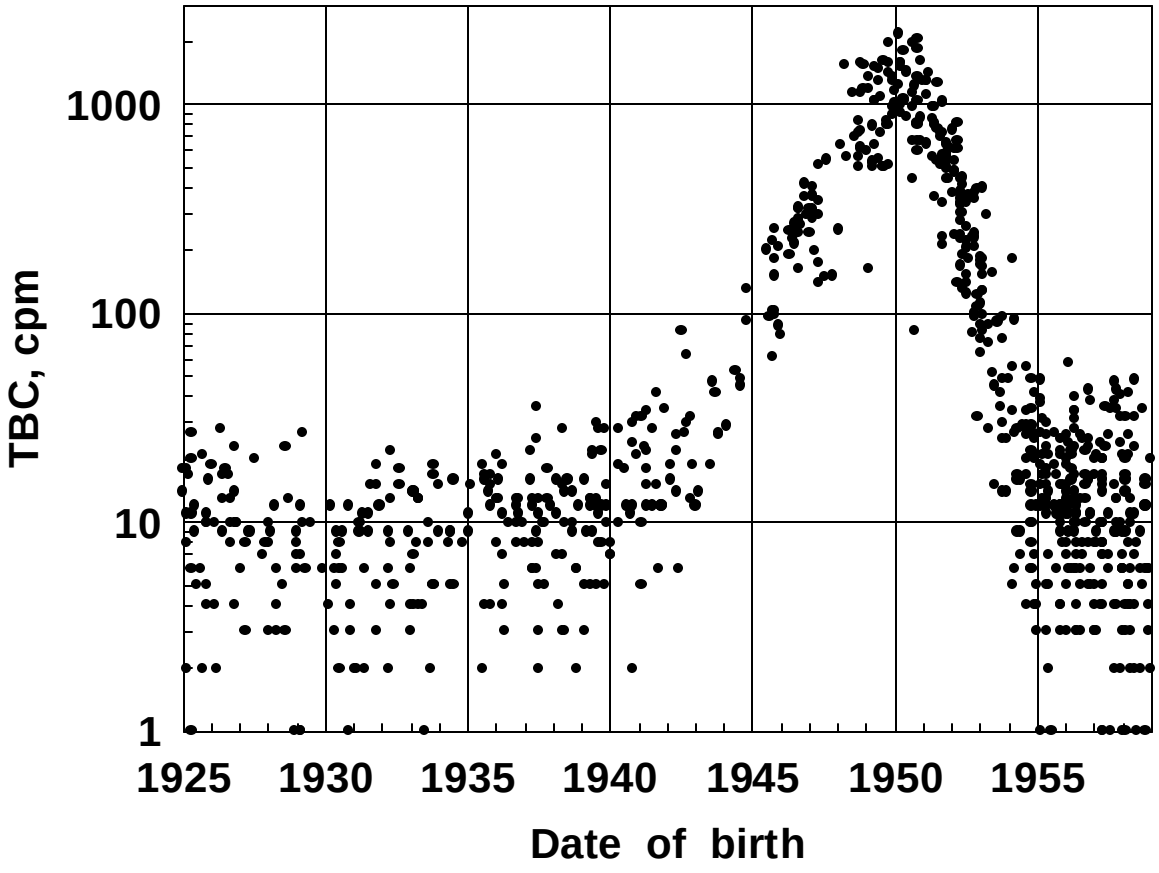

Fig. 8. Results of TBC measurements for permanent residents of Muslyumovo.

Fig. 9 illustrates the process of crown-enamel formation. As seen, the majority of enamel in incisors is formed during a short period of time (age period of 0–1 y); this leads to the appearance of a sharp peak in the curve in Fig. 7a. The maximal level of ^{90}Sr in incisor teeth was found for persons born in 1949–1951 (Fig. 8). Thus, for persons born in 1949–1951, ^{90}Sr releases (or ^{90}Sr intake) are coincident with the period of rapid mineralization. The maximal release was in 1950–1951, therefore, the period of rapid mineralization corresponds to an age of 0.5–2 years. According to Table 15 this is the period of beginning of calcification, and the maximal rate of mineralization is observed during the early period of crown formation.

Radiochemical data. The samples used for radiochemical measurements were predominantly of posterior teeth (molars and premolars). The radiochemical technique gives average ^{90}Sr concentration in the tooth as a whole. It is well known that for healthy teeth the enamel is only about 17–30% of the total dental mass (ICRP 1995). For carious teeth, which are usually the ones available for analysis, part of the enamel has been lost and in some cases the crown has been destroyed completely. Thus, available radiochemical data could be interpreted with a satisfactory level of accuracy as the average ^{90}Sr concentration in dentin of molars and premolars.

As seen from Fig. 7b, ^{90}Sr concentration in dentin of posterior teeth is not age dependent for adults (age 25 and more) and is equal to about 16 Bq g^{-1} Ca. As discussed above, the mineral turnover in adults is determined by secondary and reparative (irritation) dentin formation, and the constant ^{90}Sr contents for adult teeth over a long age period indicate that these processes occur at a relatively constant rate.

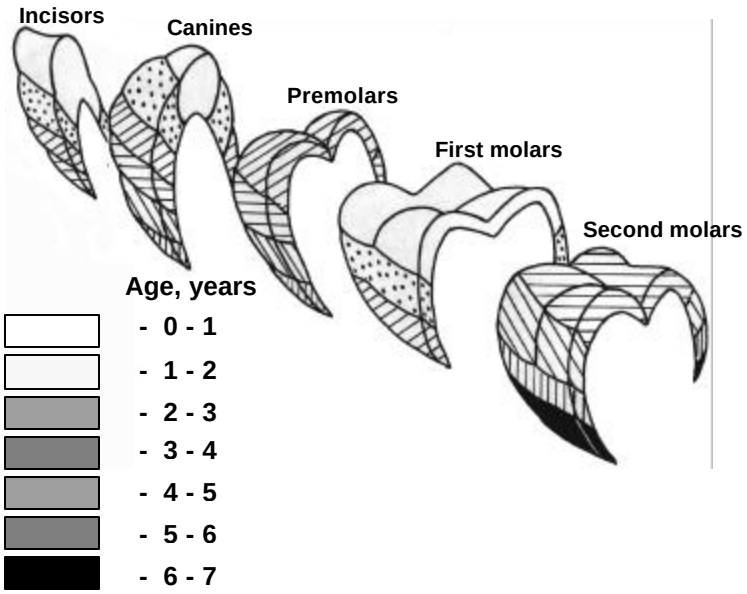

Fig. 9. The process of formation of crown enamel (according to Massler et al. 1941).

The ^{90}Sr concentration in tooth dentin of persons who were younger than 15 y at the time of intake was about eight times higher than for those who were adults (Fig. 7b), and maximum values were registered for infants who were born in 1949–1950. The scheme of permanent tooth development (Fig. 10) shows that in this age period the processes of mineralization occur practically in all teeth (in the crown or in the root). Permanent dentition for all teeth (except wisdom teeth) is completed by the age of 12–15 y. In accordance with this, a sharp decrease of the ^{90}Sr concentration in molars and premolars is observed for persons who were older than 15 years at the time of maximal intake (Fig. 7b).

^{90}Sr elimination rate in teeth. A long period of observation with the use of the TBC method has given data on the changes of ^{90}Sr content in front teeth with time after the onset of intake and the rate of elimination of ^{90}Sr from these front teeth. The excretion of tooth minerals is a complicated process, which has not been studied sufficiently in order to define completely the process. For enamel the role of the following processes affecting calcium elimination can be noted: diffusion, the surface-reaction process of dissolution or demineralization, and mechanical attrition (Suga and Watabe 1992). Diffusion and ion exchange on the surface of dentinal tubules and pulp characterize the processes in dentin. Quantitative parameters characterizing these processes have not been found in literature.

Assessment of the ^{90}Sr-elimination rate based on repeated TBC measurements of single individuals shows an exponential decrease of the TBC signal with time (Kozheurov and Degteva 1994). This decrease occurs due to radioactive decay of ^{90}Sr (2.35% per year) and biological elimination. Fig. 11 exemplifies individual data for two residents, and Fig. 12 presents the time

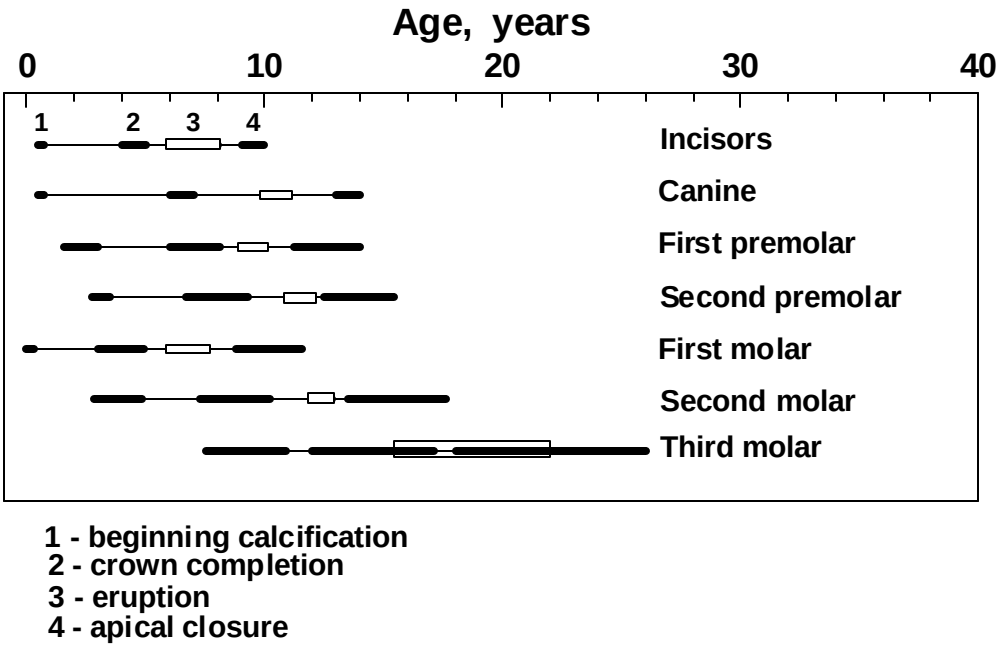

Fig. 10. The processes of dentition in permanent teeth (Lewis and Garn 1960; Kolesov 1991).

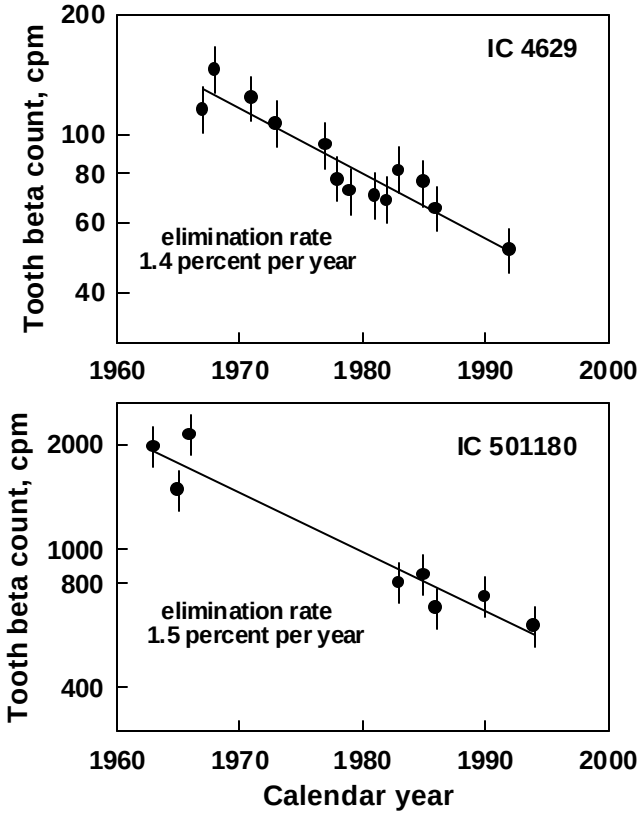

Fig. 11. Examples of TBC repeated measurements for two persons from the Techa River (Identification Codes 4629 and 501180).

pattern of the TBC levels averaged for the age cohorts born in 1949–1951. This age group has maximal TBC levels and the smallest error (less than 10%) of reproducibility. The average biological elimination rate is evaluated as 1.9% per year. This value is very close to the minimal limit for ^{90}Sr-elimination rate for adult compact bone (ICRP 1995).

Measurements of ^{90}Sr in some teeth of residents of the Techa River region were also made in 1994–1995 (Wieser et al. 1996). The ^{90}Sr content in dental roots from nine persons born before 1937 were investigated with low-level beta counting. It is possible to predict the ^{90}Sr concentration in teeth in 1994 on the basis of radiochemical measurements from the 1960–1964 period and the use of the estimated rate of elimination of ^{90}Sr. Table 16 demonstrates that the results calculated for 1994 on the basis of radiochemical measurements in 1960–1964 are not contradictory to the ^{90}Sr-measurement results in root dentin in 1994. For a preliminary assessment of cumulative enamel dose it was assumed that all ^{90}Sr was ingested during the first year of intake (1950) and after that the ^{90}Sr concentration in teeth decreased with an effective rate of 4.25% per y.

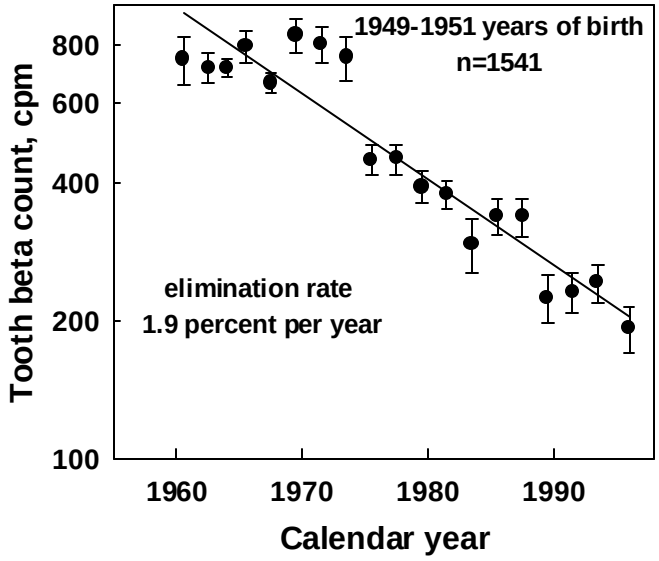

Fig. 12. The decrease of annual mean TBC levels with time. Strontium-elimination rate was evaluated using the results of 1,541 TBC measurements performed on 621 persons born in 1949–1951 in the communities located on the upper and middle Techa River.

5.2.3. Assessment of enamel dose from ^{90}Sr

The enamel dose accumulated since the moment of intake can be calculated as the product of the total amount of radioactive disintegrations of ^{90}Sr per gram of source tissue (enamel, dentin) and the corresponding dose coefficient (dose rate in enamel per unit

Table 16. Concentration of ^{90}Sr in teeth: results of measurements and calculated values.

Year of birth	Age at the onset of contam-ination	^{90}Sr in teeth, Bq (g Ca)$^{-1}$				
		1960-1964		1994		
		Radiochemical measurements	Number of teeth measured	Values calculated from radiochemical data[a]	Low-level beta-counter measurements[b]	Number of teeth measured
≤1926	≥24	16 ± 5	33	4 ± 1	4 (0–9)	4
1927–1933	17–23	39 ± 23	8	9 ± 5	6 (5–7)	3
1934–1937	13–16	110 ± 53	8	26 ± 13	28 (27–29)	2

[a] - With use of an effective rate of 4.25% per y.
[b] - In parentheses are the minimal and maximal estimates.

concentration of ^{90}Sr in source tissue). Monte Carlo simulations of the paths of beta-particles (emitted by ^{90}Sr/^{90}Y) with use of a geometric model of teeth should be regarded as the most appropriate method for calculations of dose coefficients for different tooth positions (Shved and Shishkina 2000a,b; Tolstykh et al. 2000; Shishkina et al. 2001). Experimental data and model simulations have shown that the main source of ^{90}Sr exposure and dose for tooth tissues is self absorption.

All EPR measurements of enamel samples for the Techa River residents were extracted from database "TOOTH" for a preliminary analysis of the age dependence of enamel doses from ^{90}Sr incorporated in tooth tissues. There are 155 EPR measurements for persons who lived on the Techa River during the period of releases (1949–1956). The majority of these persons are members of the Extended Techa River Cohort (ETRC), but there are some persons (born in the period of releases) who are the members of the Techa River Progeny Cohort (TROC).

It was found that the majority of persons have enamel doses lower than 2 Gy, but nine persons (born in the period 1943–1949) have high enamel doses (more than 4 Gy); among the latter are five persons (born in 1945–1949) with ultrahigh enamel doses (more than 10 Gy). All five persons with ultrahigh doses lived on the Techa River during the period of massive releases (March 1950–November 1951), and the age of the beginning calcification of their teeth overlapped with the period of massive releases (Table 17). Therefore, such very high doses in enamel are caused by beta particles emitted by ^{90}Sr/^{90}Y absorbed in the enamel itself.

To consider this effect in more detail we have selected the following two groups of tooth samples with different maturation times (Table 15):

1. Permanent teeth for which calcification begins during the first year of human life and the completion of the crown is finished at the age of 3–5 years. These teeth are the first and second incisors and the first molars (positions 1, 2, and 6) and
2. Permanent teeth for which calcification begins at the age of 3–5 years and crown completion is finished at the age of 7–10 years. These teeth are the second molars and the second premolars (positions 5 and 7).

Table 17. Data for persons with EPR-measured doses in enamel higher than 10 Gy.

Identification code	Tooth position	Age at beginning of calcification for the measured tooth	Age in the period of massive releases
31391	2U	9–12 mo.	4–22 mo.
11317	5U	2.7–4.2 y	2.25–3.75 y
213278	5U	2.7–4.2 y	4.17–5.67 y
215177	7L	2.8–4.8 y	4.42–5.92 y
525276	7L	2.8–4.8 y	2.83–433 y

The results of EPR measurements for these groups (averaged according to birth year of tooth donor) are presented in Fig. 13 (a, b). This figure demonstrates that both curves have sharp peaks of enamel doses that occur within a narrow range of age cohorts, but the peak positions of enamel dose due to ^{90}Sr are different for the two groups of teeth. For the first group of teeth very high enamel doses are observed for persons born in 1949. In the period of massive releases they were 0–2-y old (the age at beginning of calcification of the crown). For the second group of teeth very high enamel doses are observed for persons born in 1945–1947. In the period of massive releases they were 3–6-y old (for the second premolars and the molars this is the age when calcification of the crown begins). This corresponds to data from Fig. 7a discussed above that the maximal rate of mineralization is observed in the early period of crown calcification.

It should be stressed that such an effect as "the presence of ^{90}Sr in enamel" results in one-to-two orders of magnitude increase in enamel dose. For some cases the dose to teeth becomes higher than the upper limit of the EPR-dosimetry method (the concentration of radiation-induced radicals and hence the intensity of the EPR signal increases linearly with absorbed dose of radiation only up to 20 Gy). Also, it should be noted that such very high levels of absorbed dose are observed only for tooth tissues and don't correlate with the doses absorbed in other organs and tissues of the human body (average path lengths of beta particles in dental tissues are equal to 0.2–0.3 mm for ^{90}Sr and 2–3 mm for ^{90}Y). It seems obvious that tooth samples with ^{90}Sr incorporated in enamel are useless for the purposes of validation of calculated external doses, and teeth for which the period of enamel calcification overlapped with the period of ^{90}Sr intake must be excluded from the validation study.

For persons whose enamel formation had been completed at the beginning of ^{90}Sr intake the main source tissue for beta exposure of enamel is dentin. Monte Carlo modeling of the ^{90}Sr/^{90}Y absorbed dose in dental tissues (Shved and Shishkina 2000a,b; Shishkina et al. 2001) shows that the contribution of "the dentinal ^{90}Sr" to enamel dose is one order of magnitude lower compared to the dose resulting from self exposure (i.e., from ^{90}Sr/^{90}Y in the enamel tissue itself). Such a contribution is comparable to the other contributions to enamel dose and can be taken into account in a validation study.

5.3. Preliminary analysis of different contributions to the EPR signal for teeth from members of the ETRC

As noted above, for the purposes of validating calculations of external doses for members of the Extended Techa River Cohort (ETRC) it is necessary to develop procedures for evaluating and subtracting background dose and dose from incorporated ^{90}Sr/^{90}Y from the measured total EPR signal in enamel. These contributions depend on the age and the residence history of a particular person and also on the position of the sampled tooth. We consider in this section the example of the expected structure of EPR-measured dose in tooth enamel for the first molars for those persons who were adults during the period of massive releases and who lived permanently in the upper Techa River region (Metlino) and the middle Techa River region (Muslyumovo). This is a preliminary evaluation based on a limited number of EPR measurements of Urals background teeth and calculations of ^{90}Sr/^{90}Y-enamel dose performed using the simplified tooth model described in Tolstykh et al. (2000).

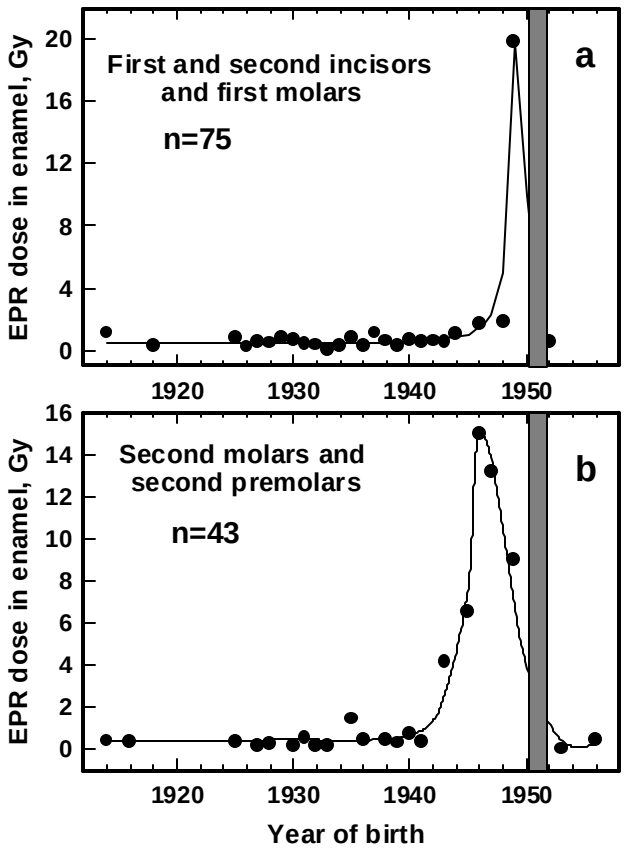

Fig. 13. Age dependencies of enamel doses in permanent teeth measured by EPR for residents of the Techa River communities: a) first and second incisors and first molars and b) second molars and second premolars. The period of massive radioactive releases into the Techa River is indicated by the shaded area.

The total-enamel dose is calculated as the sum of three contributions: background dose, dose due to $^{90}Sr/^{90}Y$ in dentin, and external gamma dose (Table 18). A lognormal distribution was assumed for background dose with the parameters estimated from a fit to the IMP data presented in Section 5.1 of this report. For dose due to ^{90}Sr in dentin the average enamel dose for the first molars of adult Muslyumovo residents calculated according to the model described in Tolstykh et al. (2000) is used to derive a deterministic estimate of accumulated dose. It is suggested that the distributions of Individual-to Model Ratios (determined in Degteva et al. 2000) for Metlino and Muslyumovo could be used to simulate the village specific distributions of ^{90}Sr levels in dentin. The contribution of external exposure is evaluated in the same way as for the TRDS-2000 (Degteva et al. 2000) using the conversion factor from absorbed dose in air to absorbed dose in enamel equal to 0.996 (Wieser et al. 2000b). The results of these preliminary calculations are presented in Table 18.

Table 18. Expected values of different contributions to the total enamel dose for adult permanent Techa Riverside residents. In these examples doses are calculated for the first molars, and 95% confidence intervals are given in parentheses.

Settlement	Distance from site of release, km	Background dose, mGy	Dose due to ^{90}Sr in dentin, mGy	External dose, mGy	Total enamel dose, mGy
Metlino	7	140 (50–320)	30 (3–100)	530 (380–890)	700 (500–1100)
Muslyumovo	78	140 (50–320)	40 (10–110)	20 (10–40)	200 (100–400)

As seen, for the upper Techa River region we expect EPR measured enamel doses to be in the range of 0.5–1.1 Gy, of which the external exposure contributes 75%. The contribution from background dose is estimated to be 20%, and thus it cannot be neglected. The average contribution of ^{90}Sr is expected to be relatively low (about 5%). A rather different picture is expected for residents of the middle Techa River region, where background exposure is estimated to contribute 70% of the total enamel dose (which is evaluated to be 100–400 mGy). Contributions of internal and external exposure due to the contaminated river are evaluated to be 20% and 10%, respectively. Therefore, the correct evaluation of background and ^{90}Sr contributions to enamel dose is very important for the purposes of validating the TRDS-2000 calculations of external dose.

The uncertainty of dose reconstruction by use of the EPR method depends not only on the uncertainty of the measurement of absorbed dose in tooth enamel, but is determined also by the separation of dose due to the exposure event of interest. In the next section we discuss possibilities of how to minimize the uncertainties of the contributions from background and ^{90}Sr incorporation in dentin.

6. DISCUSSION

Previous sections of this report have demonstrated clearly the following statements relative to the Techa River external dose-validation study:

1. Consideration of the state-of-the-art for EPR retrospective dosimetry with teeth shows that this method can be applied to validation of the external doses calculated with the use of the TRDS-2000;
2. There are significant numbers of teeth collected from exposed and nonexposed Urals residents; these samples are stored at the URCRM and can be used for EPR measurements; and
3. An EPR measurement by itself is not sufficient as a validation without some accompanying knowledge of the contribution of ^{90}Sr and background exposure to the resulting EPR signal. EPR measurements must be supported by extensive modeling and parallel determination of ^{90}Sr in tooth tissues.

There are several groups of requirements necessary for the success of the validation study of the external doses calculated with the use of the TRDS-2000. These requirements are aimed at reducing the uncertainties in individual external doses evaluated on the basis of EPR measurements by minimizing the uncertainties associated with each of the different factors described in previous sections. Here we group these requirements according to the stages of the validation study.

Selection of samples.

It is obvious that for each sample it is necessary to trace the entire exposure history of the tooth donor (including environmental and possible occupational and medical exposure) in order to minimize the uncertainty associated with the data on exposure history. The requirements concerning personal data and the procedures for separating donors into two categories (exposed and nonexposed) were described in Section 3.1 of this report. A small portion of samples has been received from donors who cannot be identified definitely as "exposed" or "nonexposed." Such samples are kept in a separate "tooth bank," and these samples will not be used in the validation study.

As discussed above, tooth samples with ^{90}Sr incorporated in enamel are useless for the purposes of external dose validation, due to the extremely high contribution of beta exposure to the total dose to tooth enamel. Thus, teeth for which the period of enamel calcification overlapped with the period of ^{90}Sr intake are not used in the validation study. Such samples can be identified by comparison of the donor's age and residence during the period of massive releases with the age of calcification of enamel for the tooth position considered.

In order to minimize the uncertainty associated with uv exposure (which affects the EPR signal) it is recommended to select samples of posterior teeth only, where this is possible. If front teeth are used, it is recommended to use enamel from the inner side only.

EPR-dose reconstruction.

Uncertainties associated with the EPR method depend on sample preparation, signal evaluation and dose-calibration procedures.

The aim of sample preparation is to achieve the best possible separation of dentin from tooth enamel; this is required to minimize the broad native EPR signal that arises from the organic material in dentin. Optimized procedures for preparation of enamel samples have been elaborated during recent years. A recent international intercomparison has shown no clear advantage to one particular technique over another, as long as spurious signals are not inadvertently introduced. Nevertheless, the characteristics of a sample-preparation technique can be a source of increased variation in enamel response (or additional EPR signals interfering with the dosimetric signal), and a standardized sample-preparation protocol would be useful for EPR laboratories involved in the validation study.

Another source of uncertainty is a lack of information about the correct shape of the EPR spectrum of an individual sample, if it is not irradiated to serve as its own control. The shape of initial spectra for different samples can vary due to different reasons. On average, such variations could be taken into account by introducing the so-called intrinsic signal (which is specific for every sample but has an average value that depends on the peculiarities of the methodical approach, especially on the shape of the reference spectra used for simulation and subtraction of the native signal). The amplitude of the intrinsic signal is a possible cause of bias; therefore, it is recommended that each method used should be accompanied by a report on the reconstructed dosimetric signal for unirradiated samples and whether the amplitude of such a signal has been subtracted in the dose evaluation.

A special case of additional EPR signals interfering with the dosimetric signal is that of metal impurities introduced to enamel by metal dentures (discussed in Section 4.3). Work is now proceeding on the development of objective criteria that can be used to judge the acceptance of EPR spectra.

Uncertainties associated with EPR measurements of teeth have been addressed in several international EPR intercomparisons and described in the open literature. The reliable detection of absorbed doses in enamel on the order of 100 mGy with an accuracy of ±100 mGy has been described. This detection limit is lower than the expected values of absorbed dose in enamel for members of the ETRC (Table 18), but the uncertainty of the contribution due to the Techa River external exposure is strongly dependent on the accuracies and uncertainties of the derived contributions from background exposure and ^{90}Sr incorporation into dentin.

Evaluation of background contribution.

According to preliminary assessments, the background exposure contributes about 20–70% of the total enamel dose for members of the ETRC. It is impossible to separate radiation-induced EPR signals from background sources and from "Techa River sources" on the basis of only an individual measurement of an exposed sample. The only approach to evaluation of the background contribution is investigation of an adequate comparison group of subjects exposed only due to background sources (similar to a control group in epidemiologic studies). The reduction of uncertainty connected with such an approach is possible by careful selection of samples and by including a large number of subjects in this comparison group, as well as by an objective investigation of the factors influencing the level of background-EPR dose (such as tooth position and age of the donor). The evaluation of "Urals background" requires the measurement of *not less than 500 teeth* of different types (incisors, canines, premolars and molars) from persons (of different ages) who lived on the same uncontaminated areas as did the "epidemiological controls."

Evaluation of ^{90}Sr contribution.

This contribution is especially important for persons who lived on the middle and lower Techa River, where the levels of external exposure were low. For an adequate assessment of the ^{90}Sr/^{90}Y component of EPR dose it is necessary to estimate 1) ^{90}Sr concentration in tooth tissue,

which is determined by complex physiological processes, and 2) specific dose coefficients for dental tissues.

As a first step, it is necessary to develop an age-dependent model for strontium metabolism in teeth in order to reconstruct the complete time pattern of ^{90}Sr retention in dental tissues since the onset of intake. General regularities of tooth maturation and calcification and the measurements of ^{90}Sr in teeth from the Techa Riverside residents (described in Section 5.2) must be used for this purpose. A significant reduction of uncertainty in this step could be achieved by measurements of ^{90}Sr in the same dental tissues that are being used for EPR measurements. Several techniques have been suggested for the evaluation of ^{90}Sr concentration in dental tissues. These include low-level beta counting, radiochemistry, thermoluminescence measurement, and imaging on Fuji plates. It is necessary to investigate the accuracy and cost for each of these methods in order to select the best possibility for large scale measurements.

For the second step it is possible to use Monte Carlo modeling of electron transport in dental tissues on the basis of geometric models that describe different types of teeth. Several versions of such models have been developed and published during recent years. A reduction of uncertainty in such model calculations could be achieved by using the odontometric measurements performed at the URCRM since 1999. Such measurements give geometric parameters of teeth specific for the population of the Urals region, and these parameters could be used as input data for geometric models of the teeth under investigation.

Perspectives of the validation study.

There are other problems connected with the Techa River external dose-validation study. In addition to what has been discussed above it would be useful to investigate the energy dependence of the sensitivity of enamel (with special attention to the energy range of beta particles produced by ^{90}Sr/^{90}Y). Also, an important step would be the comparison of the findings derived by different methods of retrospective dosimetry and biodosimetry for residents on the Techa River. For example, recent successes in the measurement of environmental doses by thermoluminescence of natural materials in Metlino and Muslyumovo (Bougrov et al. 1998) could also be used for additional validation of external doses near the Techa River bank. And also, FISH-based analysis of stable chromosome translocations in members of the Techa River population (Bauchinger et al. 1998) could provide useful information for a retrospective biodosimetric interpretation. Such an integrated undertaking would be a complicated study that must use a combination of different experimental and calculational methods; any such study must be done in close cooperation and with good coordination of different groups of researchers.

It must be stressed that 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 epidemiologic studies they support.

7. CONCLUSIONS

The data presented and the results discussed above lead to the following general conclusions:

1. A special database named "TOOTH" has been established at the URCRM. This database (DB) contains data on all tooth samples and all tooth donors belonging to the ETRC and the population of background areas of the Urals region. The matching of subjects registered in this DB with the other URCRM data bases (such as DB "MAN") provides the availability of individual-exposure histories, ^{90}Sr-body burdens, tooth-beta count, etc., for the exposed donors. Also, results have been collected into this DB for all available EPR measurements performed in the Urals (or on Urals teeth) since 1992.
2. The state-of-the-art for EPR retrospective dosimetry with teeth shows that this method can be applied for the validation of the TRDS-2000 external doses. The results of several intercomparisons among the laboratories involved in dose-reconstruction work with teeth from the Southern Urals have been discussed; the uncertainty of absorbed dose measured in tooth enamel has also been discussed. An analysis of the results of the intercomparisons demonstrates that contemporary EPR-dosimetry systems can reconstruct doses within ±25 % and ±100 mGy for doses below 400 mGy with a confidence of 0.95.
3. A preliminary analysis has been performed on available data on background levels of the EPR signal of tooth enamel from the residents of non-contaminated areas of the Southern Urals. It is expected that background exposure contributes about 20–70% to the total enamel dose for the members of the ETRC; therefore, an accurate evaluation of this contribution is an important part of the Techa River validation study.
4. The Techa River data on ^{90}Sr in dental tissues (measured using different experimental techniques since the late fifties) provides a basis for the evaluation of age-dependencies of strontium metabolism in teeth. For an adequate assessment of the ^{90}Sr component of EPR dose it is necessary to continue measurements of ^{90}Sr concentration in tooth tissue and to develop biokinetic and dosimetric models specific for dental tissues.
5. The requirements for the TRDS-2000 external dose-validation study have been discussed. This complicated study requires the use of a combination of different experimental and calculational methods and must be done in close cooperation and with good coordination of different groups of researchers. It must be stressed that 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 of the companion epidemiologic studies they support.

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APPENDIX 1

DATA INPUT AND EDITING THE FILES OF DATABASE "TOOTH"

Database "TOOTH" has two variants for input of data or the editing of existing data about the donor, teeth and measurements.

First variant. New records are simply noted in the corresponding files. Such record addition is convenient, when only a small amount of information needs to be changed or must be added to the files.

Second variant. In the database "TOOTH" special forms for data input and editing were created by using the capability of Microsoft Access. "Form" is a Microsoft Access database object on which are placed controls for entering, displaying, and editing data in fields. There are four forms in the database "TOOTH":

1. Form "Donors and teeth;"
2. Form "EPR-measurements;"
3. Form "^{90}Sr concentration;" and
4. Form "Odontometrics."

Using these forms to enter data into the files is more convenient, when extensive amounts of data must be entered. The requirements and conditions for data input using these forms are described below. These requirements concern the first variant of data input, as well.

1. Form "Donors and teeth"

Form "Donors and teeth" is a form to record data about donors and their teeth. (Fig. A1-1). This form consists of the main form "Donors" and the subform "Teeth." All fields in the file "Donors" are represented in the main form "Donors":

1. Identification code – field "Identification_code." This field must be filled. The entered value is automatically checked to ensure that it is more than zero, less than 9002000, and has no duplicates among all values in this field.

2. Surname – field "Surname." This field may be filled in manually or by choice from the available list of common surnames. The list is located in the related file "Donor's surname."

3. Name – field "Name." This field may be filled in manually or by choice from the available list of common names. The list is located in the related file "Donor's name."

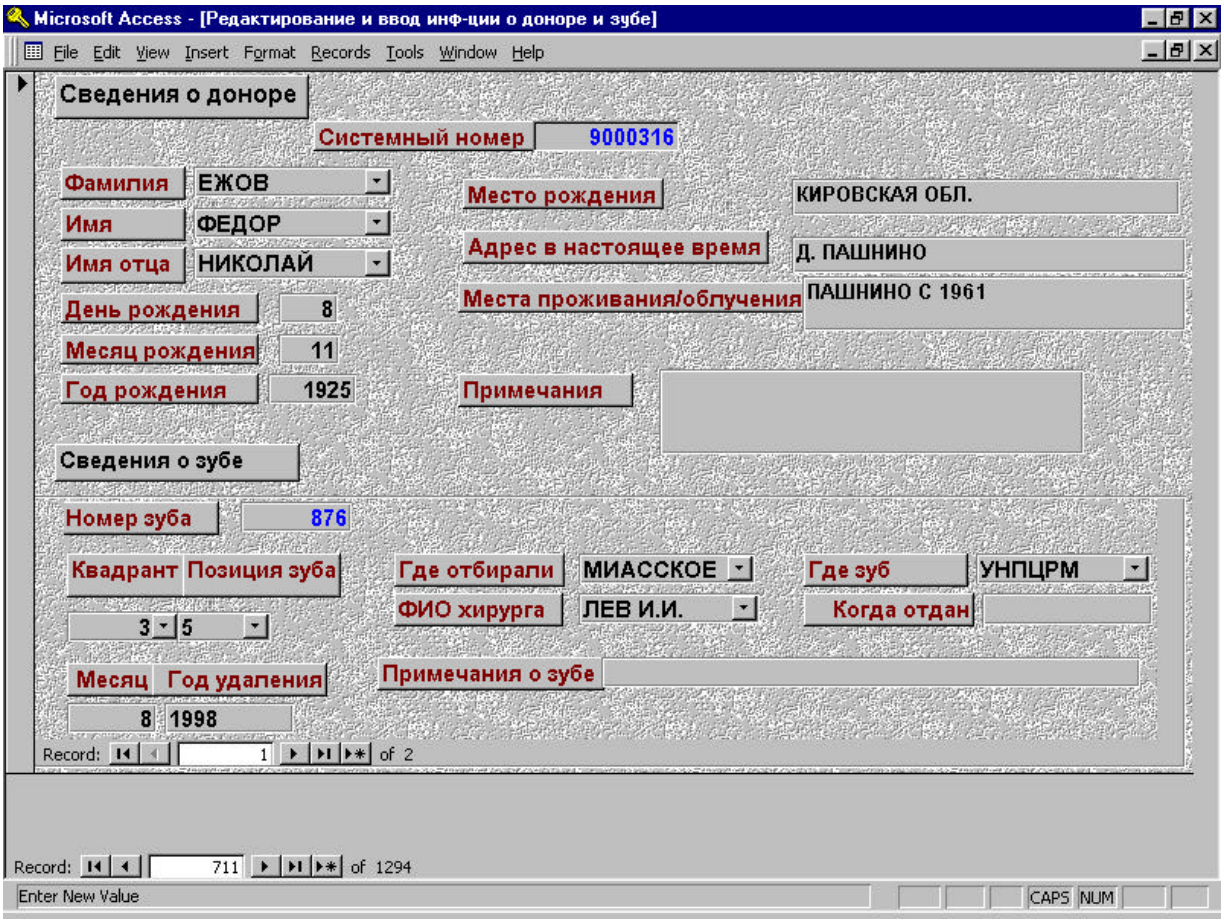

Fig. A1-1. Form "Donors and teeth."

4. Father's name – field "Father's_name." This field may be filled in manually or by choice from the available list of common male names. The list is located in the related file "Father's name."

5. Day of birth – field "Day_birth." This entry is automatically checked to be more than zero and less than 32.

6. Month of birth – field "Month_birth." This entry is automatically checked to be more than zero and less than 13.

7. Year of birth – field "Year_birth." This entry is automatically checked to be more than 1890 and less than 1999.

8. Place of birth – field "Place_birth." The entry in this field is performed manually.

9. Address – field "Address." The entry in this field is performed manually.

10. Residence history/place of exposure – field "Residence." The entry in this field is performed manually.

11. Notes – field “Notes.” The entry in this field is performed manually.

The field “Identification_code” joins the main form with subform “Teeth.” The “Teeth” subform includes all fields from the file “Teeth” and contains information about extracted teeth.

The fields of subform “Teeth” are

1. Tooth code – field “Tooth_code.” This field must be filled. When the value is entered, it is checked automatically to ensure that the value is more than zero and that it has no duplicates among all values in this field.

2. Quadrant – field “Quadrant.” This field is filled by choice from the available list of all variants of mouth quadrants.

3. Tooth number – field “Tooth_number.” This field is filled by choice from the available list of all tooth-number positions.

4. Month of extraction – field “Month_extraction.” Upon entry the value is checked automatically to ensure it is more than zero and less than 13.

5. Year of extraction – field “Year_extraction.” The entered value is checked automatically to ensure that is more than 1990.

6. Dental clinic – field “Dental_clinic.” This field is filled by choice from the available list of dental clinics.

7. Dentist’s name –field “Dentist’s_name.” This field is filled by choice from the available list of dentists.

8. Place storage – field “Place_storage.” This field is filled by choice from the available list of places of storage.

9. Date delivery – field “Date_delivery.” The entered value is checked automatically to ensure that is more than 1991.

10. Notes – field “Notes.” The entry in this field is performed manually.

In the lower left corner of the form window the navigation buttons are situated. Navigation buttons provide an efficient way to move to the first, previous, next, last, or blank (new) record. The upper row of navigation buttons is for the subform and the lower row of buttons is for the main form. The record-number box displays the current record number. The total number of records is displayed next to the navigation buttons. Input of a number in the record-number box moves the display to a particular record. In Fig. A1-1 the total number of records in the main form is 1294. The current record number is 711. The total number of records in the subform is 2. This indicates that there is information about two teeth for a donor with identification code 9000316 in database “TOOTH.”

2. Form “EPR-measurements”

The purpose of Form “EPR-measurements” (Fig. A1-2) is to record the results of EPR measurements on tooth tissues. This form consists of a main form and a subform. In the main form some fields from the file “Teeth” are displayed. Data are entered in the subform “EPR-measurements.” This subform involves all fields from the file “EPR-measurements.”

The fields of subform “EPR-measurements” are

1. Tooth tissue – field “Tooth_tissue.” This field is filled by choice from the available list of all tooth tissues used for EPR-measurements.

2. Dose, mGy – field “Dose_EPR.” Upon entry this value is checked to be not less than zero.

3. Error, mGy – field “Error_EPR.” Upon entry this value is checked to be not less than zero.

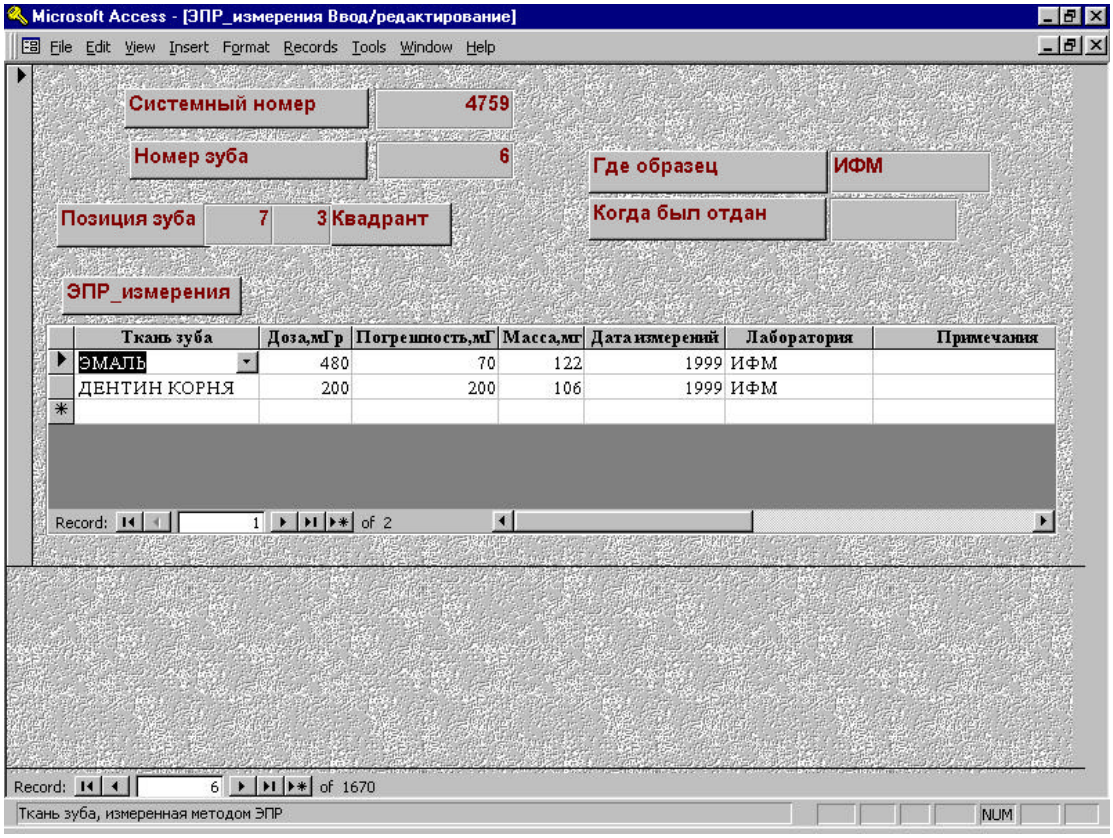

Fig. A1-2. Form “EPR-measurements.”

4. Mass, mg – field “Sample_mass.” Upon entry this value is checked to be more than zero.

5. Date of measurement – field “Date_measurement.” Upon entry this value is checked to be more than 1991.

6. Laboratory – field “Laboratory.” This field is filled by choice from the available list of laboratories carrying out EPR measurements for the Southern Urals.

7. Notes – field “Notes.” The data in this field are entered manually.

The navigation buttons for this form are shown in the lower left corner of Fig. A1-2. The current record number in the main form is 6. The total number of records in the subform is 2. This indicates that for this tooth two EPR measurements have been performed.

3. Form “^{90}Sr Concentration”

The purpose of form “^{90}Sr Concentration” is to enter the results of ^{90}Sr-concentration measurements in tooth tissues (Fig. A1-3). This form consists of a main form and a subform. In the main form some fields from the file “Teeth” are displayed. Data are entered in the subform

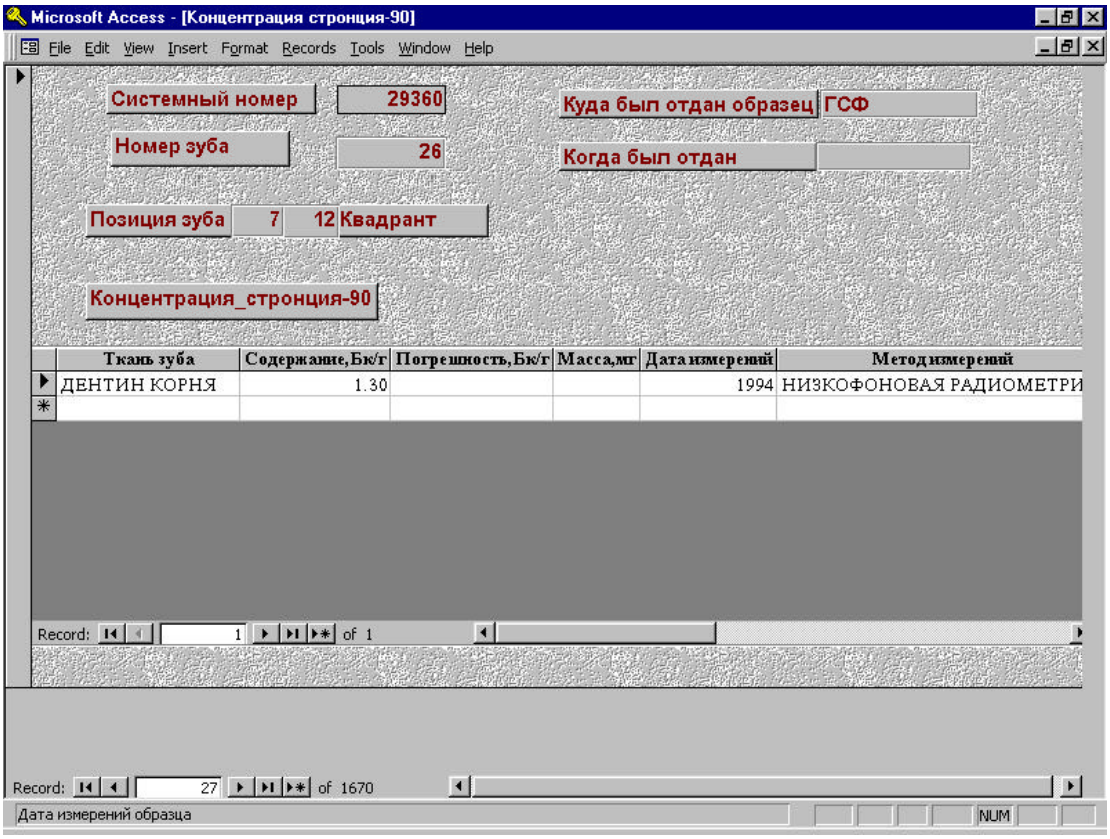

Fig. A1-3. Form “Concentration ^{90}Sr.”

"Results of ^{90}Sr concentration measurements." This subform involves all fields from the file ^{90}Sr concentration."

The fields of subform "Results of ^{90}Sr concentration" are

1. Tooth tissue – field "Tooth_tissue." This field is filled by choice from the available list of all tooth tissues used for the measurement of ^{90}Sr concentration.

2. Concentration, Bq/g – field "Concentration_Sr." The entry is checked automatically to ensure that the value is not less than zero.

3. Error, Bq/g – field "Error_Sr." The entry is checked automatically to ensure that the value is not less than zero.

4. Mass, mg – field "Sample_mass." The entry is checked automatically to ensure that the value is more than zero.

5. Method of measurement – field "Method." This field is filled by choice from the available list of all methods used for the measurement of ^{90}Sr concentration.

6. Date of measurement – field "Date_measurement." The entry is checked automatically to ensure that the value is more than 1991.

7. Laboratory – field "Laboratory." This field is filled by choice from the available list of laboratories carrying out measurements of ^{90}Sr concentration on tooth samples from the Southern Urals.

8. Notes – field "Notes" The data in this field are entered manually.

The navigation buttons are situated in the lower left corner of the form window. The current record number in the main form is 27, and total number of records in the subform is 1. This indicates that this tooth has one result of ^{90}Sr-concentration measurement.

3. Form "Odontometrics"

The purpose of Form "Odontometrics" is to record the results of odontometric measurements (Fig. A1-4). This form consists of a main form and a subform. In the main form some fields from file "Teeth" are displayed. Data are entered in the subform "Odontometric measurements." This subform involves all fields from the file "Odontometrics."

The fields of subform "Odontometric measurements" are

1. MD diameter – field "MD_diameter." The entered value is checked automatically to ensure that it is more than zero.

2. BL diameter – field "BL_diameter." The entered value is checked automatically to ensure that it is more than zero.

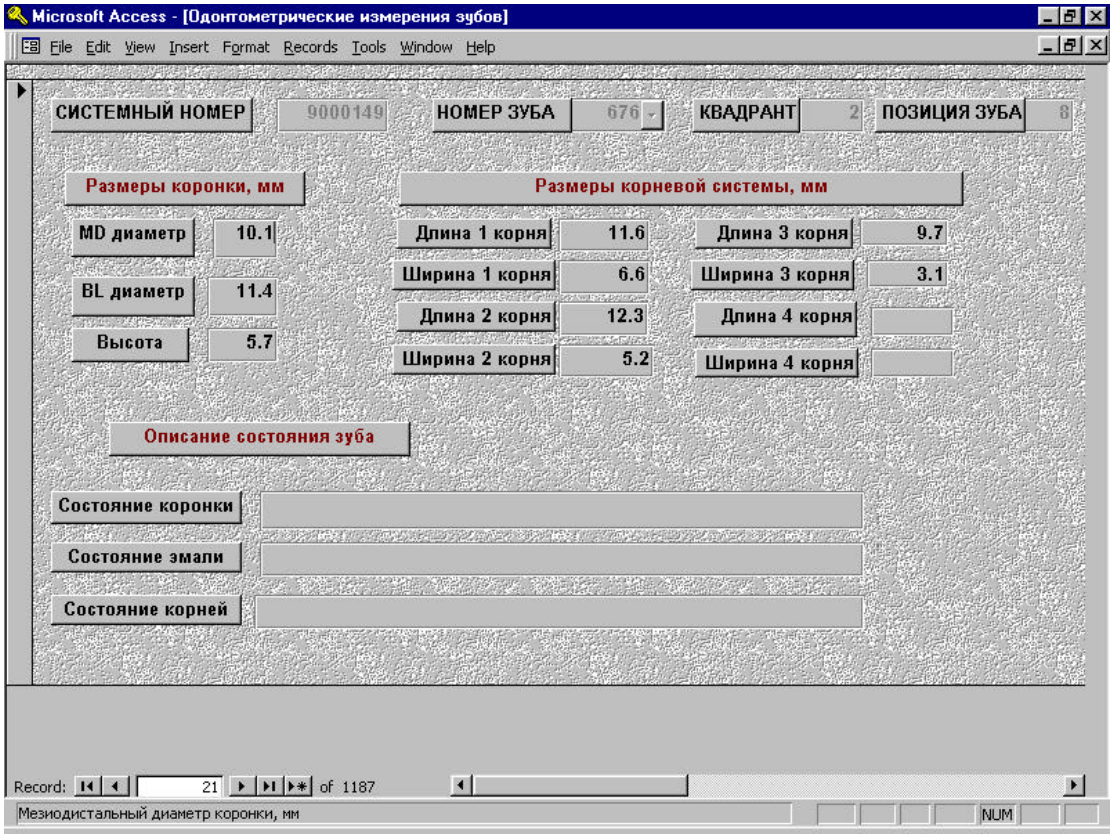

Fig. A1-4. Form "Odontometric measurements."

3. Height of crown – field "Height." The entered value is checked automatically to ensure that it is more than zero.

4. Length of 1st root – field "Length_1_root." The entered value is checked automatically to ensure that it is more than zero.

5. Width of 1st root – field "Width_1_root." The entered value is checked automatically to ensure that it is more than zero.

6. Length of 2nd root – field "Length_2_root." The entered value is checked automatically to ensure that it is more than zero.

7. Width of 2nd root – field "Width_2_root." The entered value is checked automatically to ensure that it is more than zero.

8. Length of 3rd root – field "Length_3_root." The entered value is checked automatically to ensure that it is more than zero.

9. Width of 3rd root – field “Width_3_root.” The entered value is checked automatically to ensure that it is more than zero.

10. Length of 4th root – field “Length_4_root.” The entered value is checked automatically to ensure that it is more than zero.

11. Width of 4th root – field “Width_4_root.” The entered value is checked automatically to ensure that it is more than zero.

12. Condition of crown – field “Crown_condition.” The data in this field are entered manually.

13. Condition of enamel – field “Enamel_condition.” The data in this field are entered manually.

14. Condition of roots – field “Roots_condition.” The data in this field are entered manually.

The navigation buttons for the main form are situated in the lower left corner of the form window (Fig. A1-4). There are no navigation buttons for the subform “Odontometric measurements,” as the main form and the subform join with the relationship type of “one-to-one.”

APPENDIX 2

LATE HEALTH EFFECTS AMONG INDIVIDUALS EXPOSED TO IONISING RADIATION IN THE SOUTHERN URALS

Contract No: EN B FP5RTD
Annual report for period 1 February 2000 to 31 January 2001
Work Package 3: Dose Reconstruction for TROC
Partner 2, URCRM: M.O. Degteva, N.G. Bougrov, D.V. Ivanov, E.I. Tolstykh, M.I. Vorobiova
Partner 5, GSF: P. Jacob, H.Y. Göksu, A. Wieser

Objectives of the reporting period

- To consider three pathways of radiation exposure for members of the Techa River Offspring Cohort (TROC): (i) exposure of maternal and paternal gonads before conception; (ii) exposure *in utero*; and (iii) exposure after birth, especially during the first year. To improve the dosimetry of members of the TROC by taking into account achievements obtained during the period 1996-2000 in the Techa River Dosimetry System (TRDS-2000).
- To analyze the compatibility of EPR measurements with tooth enamel performed by the Institute of Metal Physics, Ekaterinburg (performed in the frame of the ISTC project #509) and by GSF for ETRC members and for unexposed residents of the Techa region.
- To perform first luminescence measurements of absorbed dose in bricks collected from the church in Metlino.

Progress and main achievements

Radiation exposure for members of the Techa River Offspring Cohort

Methods for the calculation of fetal dose due to external exposure have been developed using the TRDS-2000 approach on the basis of measured and modeled gamma exposure rates along the river bank and estimated age-specific life styles (Degteva et al. 2000a). Methods for the calculation of fetal doses due to mother dietary intake have been developed using data on mean annual dietary intake levels of three major dose-forming radionuclides: ^{90}Sr, ^{89}Sr and ^{137}Cs (Degteva et al. 2000b).

The absorbed dose in fetal red bone marrow due to the ^{90}Sr transfer from the maternal skeleton to the embryo/fetus was evaluated on the basis of an assessment of the strontium transfer from the maternal skeleton to the fetal bone. The analysis was performed on the basis of the Techa River Cohort data on ^{90}Sr measurements both for stillborn infants and their mothers.

A method to assess the total fetal dose has been developed and applied to reference settlements on the upper and the middle Techa riverside (Tolstykh et al. 2000). According to this assessment, doses in Metlino at the upper Techa river were mainly due to external exposures during the year 1951, and doses in Muslyumovo at the middle Techa river due to the maternal dietary intake during 1950 (Table 1).

Table 1. Doses to embryo/fetus evaluated for the period of massive releases (1950-1952) due to different exposure pathways for two reference settlements on the Techa River.

Settlement (distance from the release site)	Calendar year	Fetal dose (mGy) due to		
		^{90}Sr transfer from maternal skeleton[a]	Maternal dietary intake during pregnancy	External exposure
Metlino (7 km)	1950	0.69	26.7	25.9
	1951	1.36	6.0	116
	1952	1.31	5.9	40.0
Muslyumovo (78 km)	1950	0.90	12.7	0.2
	1951	1.79	2.8	1.5
	1952	1.73	2.8	0.4

[a]: Dose to red bone marrow

For the reconstruction of internal doses during early childhood of TROC members the intake of radionuclides with milk in the period 1950-1959 has been evaluated on the basis of archival data on ^{90}Sr measurements in the local diet of inhabitants of Techa riverside settlements.

EPR measurements with tooth enamel

Two comparisons of EPR dosimetry with tooth enamel for exposed ETRC members were performed:
i) Samples were prepared at IMP, and EPR measurement and dose evaluation were performed at IMP and at GSF (Figure 1).
ii) Sample preparation and EPR measurement were done at GSF, and dose evaluation was done in the two laboratories (Figure 2).
In both cases the results correlate well (the correlation coefficients are 0.992 and 0.999). In mean the doses evaluated at IMP are 61 mGy (63 mGy) lower those evaluated at GSF. The slope of the regression line is very close to unity and is indicating that the IMP and GSF calibration for radiation sensitivity of the samples is within 1% in agreement. After a correction for the systematic shift, for doses below 400 mGy the 95% confidence interval for the deviation between IMP and GSF results was calculated as ±100 mGy for samples prepared at IMP and ±50 mGy for samples prepared at GSF.

EPR dosimetry with enamel of unexposed residents of the Techa region was compared for 30 samples that were prepared at IMP (Figure 3). EPR measurement and absorbed doses evaluation were done independently by IMP and GSF. There is only a weak correlation of the results (r = 0.54). The mean of all results determined by GSF is 145 mGy and of those determined by IMP 175 mGy. However, the 95% confidence interval of the deviation between the individual IMP and GSF results is ±180 mGy. This is possibly due to unusual additional EPR signals of the samples which are interfering with the dosimetric signal. The signals may have been caused by sample impurities that are not completely removed or introduced by the sample preparation procedures. The influence of the interfering EPR signals are considerable for low doses and negligible for high doses (Figure 1).

Luminescence measurements of absorbed dose in bricks

Sample preparation, pre-heating parameters and dose determination procedures were optimized for four exposed bricks from the church in Metlino. One brick collected from an inner wall is used to assess the background dose. Quartz grains with a size of 140 to 200 µm were extracted from a depth layer of 2 to 12 mm in the brick. All bricks

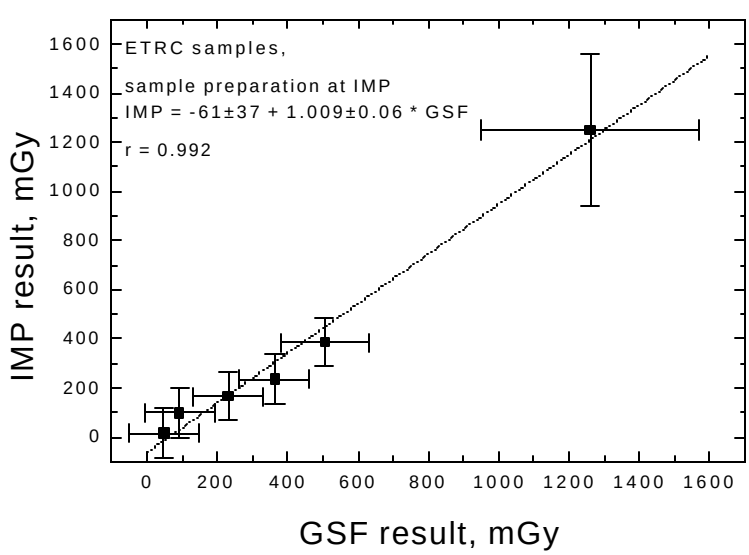

Figure 1. Comparison of IMP and GSF dose evaluation for identical enamel samples prepared at IMP. The error bars are ±25% for doses larger and ±100 mGy for doses lower than 400 mGy.

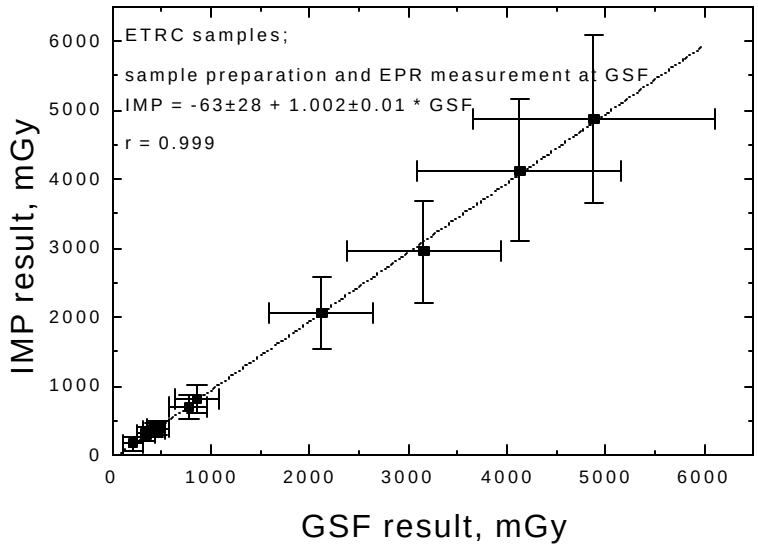

Figure 2. Comparison of IMP and GSF dose evaluation for identical enamel samples of ETRC members. Sample preparation and EPR spectrum recording was done at GSF. The error bars are ±25% for doses larger and ±100 mGy for doses lower than 400 mGy.

were covered by a 5 to 10 mm thick layer of mortar and paint. The samples facing Reservoir No 10 have about 3 times higher doses than the samples facing the village (Table 2). For the brick from an inner wall (No. 35) a first assessment of the age of 126± 20 years was derived from results for the absorbed dose, uranium and thorium content, and the beta dose rate.

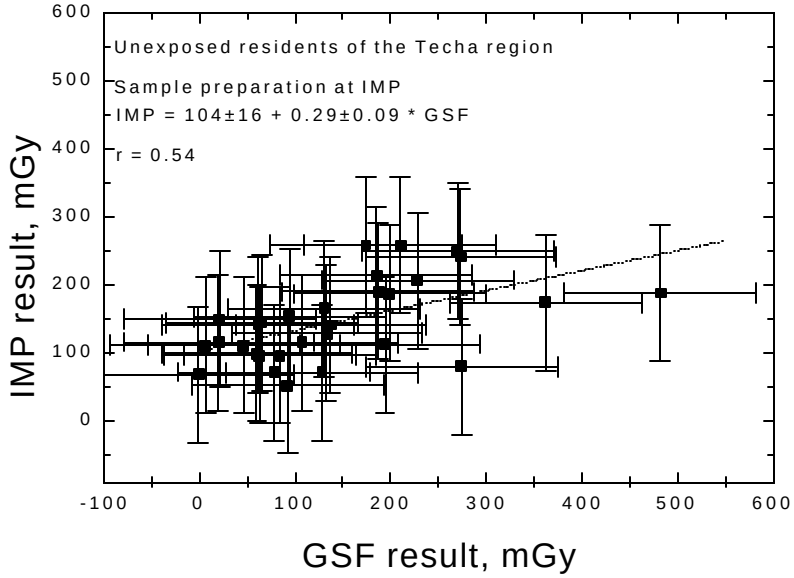

Figure 3. Comparison of IMP and GSF dose evaluation for identical enamel samples prepared at IMP from teeth of unexposed residents of the Techa region. The EPR spectra were recorded by the evaluating laboratory. The error bars are representing the exp ected error of ±100 mGy for low dose EPR measurements.

Table 2 Absorbed dose in bricks collected from Metlino church determined by different thermoluminescence methods. The uncertainty range indicates the standard deviation of the measurements and does not include systematic errors.

Code	Description	Absorbed dose (Gy), obtained by different methods
35	Inner wall, h = 1.0 m	0.36± 0.01; 0.37±0.02; 0.37± 0.02
70	Wall facing to village, h = 7.5 m	0.95±0.03; 0.91±0.04; 1.02±0.04; 0.98±0.11
72	Wall facing to village, h = 10.5 m	1.14±0.03; 1.12± 0.19
68	Wall facing to reservoir, h = 1.0 m	3.22±0.06; 3.15±0.10; 2.91±0.10; 4.39±1.40
67*	Wall facing to reservoir, h = 1.0 m	2.80±0.18

* Depth layer in the brick of 2 to 22 mm.

Work to be performed

To develop a method for the evaluation of the radiation exposure in postnatal period, especially during the first year of life. To calculate individual doses for TROC members.

To investigate the feasibility of post-cleaning of enamel samples and the re-evaluation of the currently available background samples for EPR measurements. To perform EPR dose evaluations for ETRC members.

To determine for the absorbed doses measured in bricks from the Metlino church (Table 1) the anthropogenic contribution. To perform Monte Carlo simulations of the photon transport for various source configurations with the aim to allow a comparative analysis with early gamma dose rate measurements.

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