APPLICATION OF EPR TOOTH DOSIMETRY FOR VALIDATION OF THE CALCULATED EXTERNAL DOSES: EXPERIENCE IN DOSIMETRY FOR THE TECHA RIVER COHORT

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ABSTRACT

This study applies EPR tooth dosimetry for validation of external doses calculated with the TRDS-2016. EPR-based external dose in tooth enamel is calculated by subtraction of the contributions of natural and anthropogenic sources from the exposure of interest. These subtracted terms may contribute substantially to the overall uncertainty of the EPR-derived external dose. The validation method strongly depends on the uncertainties The current study combines the results of a number of previous papers to propagate the uncertainty of EPR-derived external doses. It is concluded that the overall uncertainties of D≥500 mGy are comparable with measurement uncertainties (≤30%); the overall uncertainties of D<500mGy become higher as the EPR dose decreases because they are strongly effected by all other factors of influence. More than 70% of investigated individuals were exposed externally to doses <100 mGy with uncertainties >100%. Therefore, the validation task can be solved only based on statistical approaches. The validation of the TRDS-2016 predictions demonstrates good convergence of group-averages with EPR-based doses. The method for validation of the uncertainty of TRDS-2016 predictions should be also designed based on statistical approaches.

Keywords*:* Electron Paramagnetic Resonance; dosimetry; uncertainty; TRDS; validation

INTRODUCTION

Electron Paramagnetic Resonance (EPR) of tooth enamel is extensively applied for retrospective external dosimetry[1-3]. Particularly, EPR tooth dosimetry was used as a method for external dosimetry in the Urals region [4-5]. The environmental radioactive contamination in the Techa riverside territories of the Urals was the result of discharges of about 115 PBq of liquid wastes into the Techa River (1949–1956)[6]. The mixture of released fission products consisted mainly of 90Sr, 89Sr, 137Cs, 106Ru, 103Ru, 95Zr, 95Nb and 144Ce. Two of them, viz, 90Sr and 137Cs, are long-lived radionuclides (half-lives are almost 30 years). This led to chronic external and internal exposure of about 30,000 residents of riverside communities located downstream of the release site. External human exposure was induced due to environmental contamination with gamma emitters, mainly due to the short-lived 95Zr and 95Nb as well as the progeny of long-lived 137Cs, viz., 137mBa. Significant radionuclide intakes by the population occurred during the period of major releases (September 1950 – October 1951) inducing chronic internal radiation of bone tissues due to bone-seeking 89,90Sr as well as protracted internal exposure to short-lived isotopes and 137Cs/137mBa homogenously distributed in soft tissues.

Retrospective EPR dosimetry with teeth of the exposed population was started only 50 years after the discharges. Therefore, there was a limited availability of tooth samples. The main method of external dose reconstruction for the Techa River cohort is the mathematical modeling in the frame of the Techa River Dosimetry System (TRDS), which has been developed directly for epidemiological studies of the population in the Urals. Some of the Techa riverside residents were additionally exposed to radiation due to dispersion of 74 PBq into the atmosphere as a result of an explosion in the radioactive waste-storage facility in 1957 (the so-called Kyshtym Accident) that formed the East Urals Radioactive Trace (EURT)[7], where major dose-forming radionuclides were 144Ce, 90Sr, 95Zr, 95Nb and 106Ru. Residents of highly contaminated settlements were evacuated. For example, villages from territories with 90Sr initial deposition of 400-650 Ci km-2 (15-24 GBq m-2) were resettled in 7-14 days; villages which were contaminated with 4-65 Ci km-2 (0.15-2.4 GBq m-2) were resettled in 250-330 days. EURT dose estimates were included into the TRDS.

The assessment of external doses using the TRDS was based on archival data concerning the floodplain contamination, simulation of air kerma above the contaminated soil, and age-dependent life-styles. Risk analyses based on the TRDS-2009 have established associations between radiation doses in soft tissues and solid cancer mortality for the Techa River Cohort[8]. External dose calculations in TRDS have been improving during recent years (the last version of TRDS is TRDS-2016). It is of critical importance to validate the estimates of the doses to soft tissues with TRDS-2016 to be sure in the epidemiological conclusions. EPR tooth dosimetry provides the unique possibility to validate the calculated doses.

Cumulative absorbed dose in tooth enamel of exposed Urals residents represents the superposition of several contributions (Figure 1). Soft tissues were exposed mainly to external sources of radiation and 137Cs/137mBa isotopes circulating in the body. Tooth enamel was affected by the same sources of exposure. In terms of enamel exposure, 137Cs/137mBa circulating in the soft tissues were also external sources of radiation. Hereinafter, in describing the external exposure of teeth we will include both of these contributions. The presence of bone-seeking 90Sr in the teeth also contributes to cumulative dose in enamel. As was shown in Shishkina et al. (2014)[9], 90Sr activity concentrations in 2010 (60 years after intakes) ranged from undetectable values (<0.05 Bq g-1) up to 60 Bq g-1. Maximum activity concentrations were observed in the enamel of teeth with crown aged under 6 years (from the beginning of enamel mineralization) in September 1950, and this resulted in extra-high EPR doses[10] up to 60 Gy. Therefore, only the teeth with crowns completed at the time of maximum releases can be used for the validation task. The contribution of strontium isotopes to EPR-detected absorbed dose should be subtracted from EPR measurement results (Figure 1). Moreover, the background dose accumulated mainly due to the enamel exposure to cosmic rays and natural radionuclides should also be subtracted. The contribution from medical exposure (if any) should also be subtracted. These terms for subtraction may contribute substantially to the overall uncertainty of EPR-derived external dose in addition to measurement error. Therefore, estimation of the uncertainty of EPR-based external dose is an important task.

The aim of the study is to validate the TRDS-2016 predictions of external doses of rural Urals residents who lived in the contaminated territories. The strategy for validation of calculated doses strongly depends on the uncertainties of the validating doses. Therefore, this paper focuses on the uncertainties of EPR-derived doses obtained in the frame of the Techa River study. Different contributors to the dose uncertainty were described separately in a number of previous studies devoted to methodological approaches[9, 11-23]. The current study combines the results obtained to propagate the uncertainty on EPR-derived external doses to enamel related to the environmental contamination in the Urals.

MATHERIALS AND METHODS

**EPR measurements**

*Samples*

The investigated teeth were all extracted for medical indications at the local dental clinics in 1992-2010. Most of the enamel samples (for both exposed and unexposed donors) were measured by EPR in the year of the tooth extraction. The maximum interval between the tooth extraction and EPR measurement was 5 years. The samples were stored in refrigerators where the natural radiation background was reduced by about half.

Three hundred ninety-five EPR measurements were performed for 297 teeth of 255 donors, who were born between 1908-1968 and lived in non-contaminated villages of the Southern Urals (control). The age of the majority of the donors (70%) was within a narrower range of 50 – 70 years; the mean age was equal to 64±11 years. The number of incisors was 34% of the total number of the teeth.

Concerning the exposed population, only teeth which were fully formed at time of releases were studied to avoid extra high doses due to internal exposure to incorporated 90Sr. Four hundred sixteen teeth collected from 223 donors exposed on the Techa River born in 1913-1943 were measured. Most of the donors (173 persons) lived permanently in the Techa riverside settlements over the period from 1950 through 1952. Another 50 persons lived either part-time under conditions of external irradiation or migrated between settlements with different levels of contamination in this period. About half of the donors were additionally exposed externally to low doses (<100 mGy) on the EURT. About 20% of the exposed teeth were incisors. Most of the incisor samples were represented by the lingual enamel fraction; however, about 30% of the incisors were measured using only a labial fraction or the whole available enamel. The majority of the donors (70%) was within a narrower age range of 61-76 years; the mean age was equal to 66±7 years.

EPR measurements were also performed for 52 teeth of 36 people exposed only due to residence in the most contaminated area of the EURT (from evacuated villages) Samples are represented mainly by posterior teeth (only 3 incisors in the selection). The age range 70% of these donors is 52-74 years; the mean age was equal to 63±11 years.

*Methods of EPR dosimetry*

The teeth were measured at 6 different laboratories, viz, Institute of Metal Physics (IMP, Russia), Helmholtz Centrum Munich (HMGU, Germany), Istituto Superiore di Sanità (ISS, Italy), Medical Radiobiological Research Center (MRRC, Russia), Institute of Chemical Physics (ICP, Russia) and Institute of Biophysics (IBP, Russia). Each laboratory used its own EPR dosimetry method. It should be noted that even one and the same laboratory could modify the EPR method with time, as it was the case for IMP and HMGU. Table 1 present a summary of methods for sample preparation, EPR measurements, signal evaluation, and calibration used by different research groups.

Aside from their own prepared samples, HMGU and ISS measured samples prepared by IMP; MRRC and IMP measured the samples prepared by HMGU. ISS and IMP used the same calibration curve for posterior and anterior teeth. HMGU used different calibration systems for the whole enamel (posterior teeth), labial fraction (incisors) and lingual fraction (incisors).

Different combinations of sample preparation, measurement technique, calibration system, and type of enamel under study represent different methods with unequal performance parameters. Each of the methods has its own performance parameters (such as uncertainty and limit of detection), and its own measurement uncertainty[4]. Basic principles of data harmonization as well as treatment of non-detects were described in Volchkova et al. (2014)[14] and specified in Shishkina et al. (2016)[4].

*Uncertainty of EPR dosimetry*

Method-specific dose-dependent measurement uncertainties () were calculated based on the data on calibration experiments (when available) using the software “EPR-dosimetry performance”[16]. The computer code is a user-friendly tool for providing a full description of method-specific capabilities of EPR tooth dosimetry, from metrological characteristics to practical limitations in applications. When the original data were not available, method performances (including uncertainties) were assigned based on the results of inter-laboratory comparisons and expert decisions[4, 14].

About 20% of the teeth were measured repeatedly using different methods. The results of the repeated EPR measurements were averaged with weights (*wj*) equal to the normalized inverse square root of the relative measurement uncertainty ()[18], where *j* is the number of measurement of a tooth. The relative uncertainty of the weighted average (δw) was calculated according to Equation (1).

, (1)

where *n* is the number of repeated measurements. Other contributors to EPR-dose uncertainty were described in the previous papers[11, 13-15,17].The overall standard uncertainty of external enamel dose was calculated based on the law of uncertainty propagation (Eqn. 2), assuming the inputs (*xi*) reflecting the dose contributors are not correlated.

, (2)

where *i* is the number of the cumulative dose contributor. External doses estimated for different teeth of the same donor were also averaged to obtain the individual external dose. If the external doses were estimated to be statistically significant, exceeding (*t*-test; α=0.05) the cumulative contribution of the natural background, medical and internal, exposure, then the doses were averaged with weights (*wt*) proportional to the inverse square of overall uncertainty (1/) of the external dose estimated for tooth *t*; otherwise, the arithmetic mean dose was calculated. The corresponding uncertainties of individual average external doses (*U1* and *U2*) were calculated according to Equations (3) and (4), respectively, where *n* is the number of teeth of the same individual have been measured.

(3)

(4)

STRUCTURE OF OVERALL UNCERTAINTY OF EPR-DERIVED EXTERNAL DOSES

The overall uncertainty of EPR-based estimate of external dose is comprised of the contribution of the following factors:

- measurement uncertainty;

- individual variability of radiation sensitivity of tooth enamel;

- uncertainty of estimate of mean background dose;

- individual variability of background doses;

- uncertainty of medical dose estimates;

- uncertainty of calculated internal dose due to incorporated Sr isotopes.

**Measurement uncertainty**

Measurement uncertainties related to the epistemic uncertainties arise from experimental interpretation and can be potentially minimized. The measurement uncertainty of EPR dosimetry includes both dose-dependent measurement repeatability and non-excluded error of calibration. Measurement repeatability strongly depends on signal-to-noise ratio (SNR). Spectral noise is the instrumental noise (random white noise) affected by the signal anisotropy of native organic components and other impurities in tooth enamel hydroxyapatite (tooth-to-tooth varying background signal). Uncertainty introduced by spectral noise into the measurement result was considered as a variance of repeated measurements of unexposed samples[12]. The closer the amplitude of SNR to 1, the greater the contribution of spectral noise to the overall uncertainty of the measurement result (the case of low dose measurements). Measurement repeatability for SNR≫1 depends on the anisotropy effect of the radiation-induced signal. The impact of these factors on spectra processing results in nonlinearity of dose-response at doses below the limit of detection[17].

The error of calibration is the result of the fitting error of the data from the calibration experiment, the representativeness of calibration samples (in terms of the radiation sensitivity of tooth enamel), and the natural exposure of calibration samples. The linear fitting of the experimental data on dose response of radiation-induced signal is characterized by standard errors of slope and intercept. Minimum uncertainty of the fitting function is at the middle of the interval of the function domain; maximum uncertainty values are at the boundaries of the function domain. Table 2 describes the dose-dependent measurement uncertainties including the random component and the fitting error of calibration typical of the methods that have been applied. Table 2 shows both the average uncertainty (taking into account the number of samples measured by methods with different performances) and the range of uncertainties corresponding to the method with the best and the worth performance.

As it can be seen from the Table 2, the minimum measurement uncertainty is typical of posterior teeth. It should be noted that the methods with poor performances (limits of detection >400 mGy) were used only for measurements of high doses (≥1000 mGy).

One more source of calibration uncertainty is the use of not-representative calibration samples with different radiation sensitivity of tooth enamel than those of investigated people. This can result in a bias in fitting the slope of calibration line. Regional differences in the radiation sensitivity were described in several studies. For example, a small (2%) but statistically significant difference in radiation sensitivity of tooth enamel was found between German and Egyptian teeth[24]. A greater difference was described in Shishkina et al., (2002)[25], where the teeth of U.S. donors were found to be 15% less sensitive to radiation than those of Urals rural residents.

Moreover, no blank (unexposed to natural radiation) biological samples are available because of environmental and internal natural radioactivity. Therefore, fitting of the intercept can be biased because of the unknown non-zero dose of calibration samples used. An accurate and precise calibration system allows minimizing the biases and corresponding uncertainty of dose assesments. All non-excluded systematic uncertainties should be treated in the same way as the random uncertainties.

We placed the great deal of importance on calibration systems of participating laboratories[12]. The difference in radiation sensitivity of tooth enamel used for calibration did not exceed 2%. Unfortunately, the background dose of calibration samples is a poorly controlled parameter because of the absence of metrological standards for biological samples. The method-specific additive biases were estimated based on the measurements of background doses, which were used as a surrogate reference[19]. It was found that method-specific additive biases for EPR with posterior teeth are in the range from -60 to 140 mGy. The biases of two methods, which used the lingual enamel fraction of anterior teeth, were equal to 190 and 330 mGy; the whole/labial enamel measurements were 260-360 mGy higher than the surrogate reference. Precision of the bias estimates was about 15%-20%. These uncertainties are much smaller than those that have been induced by non-excluded bias. According to blind test[4], the subtraction of systematic errors results in a 2-fold reduction in the confidence interval of the linear regression in the plots of the reconstructed doses versus applied doses.

**Uncertainty induced by individual variability of radiation sensitivity of tooth enamel**

Variability of individual dosimetric properties of tooth enamel arises from true heterogeneity among people and is related to the aleatory type of uncertainty in dose estimates with the use of a unified calibration system. For example, the radiation sensitivity of enamel of posterior teeth in a homogeneous (in terms of nationality, ecological surrounding, and medical availability) population from Ozersk city in the Urals[15] as well as the donors in the European part of Russia[26] and Japan residents[27] is 8% or even less. Germany and Egypt residents demonstrate a variability of about 10%[24, 28]. High variability of radiation sensitivity was found to be typical of the heterogeneous population of rural residents of Chelyabinsk and Kurgan regions (Urals, Russia) equal to 16.5%[15]. This is comparable to the variability reported for residents of the Moscow region[29], which have been found to be equal to 20%. The value of 16.5% was assumed as the relative uncertainty induced by individual variability of radiation sensitivity of tooth enamel of Urals rural residents under study.

**Uncertainty of estimate of mean background dose**

Individual estimation of background dose in the enamel is impossible. Therefore, the background dose can be evaluated statistically as a population-average, which is based on the EPR measurements of teeth of unexposed people. The error of the mean describes the uncertainty of mean background dose. It should be noted that background doses are low doses, whose measurement is hampered by spectral noise. A special method for statistical reconstruction of background dose based on noisy data was elaborated[19]. The method also allows estimating the uncertainty of mean background dose under the assumption of lognormality of the dose distribution among the population. The mean dose rate was found to be equal to 0.98 mGy year1[4]. The standard error of the mean for such an estimate was equal to 5%. Much more impact on the overall uncertainty is due to the individual variability of background doses.

**Individual variability of background doses**

Individual variability of background dose accumulation mainly depends on the difference of an individual’s life style (how much of their time is spent indoors versus outdoors). The above mentioned approach for statistical reconstruction[19] considered a lognormal distribution of background doses in the population. The coefficient of variation was estimated to be 80%[4].

**Uncertainty of medical dose estimates**

X-ray examinations in rural clinics were infrequent. Doses from X-ray examinations in the URCRM clinic were only considered under retrospective study[4]. Sixty-six people were medically exposed to doses from 8 to 98 mGy. Most of the medical doses (75%) were lower than 35 mGy, and only 5 people were exposed to doses above 50 mGy due to multiple examinations of their skulls. Uncertainties of the medical dose reconstruction were estimated conservatively as 30%.

**Uncertainty of internal dose calculations due to incorporated Sr isotopes**

Internal dose in tooth enamel was calculated based on the direct measurements of 90Sr in tooth tissues if available. In this case, measurement uncertainty was considered[22]. Otherwise, the concentration was approximated by results obtained from other teeth of the same person, or it was extrapolated from the data on root dentin contamination to crown dentin. These approximations increase the uncertainty of 90Sr concentration estimates for the enamel and dentin by up to 90% and 40%, respectively. In the absence of any information about 90Sr in dental tissues of an investigated donor, an empirical model[9] was applied. In this case, the resulting uncertainties of the estimated 90Sr concentrations exceed 100%.

Biokinetic approaches for internal dose reconstruction also introduce some uncertainties (see Supplemental material to Shishkina et al., (2016)[4]), viz.:

* single intake approach (<1%);
* approach of zero rate of 90Sr biological elimination (<30%).

Uncertainties of the activity concentration–to-dose conversion factors (DCs) were also considered[4, 21]. Contamination of enamel and primary dentin results in uncertainties of corresponding DCs of about 10%. Contamination of secondary dentin results in uncertainties of 70%.

The uncertainty of internal dose calculations combined all of the above mentioned contributions. The relative uncertainty is dose independent and, on average, it is equal to about 80%. Uncertainty was defined mainly by availability of the individual measurements of 90Sr in the tooth tissues. The minimum relative uncertainty was found to be equal to 8%; the maximum reached 300%.

EPR-DERIVED EXTERNAL DOSES AND CORRESPONDING OVERALL UNCERTAINTIES

Table 3 presents the distribution of EPR-derived external doses for teeth of persons exposed on the Techa River and the EURT and corresponding mean uncertainties of estimates. As may be seen from Table 3, uncertainties of EPR-derived external doses above 500 mGy are comparable with measurement uncertainties (≤30%); for doses below 500 mGy the overall uncertainties become larger as the dose decreases because they are strongly effected by all other factors of influence. Most of the investigated teeth (>70%) were exposed externally to doses below 100 mGy with uncertainties exceeding 100%.

Therefore, external dose validation can be only done based on statistical approaches. The mean-group approach was suggested and tested in Shishkina et al. (2016)[4]. The approach involves the combining of the individuals according to their residence history.

VALIDATION OF THE CALCULATED EXTERNAL DOSES

Applying the mean-group approach to the EURT residents, all donors can be subdivided into two groups, viz.: (1) residents of Berdyanish, Satlykovo, and Galikaeva; (2) residents of other EURT territories. Table 4 presents the results of dose reconstruction for these two groups of samples in comparison with the TRDS-2016D predicted enamel doses. As may be seen from Table 4, reasonable agreement was found. Similarly, good agreement is observed in the comparison of EPR-derived doses and those predicted by TRDS-2016D for the Techa riverside residents. Figure 2 is an updated version of a previously published figure[4], which had been plotted for an interim version of TRDS. Moreover, the term “external dose” assumed the exposure to sources of radiation external to the body, in contrast to the current study where this term refers to the tooth. In other words, the contribution of 137Cs circulating in the soft tissues was subtracted from the EPR dose. The new analysis takes into account the fact that the 137Cs contribution was calculated with TRDS, and therefore it should be better to assign it to validated predictions (X-axis in Figure 2). As may be seen from Figure 2, the mean-group doses derived from EPR tooth dosimetry demonstrate good agreement with the TRDS-2016 predictions.

APPROACHES TO VALIDATION OF CALCULATED UNCERTAINTIES OF EXTERNAL DOSES

The improved TRDS-2016 was implemented in two versions in 2016. The first is based on the traditional analytical (deterministic) method of dose calculations (TRDS-2016D), which have to be validated by themselves. The second one is the supplemental version based on stochastic modelling to estimate both mean radiation doses and the corresponding uncertainties of dose calculations (TRDS-2016MC) to provide insight regarding the degree of certainty of the risk estimates[30]*.* The approach to dose uncertainty estimation is to use Monte Carlo replications of the basic model (TRDS-2016D) with uncertain input parameters. The parameters that describe the contamination of the environment, in which the subjects live, generally have a shared uncertainty. Only inputs that are exclusive to a single individual are unshared; there are actually quite few of these in the TRDS. TRDS-2016MC generates 1500 realizations of sequential annual organ absorbed dose for every cohort member. Figure 3 demonstrates an example of stochastic estimates of individual doses (as distributed values) using TRDS-2016MC. Cohort calculations of the doses with TRDS-2016MC are in progress now.

It should be noted that the uncertainties of input parameters for TRDS-2016MC system are also uncertain. For example, behavior factors assigning the fraction of time spent in different locations for different age groups were estimated from the literature data and can be different for those typical of the Techa River residents. In other words, the results of stochastic modeling should be validated too. The validation of model uncertainty with EPR can be only done using the knowledge about the uncertainties of EPR-based doses obtained.

The approaches to be applied to uncertainty validation could be individual and statistical. According to Table 3, no more than 9% of the EPR-derived doses available (for 25 individuals) demonstrate uncertainty ≤ 30%. Therefore, the individual approach, such as individual comparison of the confidence intervals of validated and validating values, could be applied only to people with external doses exceeding 500 mGy typical of the some of the residents of the Upper Techa. It should be noted that high external doses could be the result of unpredictable exposure to radiation (for example, visiting highly-contaminated areas to hunt or to fish) which cannot be accounted for in TRDS. Therefore, the EPR-derived high doses can deviate from TRDS prediction with higher probability compared to low doses. Therefore, doses below 500 mGy should be also considered in the validation task. For this purpose, methods of analysis based on statistical approaches are now being developed.

CONCLUSIONS

1. Overall uncertainties of EPR-derived external doses for the Techa riverside residents which exceed 500 mGy are comparable with measurement uncertainties (≤30%); for EPR-derived external doses below 500 mGy the overall uncertainties become larger as the dose decreases because they are strongly effected by all other factors of influence.
2. More than 70% of investigated individuals (both the Techa riverside and the EURT residents) were exposed externally to doses below 100 mGy with uncertainties exceeding 100%.
3. The validation of TRDS-2016 predictions for external doses using EPR tooth dosimetry demonstrates good convergence of group averages.
4. The method for validation of uncertainty of TRDS-2016 predictions should be designed based on statistical approaches.

***Acknowlegements****: This work was funded by the U.S. Department of Energy’s Russian Health Studies Program and the Federal Medical Biological Agency of the Russian Federation under the auspices of the Joint Coordinating Committee for Radiation Effects Research Project 1.1, Techa River Population Dosimetry. The EPR study was also supported by the EC within the framework of the project SOLO (in the past) and partially by Russian state program “Spin” (№ 01201463330).*

# REFERENCES

# Ikeya, M., Miyajima, J., Okajima, S. ESR Dosimetry for Atomic Bomb Survivors Using Shell Buttons and Tooth Enamel. Japanese Journal of Applied Physics, 23 p.2 (9), L697–L699 (1984)

# Skvortsov, V.G., Ivannikov, A.I., Stepanenko, V.F., Tsyb, A.F., Khamidova, L.G., Kondrashov, A.E., Tikunov, D.D. Application of EPR retrospective dosimetry for large-scale accidental situation. Appl Radiat Isot. 52(5), 1275-1282 (2000).

1. Fattibene, P. and Callens, F. EPR dosimetry with tooth enamel: A review. Appl Radiat Isot. 68, 2033-2116 (2010).
2. Shishkina, E.A., Volchkova, A.Yu., Timofeev, Yu.S., Fattibene, P., Wieser, A., Ivanov, D.V., Krivoschapov, V.A., Zalyapin, V.I., Della Monaca, S., De Coste, V., Degteva, M.O., Anspaugh, L.R. External dose reconstruction in tooth enamel of Techa riverside residents. Radiat. Environ. Biophys., 55 (4), 477-499 (2016).
3. Degteva, M.O., Shagina, N.B., Shishkina, E.A., Vozilova, A.V., Volchkova, A.Yu., Vorobiova, M.I., Wiser, A., Fattibene, P., Della Monaka, S., Ainsbury, L., Moquet, J., Anspaugh, L.R., Napier, B.A. Analysis of EPR and FISH studies of radiation doses in persons who lived in the upper reaches of the Techa River. Radiat. Environ. Biophys. 54(4), 433-44 (2015).
4. Degteva, M.O., Shagina, N.B., Vorobiova, M.I., Shishkina, E.A., Tolstykh, E.I., Akleyev, A.V. Contemporary understanding of radioactive contamination of the Techa River in 1949–1956. Radiat. Biology. Radioecology, 85(5), 532-534 (2016).
5. Akleev, A.V., Krestinina, L.Yu., Degteva, M.O., Tolstykh, E.I. Consequences of the radiation accident at the Mayak production association in 1957 (the ’Kyshtym Accident’). J. Radiol. Prot. 37, R19–R42 (2017).
6. Schonfeld, S.J., Krestinina, L.Yu., Epifanova, S., Degteva, M.O., Akleyev, A.V., Preston, D.L. Solid cancer mortality in the Techa river cohort (1950-2007). Radiat Res. 179(2), 183-189. (2013).
7. Shishkina, E.A., Tolstykh, E.I., Verdi, E., Volchkova, A.Yu., Veronese, I., El-Faramawy, N.A., Göksu, H.Y., Degteva, M.O. Concentrations of 90Sr in the tooth tissues 60 years after intake: results of TL measurements and applications for Techa River dosimetry. Radiat Environ Biophys. 53, 159-173 (2014).
8. Shishkina, E.A., Degteva, M.O., Tolstykh, E.I., Volchkova, A., Ivanov, D.V., Wieser, A., Della Monaca, S., Fattibene, P. Extra high doses detected in the enamel of human teeth in the Techa riverside region. Radiat Meas. 46, 760-764 (2011).
9. Fattibene, P., De Coste, V., Güttler, A., Ivanov, D., Shishkina, E., Wieser, A. EPR dose response of incisor teeth. In: 15. International Conference on Solid State Dosimetry (SSD 15). Book of Abstracts; July 8-13, 2007; Delft. 2007, P. 48 (2007).
10. Wieser, A., Fattibene, P., Shiskina, E., Ivanov, D., De Coste, V., Güttler, A., Onori, S. Assessment of performance parameters for EPR dosimetry with tooth enamel. Radiat Meas. 43, 2008, P. 731-736.
11. Ivanov, D.V., Shishkina, Е.A., Volchkova, А.Yu., Timofeev, Yu.S. Changing of opportunities of EPR dosimetry on dental enamel during the process of long-term equipment operation in the Institute of Physics of Metals. ANRI (Instruments and Methods of Radiat. Meas.). 3, 65- 71 (2011).
12. Volchkova, A., Shishkina, E.A., Ivanov, D., Timofeev, Yu., Fattibene, P., Della Monaca, S., Wieser, A., Degteva, M.O. Harmonization of dosimetric information obtained by different EPR methods: Experience of the Techa river study. Radiat Meas. 46, 801-807 (2011).
13. Shishkina, E., Tolstykh, E., Degteva, M., Ivanov, D., Aladova, E. Variability of the radiation sensitivity for tooth enamel of the Ural residents. ANRI (Instruments and Methods of Radiat. Meas.). 69, 41–50 (2012) (in Russian).
14. Shishkina, E.A., Timofeev, Yu.S., Ivanov, D.V. Software for evaluation of EPR-dosimetry performance. Radiat Prot Dosimetry. 159, 188-193 (2014)
15. Ivanov, D.V., Wieser, D.V., Shishkina, E.A., Ustinov, V.V. Effect of spectrum processing procedure on the linearity of EPR dose reconstruction in tooth enamel. Radiat Meas. 68, 7-13 (2014).
16. Zalyapin, V.I., Shishkina, E.A., Fattibene, P., Wieser, A., Ivanov, D.V., Degteva, M.O. Statistical analysis of the EPR measurements. Bulletin of Southern Urals State University (SUSU). 27, 36-44 (2008) (in Russian).
17. Zalyapin, V.I., Timofeev, Yu.S., Shishkina, E.A. Statistical reconstruction of background dose distribution based on the results of EPR measurements. Bulletin of Southern Urals State University (SUSU), Issiu «Mathematic. Mechanics. Physics». 6, 22-27 (2014).
18. Volchkova, A.Yu., Shishkina, E.A. Uncertainty in Evaluation of Internal Dose in the Tooth Enamel from Incorporated 90Sr: Effect of Variation in Tooth Geometry. Health Phys. 103(2), 19, (2012).
19. Volchkova, A.Yu., Shishkina, E.A. Age dependence of dose rates in the enamel of teeth contaminated by 90Sr. In: Experience in minimizing consequences of the 1957 accident. In Proceedings of the International Conference, October 2-3, 2012, Chelyabinsk, P.17 (2012) (in Russian).
20. Shishkina, E.A. Performance parameters and uncertainty of the method for assessment of 90Sr concentration in small powder samples using -Al2O3:C beta detectors. Radiat Meas. 47, 19-26 (2012)
21. Shishkina EA, Napier B, Krivoschapov VA, Tolstykh EI, Degteva MO. Dosimetric uncertainties in the retrospective study for the Techa River cohort. In proceedings of 62nd Annual International Meeting of Radiation Research Society, 15-19 October 2016, Waikoloa Vilage, HI, USA, CRHPS-10 (2012).
22. Wieser, A., El-Faramawy, N., Meckbach, R. Dependencies of the radiation sensitivity of human tooth enamel in EPR dosimetry. Applied Radiation and Isotopes. 54, 793-799 (2001).
23. Shishkina, E.A., Shved, V.A., Tolstykh, E.I., Degteva, M.O., Anspaugh, L.R. Investigation of the Tooth as a Complex Dosimeter: Formation of Dose in Tooth Enamel. Unscheduled report. Urals Research Center for Radiation Medicine and University of Utah, Chelyabinsk and Salt Lake City, June 2002 (2002).
24. Ivannikov, A.I., Skvortsov, V.G., Stepanenko, V.F., Tsyb, A.F., Khamidova, L.G., Tikunov, D.D. Tooth enamel EPR dosimetry: Sources of errors and their correction. Applied Radiation and Isotopes. 52, 1291-1296 (2000).
25. Iwasaki, M., Miyazawa, C., Uesawa, T., Itoh, I., Niwa, K. Differences in the radiation sensitivity of enamel in an individual and among the individuals in dental ESR dosimetry. Radioisotopes, 44, 785-788 (1995).
26. Egersdorfer, S., Wieser, A., Miiller, A. Tooth enamel as a detector material for restrospective EPR dosimetry. Applied Radiation and Isotopes. 47, 1299-1303 (1996).
27. Pass, B., Baranov, A.E., Kleschenko, E.D., Aldrich, J.E., Scallion, P.L., Gale, R.P. Collective biodosimetry as a dosimetryc “Gold standard”. A study of three radiation accidents. Health Physics. 72, 390-396 (1997).
28. Zhang, Z., Preston, D.L., Sokolnikov, M., Napier, B.A., Degteva, M., Moroz, B., Vostrotin, V., Shishkina, E., Birchall, A., Stram, D.O. Correction of confidence intervals in excess relative risk models using Monte Carlo dosimetry systems with shared errors. PLOS ONE. 12(4), e0174641 (2017).

FIGURE LEGENDS

Figure 1. Cumulative absorbed dose in tooth enamel of exposed Urals residents represents the superposition of several contributions.

Figure 2. Comparison of EPR-derived doses and those predicted by the TRDS-2016D for Techa riverside residents

Figure 3. The results of 1500 realizations of stomach wall (solid black line) and active marrow (dashed gray line) absorbed doses for a resident of Metlino village (7 km from the site of releases): a) for doses due to sources external to the body (*Dext*); b) for doses due to body-seeking radionuclides (*Dint*). The individual was born in 1932 and permanently lived in the village up to 1956.

Figure 1



Figure 2

**a)**

**b)**

Figure 3.

Table 1. Summary of methods for sample preparation, EPR measurements, signal evaluation and calibration used by different research groups

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Laboratory/references | Sample preparation | Spectrum record | Processing of radiation signal (RS) | Calibration |
| IMP  Romanyukha et al. (1996)  Zdravkova et al. (2003)  Ivanov (2005)  Shishkina et al. (2003)\* | Chemical, etching,  grains 0.1-0.6 mm.  In 1992-1998 and  2002-2008: 20% NaOH.  In 1999-2001: 28% KOH. | ERS231, microwave cavity ZSX18,  microwave power: 13 mW, magnetic  field modulation amplitude: 0.45 mT;  no reference signal | Powder spectrum simulation of RS | In 1992-2002: Calibration  curve, additional exposure  of 5 permanent teeth from  Urals rural donors  In. 2003-2008: Calibration curve, pooled enamel of 30 teeth from Urals rural residents (Russia) |
| HMGU  Wieser et al. (1995)  Ignatiev et al. (1996)  Wieser et al. (2000b)  Wieser et al. (2001)  Zdravkova et al. (2003)  Shishkina et al. (2003)\* | Chemical 20% NaOH,  etching, grains 0.1-0.6 mm | In 1993-1995: Bruker ESP 300;  microwave power: 2 mW and 12 mW;  magnetic field modulation amplitude:  0.15 mT; no reference signal  Since 1996: Bruker ECS 106, microwave  cavity 4108TMH; microwave power:  25 mW, magnetic field modulation  amplitude: 0.15 mT; no reference signal | In 1993-1995: Selective  saturation method  In 1996-2002: Deconvolution,  semi empirical model of RS  Since 2003: Powder spectrum  simulation of RS | In 1993-1995: individual  In 1996-2002: calibration curve, additive exposure of 3 wisdom teeth from German residents  In 2003-2004: calibration curve, additive exposure of 76 teeth from Egyptian and Indian residents  Since 2005:  -for molars - calibration curve, pooled enamel of 30 molars from Egyptian residents;  - for anterior teeth – 20 buccal and lingual fractions (separately) of enamel of German residents |
| ISS  (Fattibene et al., 2004) | Mechanical/ chemical, grains 0.5-1 mm | Brucker EleXsys, Super-High-Q cavity;  microwave power: 2 mW; magnetic field  modulation amplitude: 0.2 mT; Mn2+ reference | Deconvolution, powder spectrum simulation | Calibration curve, pooled enamel of 30 teeth from Urals rural residents (Russia) |
| MRRC  (Tikunov et al, 2006) | Mechanical, grains 0.5-2mm | Brucker ESP300E; microwave power: 10mW, 0.3 mT; magnetic field modulation amplitude: Mn2+ reference | Subtraction, standard | Calibration coefficient, additive irradiation of 8 teeth from residents of Kaluga region (Russia) |
| IBP  (Shishkina 2001) | Mechanical, grains 0.5-1mm | Bruker ER 30D;  unknown parameters for spectrum record; Mn2+ reference | Subtraction, model of RS based on combination of Lorenz lines | Individual |
| ICP  (Serezhenkov et al, 1992) | Mechanical, grains 0.5-2mm | Radiopan, Poland;  unknown parameters for spectrum record; Mn2+ reference | Subtraction, standard | Calibration coefficient, 38 teeth from Moscow residents (Russia) |

\*Analytical reports with detailed description of each step of the EPR method, improvements and modifications.

Table 2. The dose-dependent measurement uncertainties (including random component and fitting error of calibration) for posterior teeth, lateral/whole enamel of anterior teeth and labial enamel layer of anterior teeth: average values and the range of method-specific values (in parentheses)

|  |  |
| --- | --- |
| Dose, mGy | Relative uncertainty, % |
| Posterior teeth | |
| Limit of detection: 260 (100 – 670)\* | 34 (22-47) |
| 500 | 18 (5 -50) |
| 1000 | 10 (2-27) |
| Anterior teeth, lingual layer of enamel | |
| Limit of detection: 280 (150 – 770) \* | 36 (23-80) |
| 500 | 24 (7-60) |
| 1000 | 16 (4-48) |
| Anterior teeth, labial/whole enamel |  |
| Limit of detection: 350 (150 – 770)\* | 38 (22-60) |
| 500 | 29 (8-98) |
| 1000 | 16 (4-49) |

\* - average values (the range of method-specific values)

Table 3. Distribution of the EPR-derived external doses for teeth of the Techa River and the EURT residents and corresponding overall uncertainties

|  |  |  |  |
| --- | --- | --- | --- |
| Dose range, mGy | N of individuals | Fraction of the total number of measurements, % | Mean relative standard uncertainty |
| < 50 | 159 | 61 | 350% |
| 50 – 100 | 28 | 11 | 200% |
| 100 – 300 | 30 | 12 | 70% |
| 300 – 500 | 17 | 7 | 40% |
| 500 – 1000 | 16 | 6 | 30% |
| >1000 | 9 | 3 | 20% |

Table 4. Group-average EPR-derived external dose (*D*) of the EURT residents in comparison with those calculated with the TRDS-2016D.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Group | Initial 90Sr  deposition, Ci km-2 | Terms of evacuation, days | N of individuals | *D*, mGy | TRDS-2016D, mGy |
| 1 | 400 – 650 | 7-14 | 10 | 180±70 | 177±5 |
| 2 | 4-65 | 250-330 | 26 | 70±30 | 34±20 |