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A mathematical model for calculation of ^{90}Sr absorbed dose in dental tissues: elaboration and comparison to EPR measurements

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Abstract

A mathematical model for calculation of the ^{90}Sr absorbed doses in dental tissues is presented. The results of the Monte-Carlo calculations are compared to the data obtained by EPR measurements of dental tissues. Radiometric measurements of the ^{90}Sr concentrations, TLD and EPR dosimetry investigations were performed in animal (dog) study. The importance of the irregular ^{90}Sr distribution in the dentine for absorbed dose formation has been shown. The dominant dose formation factors (main source-tissues) were identified for the crown dentine and enamel. The model has shown agreement with experimental data which allows to determine further directions of the human tooth model development.

Keywords: Tooth tissues; Strontium-90; Monte-Carlo simulation; EPR dosimetry

1. Introduction

Electron paramagnetic resonance (EPR) using tooth enamel is a well-known method for retrospective measurements of external exposure to γ-rays. It has already been used to deduce the exposure doses received by survivors of the atomic bombs in Hiroshima and Nagasaki, and the Chernobyl accident, as well as to monitor the doses to nuclear workers in the Southern Urals. Nevertheless, there are some problems in the use of EPR tooth-enamel dosimetry for reconstruction of doses from a combination of internal and external exposure as, e.g., in the case of environmental contamination of the Techa River basin (Degteva et al., 1996). The Techa River and its adjacent territories (Southern Urals, Russia) were contaminated as a result of the release of radioactive wastes by the Mayak plutonium facility from 1949 to 1956 (review by Vorobiova et al., 1999). Preliminary EPR studies conducted for the Techa river population have shown that a dose absorbed in tooth enamel consists of three main components: external exposure mainly from the Techa River bottom sediments and contaminated floodplain; internal exposure mainly due to ^{90}Sr; background radiation, including all other sources of exposure (Romanyukha et al., 1996). The development of a special method for evaluating the ^{90}Sr contribution to the total dose is the main task of this paper.

The Monte-Carlo calculations using a mathematical tooth model for ^{90}Sr should be regarded as the most appropriate method to achieve this purpose. The approaches to the elaboration of the tooth dosimetric

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model have been published (Tolstykh et al., 2000). The simplest cylindrical model was used for the description of tooth geometry. Based on the model preliminary enamel dose assessment and estimation of the external component of dose for Techa River residents were performed. The present paper should be regarded as a continuation of the tooth mathematical model development.

Practically, an animal study is the only way to verify the model because in this case high ^{90}Sr concentrations can be used, and the experimental conditions allow to exclude external exposure. Moreover, the complete denture was sampled and investigated unlike the isolated samples of the human teeth extracted on medical indications. The tooth enamel dose detected by EPR depends on the ^{90}Sr content in different tooth tissues. In turn, ^{90}Sr retention in tooth tissue is determined by a complex of physiological processes (Tolstykh et al., 2000).

The experimental animal study allowed to investigate the variability of ^{90}Sr retention in different teeth (tooth tissues) and determine the importance of adjacent tissues in the absorbed dose formation. The experimental study and model validation were performed on dog teeth. In deciding on the experimental object, the following reasons were taken into account: (1) The formation of teeth in dogs as well as in humans occurs within a very limited period compared to the time period of skeleton mineralization (Khromov et al., 1972); (2) The histological structure of dental tissues is identical both in dogs and humans. The chemical tooth compositions are identical too (Khromov et al., 1972; Dalmane and Koroleva, 1974; Derise and Ritchey, 1974); (3) The geometric parameters of dog jaws are comparable with the human one.

To enable the solution of the specific dosimetric task, viz., ^{90}Sr enamel dose estimation, the following four tasks were formulated:

1. Experimental study of quantitative features of ^{90}Sr distribution in the dog teeth.
2. Development of a mathematical model for estimation of ^{90}Sr absorbed doses in dental tissues. Calculation of dose coefficients for different tooth tissues which were assumed as source and target tissues.
3. Analysis of dose-forming factors for enamel and crown dentine.
4. Comparison of the model predictions (calculated on the basis of actual ^{90}Sr tissue concentration) and measured absorbed doses.

2. Experimental materials and methods

2.1. Description of experiment

A normal dog weighing 8.1 kg, aged 3.5 yr was used for this study. The radiopharmaceutical [^{90}Sr] $SrCl_2$ was injected into this dog intravenously at a dosage of 3 ml of 88.8 MBq solution (10.96 MBq/kg) over a 1.5-min period. The dog was sacrificed 52 h after the injection because at this stage a maximum content of ^{90}Sr in the skeleton is observed (Starichenko et al., 1993). After that, the dog skull with teeth was extracted for radiometric and dosimetric studies. This experiment on the dog was carried out in compliance with the Russian national regulations relating to animal experimentation.

The dog teeth were investigated by using the TLD method, and then 40 samples were extracted from the skull. Four of them were measured using the EPR method. Sixteen teeth were cut into half, then, the samples of tissue fragment were extracted (using a dental drill) for investigation of the ^{90}Sr distribution and absorbed dose distribution in different tissues. Table 1 presents a list of extracted teeth and the method of their investigations.

Table 1
Teeth studied and methods of investigations: thermoluminescent dosimetry (TL), EPR dosimetry, radiometry (RM)

Tooth position	Methods of investigations			
	Upper jaw		Lower jaw	
	Left side	Right side	Left side	Right side
1st incisor	TL	TL	TL	TL
2nd incisor	TL	TL	TL	TL
3rd incisor	TL	TL	TL	TL
Canine	TL, RM[a]	TL, RM[a]	TL, RM[a]	TL, RM[a]
1st premolar	TL, RM[a]	TL, RM[a]	TL, RM[a]	RM[a]
2nd premolar	TL	TL	TL, RM[a]	RM[a]
3rd premolar	TL, RM[a]	RM	—	TL
4th premolar	TL, RM, EPR	TL, RM, EPR	RM[a]	—
1st molar	TL, RM[a]	TL, RM[a]	TL, RM, EPR	TL, RM, EPR
2nd molar	TL, RM[a]	RM[a]	TL, RM[a]	TL
3rd molar	—	—	TL, RM[a]	TL

[a] ^{90}Sr radial distribution in crown dentine was investigated.

2.2. Dosimetric methods

The detectors used in the *TL dosimetry* were based on corundum monocrystals (TLD-500 K). The detectors were developed at the Urals State Technical University (Yekaterinburg, Russia) (Akselrod et al., 1990). The batch of detectors has a 5% variation in sensitivity. The detectors were calibrated using a standard source of $^{90}Sr + ^{90}Y$. The experimental dependence of thermoluminescence yield on exposure time is linear in the interval from 0 to 4 days. It was revealed that the dose delivered by the reference standard $^{90}Sr + ^{90}Y$ was 0.33Gy per 1 h. It should be taken into account that this value has been calculated according to uniform ^{90}Sr distribution in the standard source. The actual isotope distribution in the calcified tissues of the teeth is non-uniform. Therefore, the results of measurements on the tooth surfaces were used as qualitative characteristics of radionuclide content in different locuses (Lyubashevsky et al., 1996), so, there was no need to use any dose conversion factors.

Before being used, the detectors were annealed in air at 300°C for 15 min to empty dosimetric traps. The background signal was assumed to be equal to zero because it was within the range of uncertainties of TL measurements. Measurements were made using the automatic dosimetric device "CORUND" (Akselrod et al., 1990). The integration area of the spectra was from 100°C to 300°C. The heating rate was 5°C per second. The voltage of the photomultiplier tube was 1000 V. The relative uncertainty of the TLD measurements was 10%.

The TLD measurements were performed when the dog teeth were still in their proper places in the skull (Table 1). The detectors were fixed on the dog teeth enamel by sticking plaster on the internal (lingual) side and on the external (labial) side of the teeth. The time of exposition was 24 h which allows to consider the detector reading as a daily dose rate. Three series of measurements were performed at 3-day intervals (40–50 days after sacrifice). The results of measurements for every tooth were averaged. The comparison between the TLD measurements performed on the labial and lingual sides of the tooth allows one to investigate the contribution of skull radiation to the enamel dose formation.

The EPR measurements of absorbed doses were performed for enamel, crown dentine, root dentine and alveolar bone adjacent to the root. It should be noted that the masticatory part of the enamel was preferably sampled for EPR measurements because the lateral part of the dog enamel was too thin and frail to be processed. The techniques of enamel and dentine sample preparation, EPR spectra measurements and the evaluations of daily dose rates, were described in detail elsewhere (Ignatiev et al., 1999). The relative uncertainty of EPR dose assessment was estimated as 10%. These published data were used for comparison of measured absorbed doses and doses calculated on the basis of the tooth model.

2.3. ^{90}Sr content measurements

The tooth enamel, dentine, cement, and alveolar bone were sampled in the same way as for the purposes of EPR measurements. The parts of alveolar bone (samples of compact bone) adjusted to the tooth were extracted using a disk diamond saw. The teeth extracted by this tool were sawed into root and crown which in its turn was cut into half. The sampling of cement and pulp was made manually using an eye scalpel. Dentine was extracted using a dental drill. After that the internal surface of the enamel was carefully cleaned of the remaining dentine. Each procedure was performed with clean tools under conditions excluding the mixing of the contaminated tissues.

In order to estimate the ^{90}Sr distribution within the dentine, layer-by-layer sampling was performed using a dental drill. The minimal thickness of the layer was not fixed (0.25–0.4 mm), and was dependent on the dental drill diameter. The tooth dentine from different teeth (Table 1) was separated into 5–10 layers. The number of layers was dependent on the tooth size. The sampling was performed in the radial direction: from pulp channel to enamel.

The measurements of ^{90}Sr contents in tooth tissues were made using the standard radiometric method. The tissue samples were ashed in a muffle furnace. Then, the ashes were kept for 2 weeks to reach a balance between ^{90}Sr and ^{90}Y. The measurements of activity were made with the impulse counter 10 MHz ZÄHER VAG-120 with an uncertainty of 10–15%. The readings of the device were compared with the measurements of the reference sample (solution of $SrNO_3$ ($V = 1$ ml, $A = 1110$ Bq/ml)).

3. Experimental results

3.1. ^{90}Sr tissue distribution in the teeth

Table 2 demonstrates the measured ^{90}Sr concentration in different teeth. The teeth differed in terms of ^{90}Sr content depending on tooth position (right, left, upper, lower) and type of tooth. Among the calcified tissues studied, the samples of alveolar bones adjacent to the root showed the maximum ^{90}Sr concentrations (average value 70, maximal value 190 kBq/g). Results of alveolar bone measurements are characterized by maximal variability. The lowest values were found to be in the enamel (average value 4.5, maximal value 7 kBq/g). Crown dentine, root dentine, and cement contain similar

Table 2
^{90}Sr concentration in tooth tissues and adjusted alveolar bone (kBq/g) for teeth from left and right jaw sides

Tooth	Enamel		Crown dentine		Root dentine		Cement		Alveolar bone		Pulp	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
Upper jaw, side												
Canine	1.3	1.7	10	10[a]	10	—	20	—	35	—	436	400
1st premolar	3.4	6.3	32[a]	22[a]	27	37	32	44	33	64	196	140
3rd premolar	—	—	—	—	—	20	—	30	—	45	300	—
4th premolar	6.4	4.9	23	19	31	27	41	35	69	95	200	200
1st molar	7.0	3.2	32[a]	31[a]	30	25	43	40	110	60	399	196
2nd molar	5.0	4.5	34[a]	22[a]	34	20	60	—	170	—	252	180
Lower jaw, side												
Canine	7.1	5.9	28[a]	21[a]	22	15	19	15	60	—	440	292
1st premolar	4.4	4.2	16[a]	27[a]	26	15	16	13	46	40	240	200
2nd premolar	4.1	4.7	16[a]	20[a]	48	62	30	42	79	62	240	220
4th premolar	5.9	—	40[a]	—	50	—	45	—	100	—	190	—
1st molar	3.4	1.5	33	16	28	22	14	20	190	80	200	200
2nd molar	3.4	—	17[a]	—	—	—	—	—	—	—	200	—
3d molar	6.3	—	21[a]	—	—	—	—	—	—	—	120	—

[a] ^{90}Sr concentration in crown dentine was determined as averaged value from layer-by-layer measurements.

quantities of ^{90}Sr: the average value is 26 kBq/g, the maximal value 60 kBq/g. The average ^{90}Sr concentration in the pulp was significantly higher (240 kB/g). This can be explained by the fact that a short time passed after ^{90}Sr injection resulting in high ^{90}Sr concentrations in the soft tissues. As opposed to the soft tissues (just after the acute intake), the strontium retention in the enamel of adult mammals is extremely low. In an experiment with ^{32}P, it was shown that the ^{32}P concentration ratio in enamel to that in dentine for human teeth was 1:5 (Fedorov, 1970). The respective values for dog teeth were 1:4 and 1:8 for premolars, and about 1:10 for molars (Table 2).

As for the ^{90}Sr distribution within the tooth tissue, a significant irregularity of ^{90}Sr contents in different layers of dentine has been found. Fig. 1 presents examples of radial ^{90}Sr distributions within the dentine body. As can be seen, the radial ^{90}Sr distributions in the dentine for different teeth are not exactly identical. However, some common features were found: the maximum of the ^{90}Sr concentration was observed in the layer of dentine near the pulp. The trend has been towards an increase in ^{90}Sr concentration in the dentine layer nearest to the enamel. These facts have a reasonable interpretation: near the enamel the dentine tubes are branched out increasing the surface area for mineral exchange; the dentine layer adjacent to the pulp has the most intensive blood supply. Similar ^{90}Sr distributions were observed in all teeth: molars, canines and premolars.

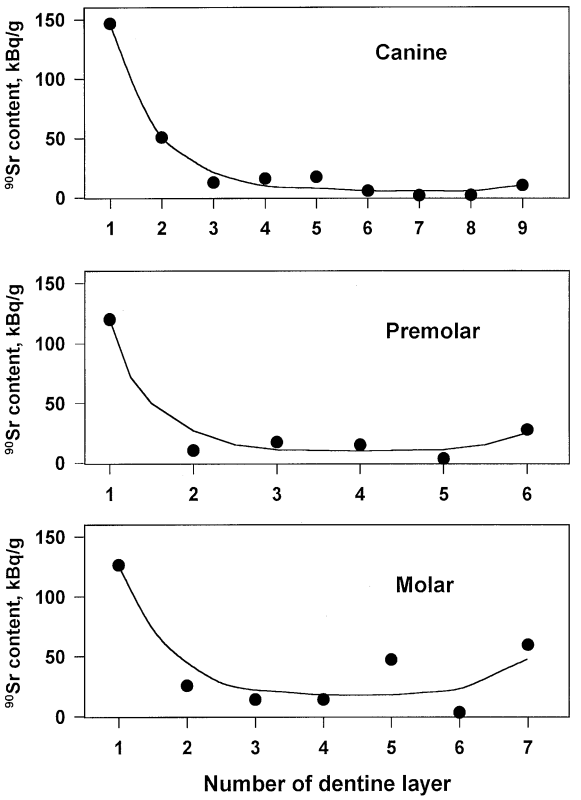

Fig. 1. ^{90}Sr concentration in dentine layers for lower-left canine, second lower-left premolar and second upper-left molar. The sampling was performed in order from pulp to dentine; thus, the first layer is adjacent to the pulp, the last layer is adjacent to the enamel. Specific thickness of dentine in the tooth studied, and the diameter of dental drill determined the number of layers.

3.2. Absorbed dose distribution in the teeth and tissue samples

The information about dose distribution on the enamel surfaces of different teeth was obtained using TL detectors. The measurements were performed before the teeth were extracted from the skull. The readings of the TL detectors were the same on the external (lingual) and internal (labial) sides of the teeth. Therefore, the measurements were unaffected by exposure to the skull seeking ^{90}Sr, and in further investigations this source of exposure (skull) was not taken into account.

The TLD-measured dose distribution was extremely non-uniform. Fig. 2 presents the results of TL measurements of the teeth in terms of the daily dose rate. The readings of detectors on the various teeth differ by a factor of 10. As a whole (Fig. 2), the dose rates registered by the detectors placed on the lower jaw were higher than those measured by the detectors placed on the upper jaw by a factor of about 2.4.

The following interpretations of these results can be suggested: (1) The teeth from the lower jaw vary in size and shape compared to their antagonists. The variability of the geometric size of teeth influences the dose absorption because of the specific geometry of exposure. Furthermore, as was shown in Table 2, the enamel and dentine have a different opportunity to uptake ^{90}Sr, and relative contributions of tooth tissues (enamel to dentine ratio) vary depending on the type of tooth. (2) The teeth from the lower jaw are more intensively washed by saliva, which plays an important role in the mineral (calcium, strontium) exchange of the tooth enamel (Yartsev, 1963).

The absorbed dose distribution in dental tissues was examined by the EPR method. Table 3 presents the results of EPR measurements in terms of daily dose rate for four tooth samples (Ignatiev et al., 1999). The highest absorbed doses were determined in the root dentine and alveolar bone adjacent to the root.

The experimental data available allow to qualitatively compare the ^{90}Sr tissue distribution with the respective dose distribution. Fig. 3 presents the ratios between dose and concentration values for different tooth tissues. There was no complete correlation between radiometric and EPR data. This fact can be attributed to several reasons affecting the dose formation: (1) influence of

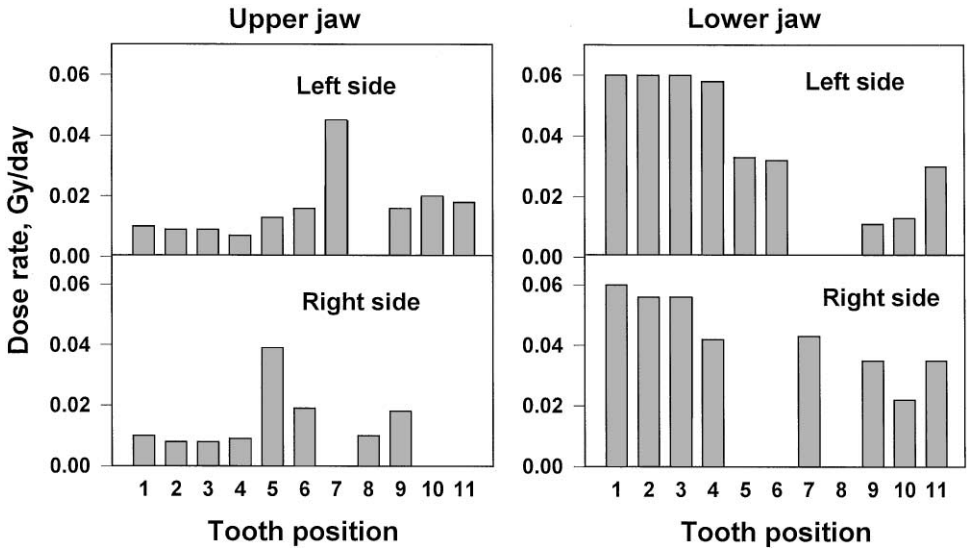

Fig. 2. Results of TL measurements of enamel dose rates for the teeth studied. The left part of the figure reflects the results for the upper jaw, the right part for the lower jaw. The numbers of tooth positions correspond to the following tooth types: 1–3, incisors; 4, canine; 5–8, premolars; 9–11, molars.

Table 3
Results of EPR measurements in terms of daily dose rate (according to Ignatiev et al., 1999)

Tooth sample	Daily dose rate in Gy per day for tooth tissue			
	Enamel	Crown dentine	Root dentine	Alveolar bone adjacent to root
4th upper right premolar	0.19 ± 0.02	0.39 ± 0.03	0.68 ± 0.05	—
4th upper left premolar	0.33 ± 0.02	0.44 ± 0.03	1.08 ± 0.07	1.07 ± 0.07
1st lower right molar	0.24 ± 0.02	0.39 ± 0.03	0.66 ± 0.05	0.75 ± 0.05
1st lower left molar	0.19 ± 0.02	0.38 ± 0.03	0.67 ± 0.05	0.60 ± 0.06

exposure to neighboring tissues; (2) geometry of exposure, which varyies for different tooth tissues; (3) heterogeneous distribution of ^{90}Sr in tissues. The mathematical (dosimetric) tooth model should take these features into account.

4. Dosimetric tooth model

4.1. Description of tooth crown geometry

The model was elaborated for the cylindrical teeth (molars and premolars). The tooth could be considered as a system of layers each of which is a tissue with different chemical–physical characteristics. The following tooth tissues (sources and targets of exposure) were taken into account: root dentine, cement, alveolar bone, crown dentine, pulp, enamel and the enamel of the neighboring teeth. In the case of ^{90}Sr intake, the tooth tissues represent both sources and detectors of exposure to ^{90}Sr + ^{90}Y energy spectra.

For modeling purposes the crown of posterior teeth (molar and premolar) was described as a system of inserted cylinders (Fig. 4). The enamel of the neighboring teeth was described as a fragment of an adjunctive external cylinder. The dentine of the root was approximated as a plate 3 mm high adjacent to the dentine of the crown because the average passage length of ^{90}Y in dentine is about 3 mm in the approximation of continuous slowdown (ICRU, 1984). The experimental data described above were used for the model validation. Table 4 presents the geometric size of the dog teeth used for the calculations.

4.2. Monte-Carlo calculations of dose coefficients

The enamel- and dentine-absorbed dose rate coefficients were calculated by Monte-Carlo simulation of electron transport using the CASCADE-5 code elaborated for calculations of beta-, gamma- and alpha-exposure (in the range 10^{-2}–10^{9} MeV) in heterogeneous, axial-symmetric, and many-zone media (Lappa and

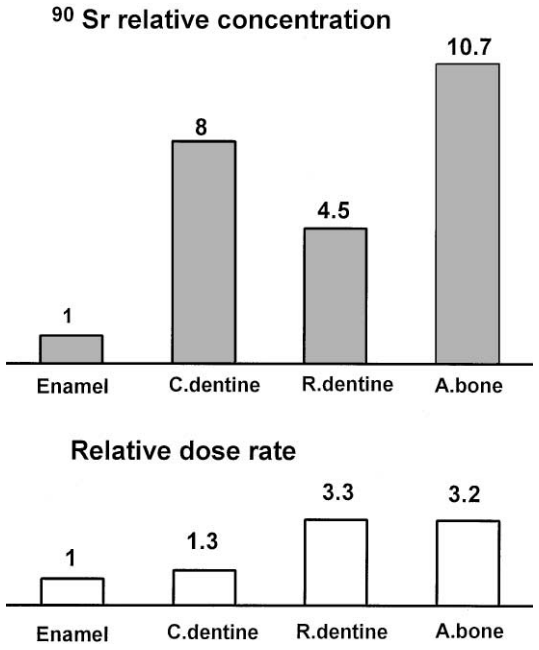

Fig. 3. Comparison of the results of dosimetric and radiometric measurements in the same tooth (fourth upper-right premolar). The numbers indicate the ratio between enamel ^{90}Sr concentration and the corresponding ^{90}Sr concentration in other tooth tissues; and the ratio between absorbed enamel dose to the corresponding absorbed doses in other tissues.

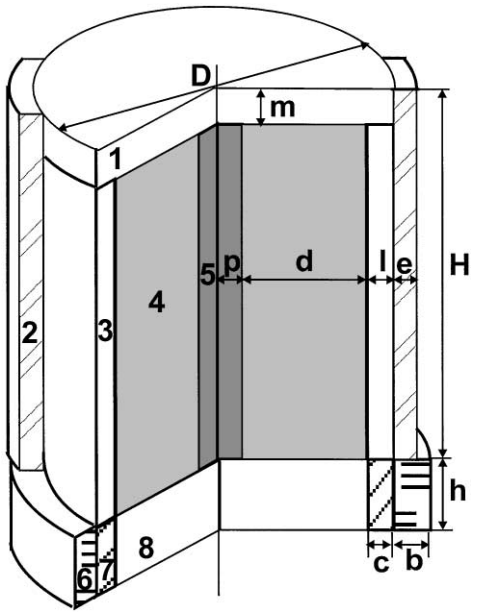

Fig. 4. Scheme illustrating the geometric model of teeth for the Monte-Carlo simulation of the electron transport. (1) masticatory layer of enamel; (2) fragment of neighboring teeth enamel; (3) lateral layer of enamel; (4) crown dentine; (5) pulp; (6) fragment of alveolar bone adjacent to root; (7) cement; (8) root dentine.

Table 4
Geometric parameters of dog teeth used for Monte-Carlo simulations

Parameters[a]	Linear size (mm)			
	4th upper right premolar	4th upper left premolar	1st lower right molar	1st lower left molar
Height of crowns (H)	4.4	4.4	4.9	5.0
Height of root fragment (h)	3.0	3.0	3.0	3.0
Diameter of crown (d)	10.76	10.76	8.1	8.86
Radius of pulp (p)	1.50	1.50	1.25	1.36
Thickness of dentine (d)	3.08	3.08	2.10	2.31
Thickness of lateral enamel (l)	0.8	0.8	0.7	0.76
Thickness of masticatory enamel (m)	1.2	1.2	1.2	1.2
Thickness of cement (c)	0.8	0.8	0.7	0.76
Thickness of neighboring teeth enamel (e)	0.8	0.8	0.7	0.76
Thickness of alveolar bone adjacent to root (b)	0.1	0.1	0.1	0.2

[a] According to Fig. 4.

Burmistrov, 1994). The enamel and dentine dose rate coefficients were calculated for different source tissues.

The photon and electron thresholds were set at 10^{-2} MeV. The constants of interaction between electron and substance were calculated using the data on the chemical composition of human tooth tissues and their density as representative of mammals (Table 5). The density of tooth tissues was assumed to be uniform. The calculations were performed for four teeth according to individual data on the geometric size (Table 4). Two sets of calculations were made: (i) for the case of a uniform ^{90}Sr distribution within the dentine and the enamel; (ii) for a non-uniform ^{90}Sr distribution using the results of radiometric measurements. For the latter case the

Table 5
Chemical composition of tooth tissues (according to Logan and Taylor, 1938; Derise and Ritchey, 1974; Driessens and Verbeeck, 1982; Bazhanov, 1984; Manly et al., 1939)

Substance	Enamel	Dentine	Cement	Pulp	Alveolar bone
% of moist weight					
Ca	36.6	23.3	16.3	9	14.7
O	24.3	34.6	35.2	45	41
C	16.5	23.5	23.8	23	27.8
P	17.7	12	17.1	10	7.0
H	3.8	5.4	5.5	12	6.4
Na	0.67	0.2	1.1	—	1.1
Mg	0.35	1	1	1	1.1
Density (g/cm^3)	2.97	2.18	2.03	0.8	1.85

Table 6
Parameters of dentine layers used for the model calculation

Dentine layer[a]	Thickness of dentine layer (R) and ^{90}Sr concentration (A) for teeth modelled							
	4th upper-right premolar		4th upper-left premolar		1st lower-right molar		1st lower-left molar	
	R (mm)	A (kBq/g)	R (mm)	A (kBq/g)	R (mm)	A (kBq/g)	R (mm)	A (kBq/g)
1	0.31	79	0.36	193	0.23	151	0.20	76
2	0.92	26	0.97	21.0	0.65	76	1.20	16
3	1.54	2.0	1.38	5.0	1.2	8.0	0.50	7.0
4	0.31	39	0.36	30	0.23	30	0.20	12

[a] First layer is adjacent to pulp, fourth layer is adjacent to enamel.

dentine-cylinder was divided into four zones depending on the activity distribution. As described above, there are differences between the ^{90}Sr concentration in the teeth of the upper and lower jaws, and between teeth in the right and left positions. The maximal heterogeneity in dentine, which was detected on the respective side of the jaw, was taken into account in the calculation. Table 6 reports the parameters of dentine layers used for calculations in each case. The estimated relative uncertainty of the Monte-Carlo calculations was less than 0.01%.

4.3. Analysis of the dose formation factors

The average path lengths of ^{90}Y beta particles in tooth tissue are about 3 mm for dentine, and about 2 mm for enamel which is comparable with the actual tooth size (Table 4). Therefore, the absorbed enamel (dentine) dose is dependent on the distance from source tissues, and on the geometry of exposure. Table 7 presents examples of calculated dose coefficients ((Gy/day)/(Bq/g)) for a premolar and a molar. As can be seen, the most important sources of enamel exposure are the enamel and dentine. For dentine these sources of exposure were most important too. The influence of enamel of the neighboring teeth is negligible. In most cases the contribution of cement, pulp, and alveolar bone adjacent to the root can be assumed as inessential. Individual features of geometric sizes of the teeth should explain the differences between the two sets of calculations.

Daily dose rates from different tooth tissues were calculated on the basis of radiometric data (Table 2) as a product of dose coefficient and the integral value of the ^{90}Sr concentration from time of intake to time of measurements. Table 8 shows an example of calculated daily dose rates for dentine and enamel in the case of the uniform ^{90}Sr tissue distribution and non-uniform ^{90}Sr distribution in dentine. According to the data presented, the self-exposure is a leading dose formation factor in most cases. It amounts to 50% of the cumulative absorbed dose for masticatory enamel and 95% for dentine. It is concluded, based on the calculations, that the exposure of lateral enamel was largely formed by dentine seeking ^{90}Sr. As can be seen in Table 8, heterogeneity of the ^{90}Sr distribution in the dentine

Table 7
Examples of calculated dose coefficients for premolars and molars

Source tissue	Target tissues of 4th upper-right premolar, dose coefficients (m Gy day^{-1} per Bq g^{-1})			Target tissues of 1st lower-left molar, dose coefficients (m Gy day^{-1} per Bq g^{-1})		
	Crown dentine	Masticatory layer of enamel	Lateral layer of enamel	Crown dentine	Masticatory layer of enamel	Lateral layer of enamel
Enamel	3.6×10^{-1}	21	3.1	3.0	21	4.0
Crown dentine	16	3.6	2.5	8.3	3.5	1.9
Root dentine	4.8×10^{-1}	5.0×10^{-3}	6.0×10^{-2}	4.8×10^{-1}	5.0×10^{-3}	3.0×10^{-2}
Cement	4.0×10^{-2}	1.0×10^{-3}	6.0×10^{-2}	4.0×10^{-2}	1.0×10^{-3}	6.0×10^{-2}
Pulp	1.0×10^{-2}	8.0×10^{-3}	4.0×10^{-6}	2.0×10^{-1}	5.0×10^{-2}	3.0×10^{-6}
Alveolar bone adjacent to root	1.0×10^{-3}	4.0×10^{-4}	6.0×10^{-2}	6.0×10^{-2}	3.0×10^{-3}	1.8×10^{-2}
Enamel of neighboring teeth	1.0×10^{-9}	5.0×10^{-4}	6.0×10^{-3}	6.0×10^{-3}	5.0×10^{-4}	6.0×10^{-3}

Table 8
Calculated absorbed doses in target tissues (in terms of daily dose rate) from the main sources of exposure for 4th upper-right premolar

Source tissue	Dose rate in target tissues from source tissue (Gy per day) and their contribution (%) to the total dose		
	Crown dentine	Masticatory enamel	Lateral enamel
Uniform distribution of ^{90}Sr in crown dentine			
Enamel[a]	0.002 (0.5%)	0.102 (59.0%)	0.015 (21.9%)
Crown dentine	0.314 (94.5%)	0.069 (39.9%)	0.047 (68.6%)
Non-uniform distribution of ^{90}Sr in crown dentine			
Enamel[a]	0.002 (0.44%)	0.102 (50.6%)	0.015 (16.75%)
Crown dentine	0.388 (95.5%)	0.098 (48.6%)	0.068 (75.95%)

[a] The source of exposure is the entire enamel

affects the absorbed doses in the enamel. The differences between the two sets of calculations were significant for enamel in contrast to dentine, which was practically unaffected by the features of the ^{90}Sr distribution. As for enamel, the allowance for actual ^{90}Sr heterogeneity resulted in an enamel dose value increased by about 10%.

It should be noted that 52 h after the acute ^{90}Sr intake, the ^{90}Sr tissue distribution is extremely irregular. In another situation, for instance, in the case of chronic ^{90}Sr intakes, a more uniform distribution should be expected.

4.4. The comparison of tooth model predictions with experimental data

The conformity of model predictions and measured values was tested on the example of crown dentine and masticatory enamel. As described above, the masticatory part of enamel was mainly sampled for EPR measurements, so this portion of enamel was sampled for comparison between the measured and calculated enamel doses. The calculation was performed on the basis of actual ^{90}Sr concentrations taking into account all sources of exposure (all target tissues from Table 7). Because the uncertainty of the ^{90}Sr measurements was 10%, the lower and upper limits of doses were calculated as doses from upper and lower estimations of ^{90}Sr concentrations. A comparison of model predictions with EPR data is presented in Fig. 5. The error bars in Fig. 5 show the corresponding dose intervals.

For dentine a good agreement between experimental and calculated values is observed if the heterogeneity of the ^{90}Sr distribution in the crown dentine is taken into account (Fig. 5, first lower-left molar, fourth upper-right premolar). The results of EPR measurements for enamel were found to be higher than the calculated values in the case of uniform ^{90}Sr distribution in dentine. In contrast, the calculations taking into account the high ^{90}Sr concentration in the pulp adjoining the dentine layer were comparable with measured dose rates. The differences between measured and calculated dose rates were within the limits of EPR uncertainties.

Therefore, the model presented can be used for the calculation of absorbed doses from incorporated ^{90}Sr if the data on ^{90}Sr tissue concentration are available, and the character of the ^{90}Sr dentine distribution is known. However, it should be noted that "individual tooth

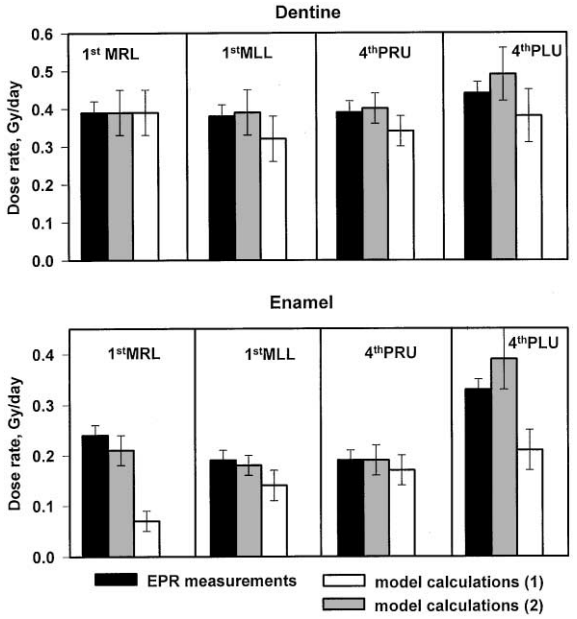

Fig. 5. Comparison of EPR dentine doses and EPR enamel doses with the results of the model calculations. (1) calculation based on a uniform ^{90}Sr distribution in dentine; (2) calculation on the basis of a non-uniform ^{90}Sr distribution in dentine.

measurements'' of geometrical parameters and ^{90}Sr tissue concentrations were introduced in the model. The use of averaged values can lead to additional uncertainties.

5. Discussion and further investigations

The experimental data and a comparison between model predictions and EPR measurements allow to determine the problems resulting from ^{90}Sr dose assessment.

The sampling of dental tissues. As a rule, the masticatory and lateral portions of the enamel are examined together. As shown in the present study, these portions of the enamel are distinguished by the dominating source tissues and, therefore, by the absorbed doses. For the dog teeth used in our experiment the ratio of masticatory and lateral enamel doses was about 2. The weight contributions of lateral and masticatory portions vary in different teeth, and they can be distinguished from average values. This is especially important for human teeth extracted on medical indications. In such tooth-samples a significant part of enamel can be lost.

The dentine sampling is complicated by the non-uniform distribution of ^{90}Sr in the dentine. Fig. 6 presents the comparison of daily dose rates in the

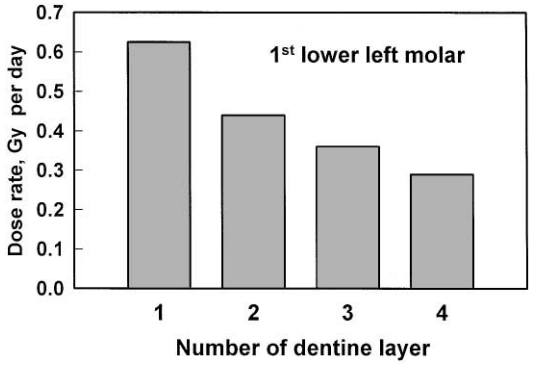

Fig. 6. Comparison of daily dose rates in the dentine layers for the first lower-left molar. Description of the dentine layers is presented in Table 6. The first layer is adjacent to the pulp, the fourth layer is adjacent to the enamel.

dentine layers for the first lower molar. Different ^{90}Sr concentrations in the dentine layers determine the radial distribution of absorbed doses. The maximal and minimal values differ by a factor of 2.2. It is obvious that the loss of part of the sample can lead to under- or over-estimation of the averaged dentine dose.

^{90}Sr concentration measurements in different dental tissues. As shown for ^{90}Sr dose calculation, ''individual'' tooth measurements are necessary, in particular, for the investigation of average ^{90}Sr concentration in dental tissues and the ^{90}Sr tissue distribution. According to the data presented, the teeth in the denture are distinguished by the ^{90}Sr retention in the same tissues (even in an adult subject). ^{90}Sr dentine concentrations differ from one another by a factor of about 4; ^{90}Sr enamel concentrations differ by a factor of about 5. According to published data (Fedorov, 1970), the differences between the same teeth from the right and left sides were negligible. However, an evident skewness of ^{90}Sr retention is observed in the experiment (Table 2). It should be explained by natural reasons, for example, a microtrauma of the jaw. TLD detectors register a similar skewness (Fig. 2). The differences between teeth should be expected to be found in humans too.

In the framework of the experimental study presented a high ^{90}Sr concentration was used. However, significant difficulties may occur if the ^{90}Sr tissue content is relatively low. The ^{90}Sr measurements (by using a low-level counter) in different layers of dentine are complicated due to a small mass of the tissue sample. As for human population, ^{90}Sr contamination occurred due to nuclear test fallouts and radioactive accidents. ^{90}Sr intakes that occurred in the period of global fallouts had a distinct maximum in 1963–1965 (UNEP, 1985). The schedule of ^{90}Sr intake after accidental contamination of the environment is similar: maximal intakes during and after the accident and subsequently a sharp decrease in

intake levels (for example the radioactive releases into the Techa River and the Chernobyl accident (a review by Vorobiova et al., 1999; Merwin and Balonov, 1993)). Therefore, it is probable that the ^{90}Sr distribution in human teeth is irregular, so the problem invites a further investigation.

Model development. The tooth model presented should be considered as a simple mathematical model. The features of tooth shape can be described in more detail. Because different ethnic groups are characterized by a specific tooth size (Kieser, 1990), additional odontometric investigations are necessary for the elaboration of a more adequate model for a specific human population. Some distinctive features of tooth geometrical parameters for Urals population have been found during odontometric studies in the Urals (Shved and Shishkina, 2000).

As seen, the accuracy of model predictions depends largely on the special assumptions (features of ^{90}Sr tissue distribution, choice of the masticatory or lateral parts of enamel). Analysis of the model sensitivity to modifications of the model parameters is the next step in the model improvement.

In this study the EPR measurements were performed on all dental tissues. However, there are some reasons to concentrate the efforts on the enamel dose assessment and crown model elaboration. (1) The enamel is the most mineralized tissue of the body, as much as 99.4% of the dry weight of enamel is inorganic material (crystallites). The corresponding value for dentine is 80%. (2) The time of the enamel mineralization is relatively shorter than those for crown and root dentine. It should be taken into account that the thickness of crown and root dentine increases during the lifetime. Thus, for humans the thickness of the walls of the root channels increases by 15–30% in the age period from 20 to 50 y (Kluev, 1976). Therefore, the interpretation of dentine EPR measurements is more difficult in comparison with enamel measurements due to different schedules of ^{90}Sr retention and, therefore, of the dose absorption process.

6. Conclusions

Fifty-two hours after an injection the ^{90}Sr distribution in teeth is dependent on tooth position (lower jaw or upper jaw; incisor, canine, molar or premolar), and on the type of tooth tissues (enamel, dentine, cement, etc.). In terms of ^{90}Sr concentration the tooth tissues are arranged in a decreasing order: cement– dentine–enamel. The ^{90}Sr dentine distribution was found to be heterogeneous. The dentine layer adjacent to the pulp contains maximal ^{90}Sr concentrations.

A tooth dosimetric model for ^{90}Sr was presented. The model allows to determine the leading dose formation factors (main source-tissues). For crown dentine these factors (in the order of importance) are as follows: self-exposure, exposure to enamel, and root dentine. The factors for masticatory enamel are self-exposure, exposure to crown dentine and lateral enamel. For lateral enamel they are: self-exposure, exposure to crown dentine, cranial bone adjacent to the root.

For crown dentine a good agreement between experimental and calculated values is observed if the heterogeneity of ^{90}Sr distribution in the crown dentine is taken into account; otherwise an underestimation of the absorbed dose was found. The situation is similar in the case of enamel: good agreement was found when the heterogeneity of ^{90}Sr distribution in dentine was taken into account; the enamel doses were significantly underestimated when dentine was assumed to be uniformly contaminated.

For adequate ^{90}Sr enamel dose calculations the following measurements and information are desirable: (1) individual measurements of the geometric sizes of teeth (or measurements for reference age, sex and ethnic group); (2) measurements of actual ^{90}Sr tissue concentrations; (3) information about the schedule of ^{90}Sr intakes.

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