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AN EXAMPLE OF PROBLEMS IN DOSE RECONSTRUCTION FROM DOSES FORMED BY ELECTROMAGNETIC IRRADIATION BY DIFFERENT ENERGY SOURCES

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Abstract—**Dose reconstruction for citizens of Belarus affected by the Chernobyl accident showed an unexpectedly wide range of doses. Using the EPR tooth enamel dosimetry method, it has been demonstrated that when the tooth enamel dose was formed due to x-rays with effective energy of 34 keV and the additional irradiation of enamel samples was performed by gamma radiation with mean energy of 1,250 keV, it led to a considerable increase in the reconstructed absorbed dose as compared with the applied. In the case when the dose was formed due to gamma radiation and the additional irradiation was performed by x-rays, it led to a considerable decrease in the reconstructed dose as compared with the applied. When the dose formation and the additional irradiation were carried out from external sources of electromagnetic radiation of equal energy, the reconstructed dose value was close to that of the applied. The obtained data show that for adequate reconstruction of individual absorbed doses by the EPR tooth enamel spectra, it is necessary to take into account the contribution from diagnostic x-ray examination of the teeth, jaw, and skull of some individuals who were exposed to a combined effect of the external gamma radiation and x-rays.**
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Key words: dose assessment; dosimetry; gamma radiation; x-rays

INTRODUCTION

IT IS known that under the effect of gamma radiation and x-rays, paramagnetic centers are formed in tooth enamel (Brady et al. 1968; Aldrich and Pass 1986; Shimano et al. 1989). In emergency situations, the dose load is mainly formed due to external gamma radiation. However, the dose in tooth enamel can also be formed at diagnostic x-ray examination of the maxillodental system. During diagnostic x-ray examination of teeth, the jaw, and the skull, local irradiation occurs, while in an emergency situation the whole body is exposed to radiation.

Previously, the relationship between the output of paramagnetic centers in tooth enamel and the energy from electromagnetic radiation has been ascertained (Iwasaki et al. 1991). In particular, the authors showed that the intensity of the electron paramagnetic resonance (EPR) signal induced by x-rays with effective energy of about 35 keV (the value used in diagnostic maxillodental examination) exceeded eight-fold the amplitude of the signal induced by gamma radiation from a ^{60}Co source with mean energy of 1250 keV.

Thus, it is possible to single out two important distinctions between the effect of x-rays and gamma radiation on tooth enamel. First is the local effect of dental x-rays in contrast to the integral character of the external emergency irradiation. Second, the accessed output of paramagnetic centers in tooth enamel under the effect of diagnostic x-rays is greater by almost an order of magnitude as compared with gamma radiation. All this should lead to a different slope of the growth curve reconstructed by EPR spectra.

Previous work has studied x-rays and gamma radiation separately, yielding the above-mentioned difference in sensitivity (Brady et al. 1968; Aldrich and Pass 1986; Shimano et al. 1989; Iwasaki et al. 1991). The aim of this study was to demonstrate experimentally the discrepancy between the applied dose and the reconstructed EPR tooth enamel spectra exposure dose formed due to x-rays.

MATERIALS AND METHODS

Sample preparation

Samples that had not been exposed to diagnostic x-rays were selected from teeth extracted for clinical reasons. The tooth crown was separated from the root and split into the buccal and lingual side of the tooth. The buccal and lingual sides of each tooth were irradiated by x-rays and gamma radiation as described below. After

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that, enamel samples were prepared from these halves pairwise. The halves of the teeth were cleaned of the remnants of organic substances; tartar and pigment patches and carious areas were removed. Enamel was separated from dentine and pulp with the help of the short-term effects of spare low-speed (30.000 rev min^{-1}) hard-alloyed borers of different sizes with water cooling. Cleaned enamel was crushed into granules of 0.5–1.0 mm in an agate mortar, and weighed samples of 100 mg were prepared.

Spectra registration

Tooth enamel spectra measurements were performed with a Bruker ECS-106 EPR-spectrometer (Bruker BioSpin, 76287 Sieberstreifen, Rheinstetten, Germany) in X-band using a 4102 ST resonator with the following registration parameters: microwave power—10 mW; receiver gain—10^5; modulation frequency—100 kHz; modulation amplitude—0.25 mT; sweep time—10 s; time constant—10 ms; sweep width—10 mT; 1024-point field resolution, number of scans—100, at room temperature.

Radiation effects on tooth enamel

The buccal and lingual sides of each tooth were irradiated through 6-mm-thick Plexiglas using electromagnetic radiation of different energies. This allowed excluding the factor of individual radiation sensitivity. Teeth were exposed to gamma radiation on a dosimetric ruler from the calibrated ^{60}Co source with an air kerma rate of 630 mGy min^{-1} at the phantom surface. X-ray irradiation was performed on "Pantak HF-320" (Gulmay Medical, Inc., 5012B Bowman Dr., Suite 300, Buford, GA, USA) at standard up-to-date x-ray diagnosis parameters of the maxillodental system (x-ray tube anode voltage 70 kV, aluminum filter thickness 2.4 mm) with an air kerma rate of 45 mGy min^{-1} at the phantom surface. Average gamma quantum energy was equal to 1,250, and the effective energy of x-rays was 34 keV. The distance from the front surface of the phantom to the ^{60}Co source and the x-ray tube focus was 2.0 and 1.5m, accordingly.

During the comparative analysis of paramagnetic centers induced by gamma radiation or x-rays, the buccal side of the tooth was irradiated from the enamel side on a dosimetric ruler and the lingual side on an x-ray machine with the same applied dose of 5 Gy. The amplitude of the radiation-induced EPR signal was assessed for three samples.

For comparative analysis of the reconstructed doses, two series of experiments were conducted. In one series, the buccal and lingual sides of each tooth were irradiated pairwise with doses of 100, 250, and 500 mGy on a dosimetric ruler, and in the other series on an x-ray machine. In both series, three pairs of samples were used for each irradiation.

Reconstruction of individual absorbed doses by EPR-spectra of tooth enamel

To determine the individual coefficient of radiation sensitivity of tooth enamel, the additive-dose method was used. Additive irradiation of samples was performed through Plexiglas of 6 mm thickness from a ^{60}Co standard gamma radiation source and by x-rays at standard for x-ray diagnosis parameters with total doses of 0.25, 0.5, 1.0, 2.0, and 4.0 Gy.

Mathematical processing of EPR spectra with consequent reconstruction of individual absorbed doses was carried out with the help of the authors' own computer program "Tooth enamel-3" (Dubovsky and Kirillov 2001; Kirillov and Dubovsky 2009).

RESULTS

Comparative analysis of EPR signals induced by x-rays and gamma radiation

Two halves of each tooth were exposed to ionizing electromagnetic radiation of different energy with an equal applied dose of 5 Gy. The lingual side of the tooth was exposed to x-rays with effective energy of 34 keV and the buccal side to gamma radiation with average energy of 1,250 keV. The radiation-induced signal in the EPR tooth enamel spectra of these halves had the same spectral characteristics in both cases. At the same time, the intensity of the EPR signal induced by x-rays was almost 10 times greater than the intensity of the signal induced by gamma radiation (Fig. 1). Previously, the relationship between the

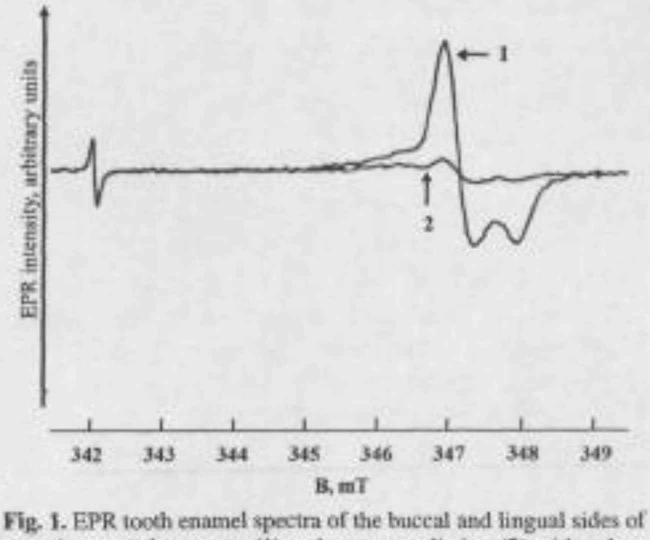

Fig. 1. EPR tooth enamel spectra of the buccal and lingual sides of a tooth exposed to x-rays (1) and gamma radiation (2) with a dose of 5 Gy.

intensity of the radiation-induced EPR tooth enamel signal of human teeth and the energy from ionizing radiation was noted in other work (Iwasaki et al. 1991).

In calibrating EPR radiation response in terms of absorbed doses in tooth enamel, the methods of both the additive-dose and the dose-response curve are used (Bougai et al. 2002). Hence, enamel preparations are being additionally exposed to gamma radiation. Therefore, taking into account the dependence of the of EPR signal intensity on the ionizing radiation energy, the presence in tooth enamel of free radicals induced by x-rays would lead to a different increase in the dose.

Reconstruction of exposure doses formed by x-rays

To confirm this supposition, two series of experiments were conducted. In the first series, the buccal and lingual sides of each tooth were exposed to x-rays. In the second series, these halves of the teeth were exposed to gamma radiation. Then enamel samples were prepared from these halves of the teeth with subsequent calculation of the exposure doses by the EPR tooth enamel spectra. Calibration straight lines were constructed with the help of the additive-dose method, using either the standard (additional irradiation by gamma radiation) or non-standard (x-rays) method of irradiation.

In the first series of experiments, nine pairs of the buccal and lingual sides of each tooth were preliminarily exposed to x-rays. The first three pairs of the halves of the teeth were simultaneously exposed to applied doses of 100, the second three pairs to 250 and the third to 500 mGy. The analysis of the EPR spectra of tooth enamel samples prepared from these halves of the teeth showed that the intensity of the radiation-induced signal grew with an increase in the applied dose.

Nine enamel samples of the buccal side of a tooth, in which the dose was formed by x-rays, were exposed to standard additional five-fold irradiation by gamma radiation for EPR dosimetry with total doses of 0.25, 0.5, 1.0, 2.0, and 4.0 Gy. Table 1 (No. 1–3) presents the results of dose reconstruction. The analysis of these data showed that doses reconstructed by the EPR spectra of tooth enamel samples were, on average, 10 times greater as compared with the applied.

Nine enamel samples of the lingual side of a tooth, in which the dose was also formed by x-rays, were exposed to non-standard additional five-fold irradiation by x-rays with total doses of 0.25, 0.5, 1.0, 2.0, and 4.0 Gy. The analysis of the applied and reconstructed doses given in Table 1 (No. 4–6) showed that their values were close to those of the applied.

Fig. 2 presents calibration straight lines of enamel samples of buccal and lingual sides of one tooth, in which the dose was formed by x-rays with the applied dose of 500 mGy. The dose load was assessed by calibration straight line 2 with the help of additional gamma irradiation, and by line 1 with the help of additional x-ray irradiation. As seen from this figure, the dose calculated by line 2 was equal to 5,382.3 mGy, i.e., it was higher than the applied dose by an order of magnitude. At the same time, the dose calculated by line 1 was equal to 491.7 mGy, i.e., it practically coincided with the applied.

Reconstruction of exposure doses formed by gamma radiation

In the second series of experiments, nine pairs of the buccal and lingual sides of each tooth were preliminarily exposed to gamma radiation. The first three pairs of the halves of the teeth were simultaneously exposed to applied doses of 100, the second to 250, and the third to 500 mGy. Registration of EPR tooth enamel spectra of these halves of the teeth revealed that the intensity of the

Table 1. Applied and reconstructed doses. Applied doses were formed due to irradiation of the buccal and lingual side of a tooth by x-rays. Doses reconstructed by EPR tooth enamel spectra were obtained by additional gamma radiation (1–3) and x-rays (4–6).

No.	Applied dose, D_{ap}, mGy	Reconstructed dose, $D_r \pm$ sem, mGy	Ratio between reconstructed and applied doses
1	100	768.1 ± 139.5	7.7
2	250	2258.7 ± 127.4	9.0
3	500	5650.9 ± 587.8	11.3
4	100	75.3 ± 6.2	0.8
5	250	230.1 ± 9.7	0.9
6	500	450.2 ± 18.7	0.9

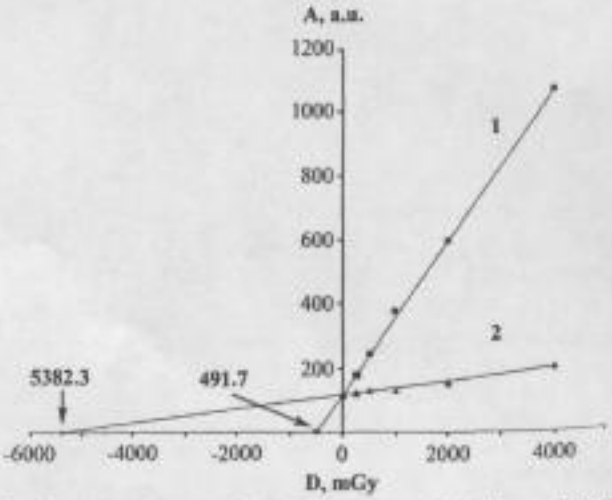

Fig. 2. Additive-dose method. Calibration straight lines and doses reconstructed by EPR tooth enamel spectra of the buccal and lingual sides of one tooth. Each half of a tooth was exposed to x-rays with the applied dose of 500 mGy. Additional irradiation of enamel samples was performed by: (1) x-rays; (2) gamma radiation.

radiation-induced signal grew with an increase in the applied dose.

Nine enamel samples of the buccal side of a tooth, in which the dose was formed by gamma radiation, were exposed to standard additional irradiation by gamma radiation. Table 2 (No. 1–3) presents the results of dose reconstruction. The analysis of these data showed that the doses reconstructed by EPR spectra of enamel samples were approximately equal to the applied doses.

Nine enamel samples of the lingual side of a tooth, in which the dose was also formed by gamma radiation, were exposed to non-standard additional irradiation by x-rays. The results given in Table 2 (No. 4–6) showed that the reconstructed doses were lower than the applied by an order of magnitude.

Fig. 3 presents calibration straight lines of enamel samples of the buccal and lingual sides of one tooth, which were preliminarily exposed to gamma radiation with the applied dose of 500 mGy. The dose load was assessed by calibration straight line 2 with the help of additional gamma irradiation, and by line 1 with the help of x-rays. As seen from this figure, the dose calculated by line 2 was equal to 528.7 mGy, i.e., it practically coincided with the applied. At the same time, the dose calculated by line 1 was equal to 68.1 mGy, i.e., it was lower than the applied by an order of magnitude.

Table 2. Applied and reconstructed doses. Applied doses were formed due to irradiation of the buccal and lingual side of a tooth by gamma radiation. Doses reconstructed by EPR tooth enamel spectra were obtained by additional irradiation by gamma radiation (1–3) and x-rays (4–6).

No.	Applied dose, D_{ap}, mGy	Reconstructed dose, D_r ± sem, mGy	Ratio between reconstructed and applied doses
1	100	158.0 ± 32.6	1.6
2	250	272.6 ± 25.6	1.1
3	500	506.3 ± 28.2	1.0
4	100	29.6 ± 11.6	0.3
5	250	19.9 ± 12.0	0.1
6	500	35.5 ± 22.4	0.1

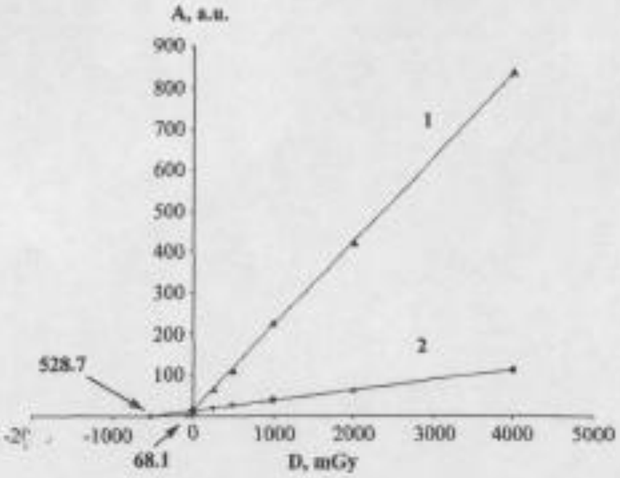

Fig. 3. Additive-dose method. Calibration straight lines and doses reconstructed by EPR tooth enamel spectra of the buccal and lingual sides of one tooth. Each half of a tooth was exposed to gamma radiation with the applied dose of 500 mGy. Additional irradiation of enamel samples was performed by: (1) x-rays; (2) gamma radiation.

DISCUSSION

The analysis of the EPR spectra in Fig. 1 shows that, with equal applied dose, the amplitude of the radiation signal induced by x-rays exceeded that induced by gamma radiation by an order of magnitude. This dependence of the EPR signal intensity on electromagnetic radiation energy was clearly seen on calibration straight lines (Figs. 2 and 3). When comparing these two figures, it is first of all obvious that the intensity of dosimetric signals of initial spectra (it corresponds to the point of intersection of calibration straight lines with the ordinate-axis in both the figures) calculated by the computer program "Tooth enamel-3," was approximately 10 times larger in Fig. 2 than in Fig. 3. Second, the inclination of calibration straight lines to the abscissa-axis (coefficient of individual radiation sensitivity) of calibration straight lines 1 (non-standard additional x-ray irradiation) was considerably larger as compared with that of calibration lines 2 (standard additional gamma irradiation). These two reasons account for the discrepancy in the applied and reconstructed dose values with the electromagnetic radiation of different energy used for dose formation and for the additional irradiation, as well as for the coincidence of these dose values in the case when the electromagnetic radiation of equal energy was used.

Analysis of the obtained results of dose reconstruction in the population of citizens of Belarus affected by the Chernobyl accident showed a considerable range of exposure dose values (Kirillov et al. 2006). In particular, the exposure doses ranged from 200 to 300 mGy in more than 60% of liquidators, but there were some individuals with the dose-load reaching 400, 570, and even 750 mGy. Studying their case histories from Dental Polyclinics revealed that they had undergone diagnostic x-ray examination of the maxillodental system performed using modern x-ray apparatus with effective x-ray energy of 34 keV. In the first case, the people's teeth were examined; in the second the jaw was examined; and in the third the skull was examined. The combined effect of the emergency gamma irradiation and x-rays led to a considerable increase in the individual absorbed dose estimated by the EPR tooth enamel spectra. These data are consistent with the results obtained in the presented work.

CONCLUSION

It has been demonstrated that when the dose in tooth enamel is formed due to x-rays and the additional irradiation of tooth enamel samples is performed by gamma radiation, it leads to a considerable increase in the absorbed dose reconstructed by EPR spectra as compared with the applied.

In this case, when the dose is formed due to gamma radiation and the additional irradiation is performed by x-rays, it results in a considerable decrease in the reconstructed dose as compared with the applied. When the dose formation and the additional irradiation are performed from external sources of electromagnetic radiation of equal energy, the value of reconstructed dose is close to the applied one.

The obtained data show that for adequate reconstruction of individual absorbed doses by EPR tooth enamel spectra, it is necessary to take into account the contribution from diagnostic x-ray examination of the teeth, jaw, and skull of some individuals who were exposed to a combined effect of the external gamma radiation and x-rays.

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