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X-ray and gamma-ray absorbed dose profiles in teeth: An EPR and modeling study

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Abstract

Dose profiles in teeth have been experimentally and theoretically studied for different energies and geometries of incident X- and gamma-rays. The experiments were conducted with teeth inside of an Alderson phantom using monodirectional radiation beams at selected energies; they revealed two effects: an apparent lack of dose attenuation between the buccal and the lingual sides of the teeth for energies higher than 120 keV and an attenuation between first and last tooth layers for low-energy beams in the range from 0.28 to 0.57. Monte Carlo simulations confirmed the experimental data and provided dose profiles for other energies and geometries. In particular, exposure in the rotational radiation field produces pronounced dose profiles only for energies lower than 60 keV. The usefulness of these data to estimate the average energy of accidental radiation field is discussed.

1. Introduction

The energy of the incident gamma radiation is considered to be a factor that influences the accuracy of the electron paramagnetic resonance (EPR) dose reconstruction technique with teeth. Frequently the spectrum of the gamma field is unknown and assumptions are needed to convert the EPR-reconstructed tooth enamel doses into some reference values and/or doses for other organs and tissues (Takahashi et al., 2001, 2002; Wieser et al., 2002; Ulanovsky et al., 2005).

As is well known (Aldrich and Pass, 1986), the attenuation of the photon radiation passing through teeth varies with the photon energy from several percent for energies of hundreds of keV to several tens of percent or more for energies of a few tens of keV—resulting in different dose profiles in the teeth (Sholom et al., 2001). Presumably, these differences can provide information on the energy of accidental exposure and could be assessed directly from EPR measurements of dose profiles in teeth. To address the reliability of these assessments, experimental and theoretical results of dose profiles in teeth for different radiation energies and different angles of incident radiation are presented. The dose profiles in teeth were generated through irradiation of a human phantom using radiation sources of gamma- and X-rays. These profiles were used to verify subsequent Monte Carlo calculations.

2. Materials and methods

2.1. Experiment

Teeth were placed in layer 6 of the head of an Alderson phantom (Fig. 1(a)). The white label in this figure indicates the area to which the incident beam was directed. The radiation was always directed to the phantom's left side where three teeth in the lower molar positions 6–8 were mounted. One tooth was placed at the right side in molar position 8. The details of the tooth locations in the phantom are shown in Fig. 1(b).

The beams were effectively parallel with an entry diameter larger than 20 cm. The radiation sources used included two sources of gamma rays (Co-60 and Cs-137, with average gamma energies of 1250 and 662 keV, respectively), and five X-ray beam qualities: H250 (with an effective energy of 211 keV), H150 (120 keV), H60 (46 keV), H50 (38 keV), and M60 (34 keV). The beam qualities consist of a letter M or H

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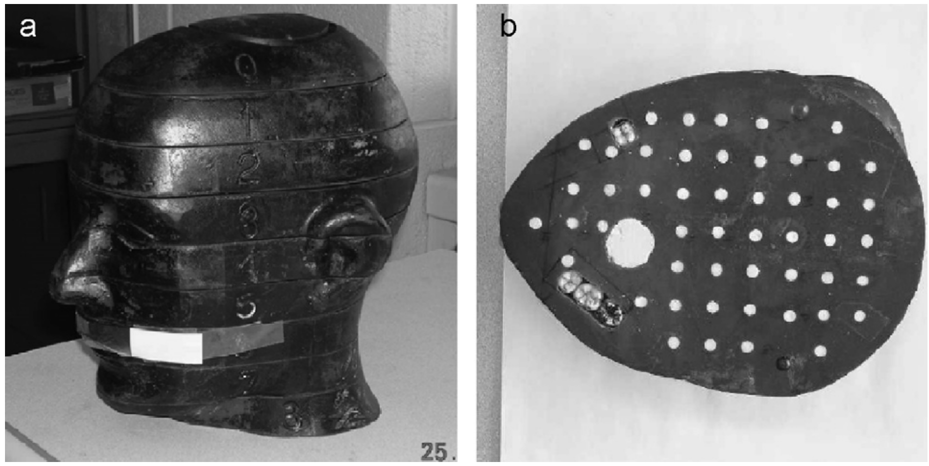

Fig. 1. (a) Picture of a phantom head used in the dose profile study. Teeth were placed in layer 6. White label indicates the position of beam incidence. (b) The phantom layer 6 with teeth inside. Regular white circles throughout the slice are plastic plugs for TL dosimeters that were not used in the present study.

(for moderate and heavy filtration, respectively) followed by the generating X-ray tube constant potential in kilovolts (Lamperti and O'Brien, 2001). For each spectrum, the four teeth were exposed, then cut into 2.5 mm layers and analyzed by EPR. The dose profiles were plotted using layer-dose values and standard deviations averaged over the three left-located teeth.

2.2. Monte Carlo calculation

MCNP-4B code was applied to a mathematical human phantom ADAM (Kramer and Drexler, 1982). The phantom was modified in the area of teeth. Part of the bone tissue of the facial skeleton was removed, and replaced with new objects that modeled the tooth area. Two situations were modeled. The first was a simulation of the experiment and is shown in Fig. 2. One bone region 10 mm in width and 30 mm in height (area 1 in Fig. 2) was introduced, and the sub-areas 2 for modeling teeth 6–8 (left side) and 8 (right side) were separated and filled by a mixture of 20% of enamel and 80% of dentine with average density of 2.58 g/cm^3, representative of average tooth material. The shape of the introduced area was specified in such a way that the relative location of the added tooth material corresponded well to that used in the experiment (see Fig. 1(b)). Tooth 7 (left side) was additionally sliced into 2.5 mm layers, and dose profiles calculated for this tooth were compared with the measured values.

The second modeled geometry was closer to the real human anatomy: in the modified bone region described above all 32 teeth were modeled and filled with the tooth material mixture; 20 lateral teeth were sliced to 2.5 mm layers. This geometry was used for the calculation of angular and energy dependencies of dose profiles for different teeth.

A parallel photon beam 20 cm in diameter was selected as a source, with energy varying in the range from 20 keV to 1 MeV. Five different directions of incident radiation were calculated: the first was the same as in the experiments, the next four were AP, PA, LLAT and RLAT (acronyms of antero-posterior, postero-anterior, left lateral and right lateral).

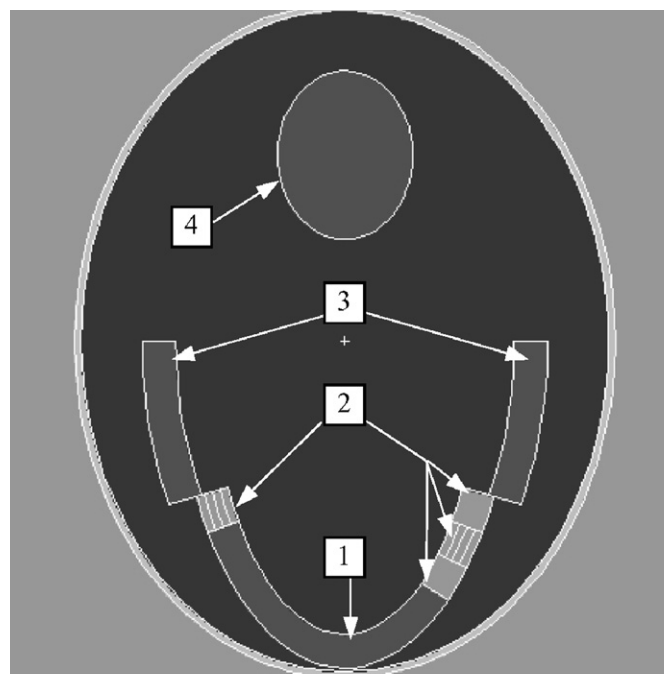

Fig. 2. Horizontal section of the mathematical phantom ADAM used for the Monte Carlo simulation: 1 is newly added bone-material dental section, 2 is an isolated area modeling tooth numbers 6–8 (left jaw), and number 8 (right jaw) and filled by average tooth material (see main text for details); tooth number 7 (left) is sliced to 2.5 mm layers for dose profile study; 3 and 4 are unmodified parts of the facial skeleton and spine correspondingly.

3. Results and discussion

The experimental dose profiles shown in Fig. 3 used two different normalizations, one to the dose of the 2.5 mm buccal layer for each specific spectrum (plot a) and the other to the dose of the 2.5 mm buccal layer of Co-60 irradiated teeth (plot b, all values were previously normalized on corresponding values of air kerma). The estimated uncertainties for EPR data in Fig. 3 were within 5% and 11% (1 sigma) for gamma- and

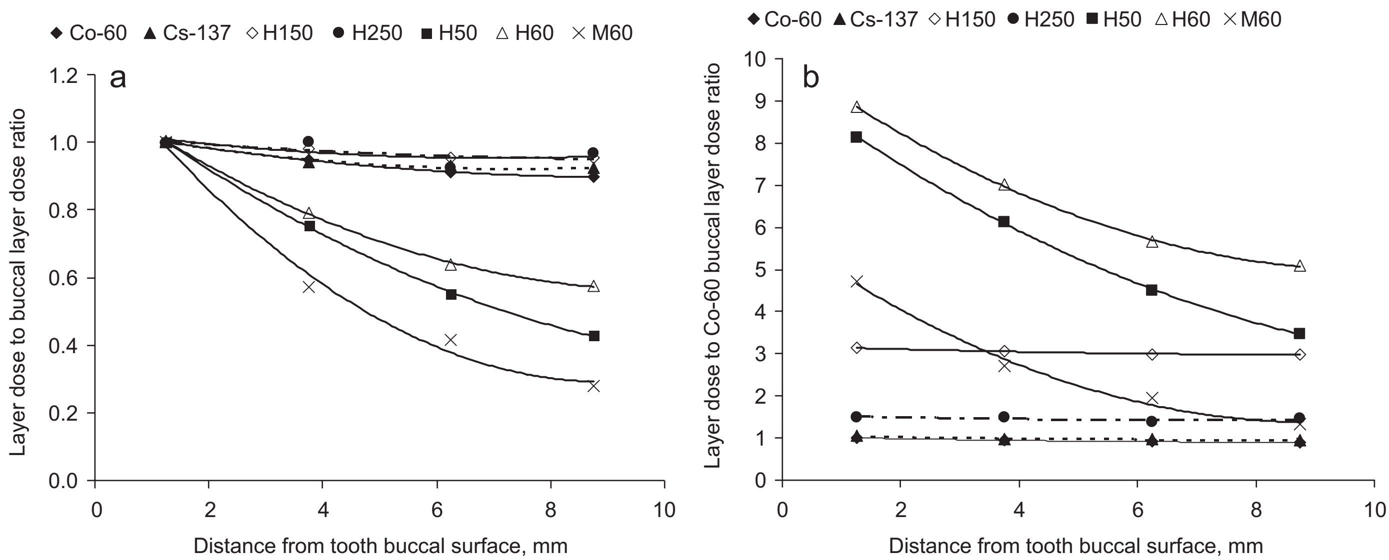

Fig. 3. Average dose profiles in teeth 6–8 LL for different gamma and X-ray beams. (a) Dose is normalized to the dose in the buccal 2.5 mm layer for specific spectrum. (b) Dose is normalized to the dose in the Co-60 irradiated buccal 2.5 mm layer (after normalization to the corresponding values of air kerma). Experimental points are fit with 2nd order polynomials.

X-ray sources, respectively. There are two apparent effects in Fig. 3: a practical absence of dose profiles for energies higher than 120 keV and an attenuation by a factor of about 2 between the first and the last tooth layers for low-energy H-beams.

These results may be explained by a large contribution of scattered radiation to the cumulative dose for teeth irradiated inside the phantom; this is confirmed by the Monte Carlo calculations.

The effect of the spectral distribution on the dose profile is more evident for low-energy X-ray beams (see Fig. 3). Among the beams studied, the strongest attenuation corresponds not to the beam with the lowest voltage studied (i.e. 50 kV for H50), but to a higher voltage beam with less filtration (M60). These results can be explained by examining the corresponding spectra (Fig. 4); obviously, the effective energy of the M60 spectrum is lower than that of H50.

Even steeper dose profiles are expected for spectra of existing dental X-ray machines because in these devices only low filtration is used. This assumption is in agreement with an experimental dose profile observed in Sholom et al. (2001) for typical dental X-ray machines in Ukraine, where dose attenuation between buccal and lingual parts was in the range of 3.3–9.

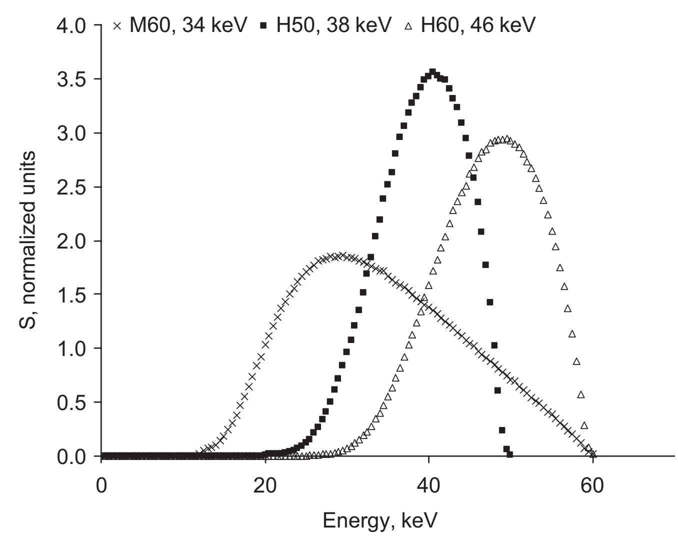

Fig. 4. Spectra of low-energy beams used in the present study. All spectra are normalized to the same area.

3.1. Comparison with the calculated values

The results of a comparison of the experimental and calculated dose profiles are shown in Fig. 5 for low-energy X-ray beams. The calculation of the X-ray dose profiles was conducted using spectra similar to those shown in Fig. 4. In all cases including the high-energy beams, an acceptable agreement was observed. Small deviations may be explained by: (1) the difference between experimental and modeled geometry of the phantom; (2) the difference between the X-ray spectra used in the experiments and those used in the calculations; and (3) the difference between the composition of the real teeth and the materials used in the Monte Carlo simulations.

3.2. Prediction of dose profiles for other irradiation geometries and energies

Results of dose profile calculation for different geometries and selected energies are shown in Tables 1 and 2. Two representative teeth were selected to exemplify the results: number 7 and number 4 from left lower jaw (7LL and 4LL), because their dose profiles were found to be typical for molar numbers 6–8 and premolar numbers 4–5, respectively. Some

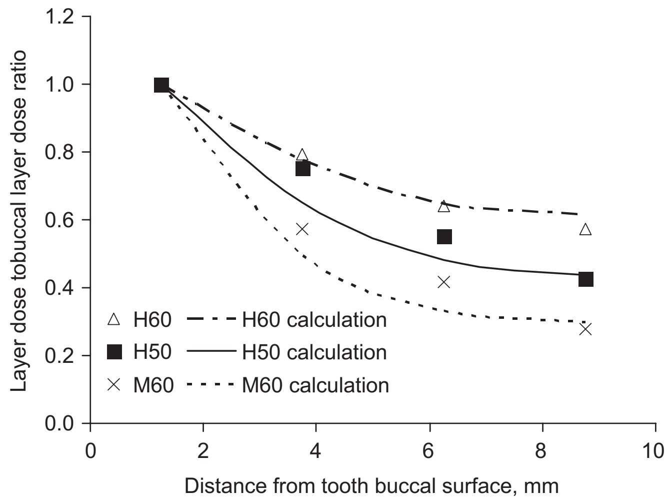

Fig. 5. Comparison of experimental and calculated dose profiles for low-energy radiation beams.

explanations should be given regarding the results presented in Tables 1 and 2:

- The values that are presented are the ratios of enamel doses to the air kerma;
- the numbering of the layers begins from 1 for the buccal side and ends with 4 for the lingual side; and
- the average geometry (last column) is an average over four calculated directions and is representative of the rotational exposure (ROT).

Due to symmetry of the phantom used, dose profiles for tooth numbers 7 and 4 from right lower jaw (7RL and 4RL) are the same as for teeth from 7LL and 4LL for AP, PA, and average geometries, and reciprocal for LLAT and RLAT geometries (i.e. dose profiles of teeth 7RL and 4RL in geometries LLAT and RLAT are the same as given in columns "RLAT" and "LLAT", respectively). Dose profiles of molars number 6 and 8 and premolar number 5 were similar to the dose profiles

Table 1
Dose profiles for tooth 7LU (7RU)

Geometry	AP				PA				LLAT				RLAT				Average			
Layer energy (Mev)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
0.02	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.01	0.00	0.00
0.03	2.55	0.44	0.16	0.21	0.01	0.01	0.01	0.05	3.83	1.33	0.52	0.33	0.02	0.02	0.04	0.13	1.60	0.45	0.18	0.18
0.04	5.16	2.35	1.42	1.44	0.14	0.12	0.18	0.41	6.45	3.95	2.68	2.27	0.23	0.28	0.45	0.83	3.00	1.68	1.18	1.24
0.05	6.60	4.34	3.34	3.33	0.45	0.43	0.58	0.94	7.49	5.75	4.77	4.45	0.82	0.94	1.22	1.81	3.85	2.87	2.48	2.63
0.06	6.70	5.27	4.51	4.54	0.74	0.75	0.90	1.25	7.30	6.23	5.60	5.49	1.33	1.49	1.81	2.41	4.02	3.44	3.21	3.43
0.07	5.97	5.09	4.66	4.67	0.87	0.91	1.07	1.36	6.34	5.72	5.32	5.27	1.52	1.70	1.99	2.50	3.68	3.36	3.27	3.45
0.08	5.28	4.70	4.38	4.39	0.91	0.94	1.10	1.34	5.53	5.16	4.89	4.86	1.58	1.74	2.01	2.41	3.33	3.14	3.10	3.26
0.10	3.82	3.60	3.45	3.47	0.84	0.88	0.96	1.14	4.01	3.85	3.67	3.72	1.38	1.51	1.72	1.97	2.52	2.46	2.45	2.58
0.15	2.18	2.09	2.05	2.02	0.61	0.63	0.69	0.77	2.26	2.22	2.17	2.16	0.94	1.02	1.13	1.22	1.50	1.49	1.51	1.54
0.20	1.63	1.55	1.51	1.50	0.49	0.51	0.56	0.61	1.66	1.63	1.61	1.59	0.76	0.82	0.88	0.96	1.14	1.13	1.14	1.16
0.30	1.28	1.22	1.17	1.14	0.43	0.45	0.49	0.52	1.31	1.29	1.25	1.23	0.65	0.69	0.73	0.76	0.92	0.92	0.91	0.91
0.60	1.08	1.03	0.99	0.95	0.47	0.48	0.51	0.54	1.09	1.07	1.05	1.02	0.64	0.66	0.69	0.71	0.82	0.81	0.81	0.81
1.00	1.02	0.98	0.95	0.92	0.53	0.54	0.56	0.60	1.04	1.02	1.00	0.98	0.68	0.70	0.71	0.73	0.82	0.81	0.81	0.81

Table 2
Dose profiles for tooth 4LU (4RU)

Geometry	AP				PA				LLAT				RLAT				Average			
Layer energy (Mev)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
0.02	1.36	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.77	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.01	0.00	0.00
0.03	5.05	1.53	0.55	0.41	0.00	0.00	0.01	0.02	3.84	1.07	0.36	0.23	0.02	0.02	0.04	0.13	2.23	0.66	0.24	0.20
0.04	7.61	4.57	3.04	2.61	0.05	0.07	0.11	0.20	6.23	3.46	2.17	1.73	0.21	0.28	0.45	0.87	3.51	2.09	1.44	1.35
0.05	8.33	6.46	5.39	5.04	0.21	0.24	0.34	0.52	6.98	5.16	4.08	3.71	0.69	0.90	1.25	1.96	4.05	3.19	2.77	2.80
0.06	7.84	6.85	6.28	6.14	0.38	0.44	0.55	0.76	6.67	5.55	4.84	4.60	1.19	1.48	1.97	2.68	4.02	3.58	3.41	3.53
0.07	6.70	6.21	5.90	5.86	0.48	0.56	0.66	0.84	5.70	5.06	4.62	4.52	1.41	1.77	2.16	2.71	3.57	3.40	3.34	3.47
0.08	5.79	5.51	5.36	5.37	0.52	0.60	0.69	0.85	4.90	4.52	4.29	4.22	1.49	1.81	2.18	2.70	3.18	3.11	3.14	3.28
0.10	4.10	4.00	3.96	4.04	0.50	0.58	0.63	0.73	3.56	3.34	3.23	3.22	1.35	1.58	1.83	2.17	2.38	2.38	2.42	2.53
0.15	2.26	2.29	2.26	2.24	0.39	0.43	0.47	0.52	2.01	1.95	1.90	1.87	0.93	1.05	1.18	1.31	1.40	1.43	1.45	1.48
0.20	1.71	1.69	1.68	1.65	0.34	0.37	0.40	0.44	1.56	1.53	1.48	1.44	0.75	0.85	0.94	1.04	1.09	1.11	1.13	1.14
0.30	1.36	1.34	1.31	1.29	0.32	0.34	0.36	0.37	1.26	1.23	1.19	1.16	0.67	0.74	0.79	0.85	0.90	0.91	0.91	0.91
0.60	1.14	1.12	1.09	1.06	0.38	0.40	0.41	0.42	1.09	1.06	1.02	0.99	0.66	0.72	0.76	0.79	0.81	0.82	0.82	0.81
1.00	1.07	1.06	1.02	1.00	0.46	0.47	0.48	0.48	1.04	1.02	0.99	0.96	0.70	0.75	0.78	0.80	0.82	0.82	0.82	0.81

of tooth number 7 and 4, respectively (the coincidence was within 10% for energies higher than 50 keV and slightly worse for lower energies). Dose profiles for the front teeth were not calculated because these teeth usually demonstrate strong UV solar exposure profiles and therefore are not used for EPR dose reconstruction.

There is a clear distinction between the calculated profiles for the average geometry compared to monodirectional. There are non-pronounced dose profiles for energies higher than 70 keV, and weakly pronounced dose profiles for lower energies. So, for the ROT geometry the range of energies that may be assessed from the dose profile measurements is narrower compared to monodirectional exposures.

4. Conclusion

An experimental study was conducted with teeth inside of an Alderson phantom using monodirectional radiation beams at selected energies. The study revealed two effects: an apparent lack of profile for energies higher than 120 keV (the observed attenuation of dose between the buccal and lingual sides was within 10%) and an attenuation between first and last tooth layers in the range from 0.28 to 0.57 for low-energy X-ray beams. Monte Carlo simulations confirmed the experimental data and generated dose profiles for other energies and geometries. In particular, exposure in the planar isotropic radiation field produced pronounced dose profiles only for energies lower than 60 keV. In case of monodirectional beams, pronounced dose profiles were obtained for higher energies.

These data may prove useful for a tooth exposed to radiation with an unknown spectrum, as it may be possible to use the corresponding dose profile to infer the average energy of spectrum. These data indicate that if dose profile is flat, it is possible only to conclude that the average energy is greater than 120 keV. If the profile is pronounced, it is possible to conclude that the average energy is lower than 120 keV, but its value will depend on the geometry of irradiation. In addition, if there are several sources that contribute to the absorbed dose profile, for example a high-energy gamma source superimposed with a low-energy X-ray source, the result will be less conclusive.

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References

Aldrich, J.E., Pass, B., 1986. Dental enamel as an in vivo radiation dosimeter: separation of the diagnostic X-ray dose from the dose due to natural sources. Radiat. Prot. Dosim. 17, 175–179.

Kramer, R., Drexler, G., 1982. On the calculation of the effective dose equivalent. Radiat. Prot. Dosim. 3, 13–24.

Lamperti, P.J., O'Brien, M., 2001. Calibration of X-ray and gamma-ray measuring instruments. NIST Special Publication, vol. 250-58, 98pp.

Sholom, S.V., Chumak, V.V., Bakhanova, E.V., 2001. Assessment of contribution of confounding factors to cumulative dose determined by EPR of enamel. In: Kawamori, A., Yamauchi, J., Ohta, H. (Eds.), EPR in the 21st Century: Basics and Applications to Material, Life and Earth Sciences, Proceedings of the Third Asia-Pacific EPR/ESR Symposium, Kobe, Japan, pp. 628–633.

Takahashi, F., Yamaguchi, Y., Iwasaki, M., Miyazawa, C., Hamada, T., 2001. Relations between tooth enamel dose and organ doses for electron spin resonance dosimetry against external photon exposure. Radiat. Prot. Dosim. 95, 101–108.

Takahashi, F., Yamaguchi, Y., Iwasaki, M., Miyazawa, C., Hamada, T., Saito, K., 2002. Conversion from tooth enamel dose to organ doses for electron spin resonance dosimetry. J. Nucl. Sci. Technol. 39, 964–971.

Ulanovsky, A., Wieser, A., Zankl, M., Jacob, P., 2005. Photon dose conversion coefficients for human teeth in standard irradiation geometries. Health Phys. 89, 645–659.

Wieser, A., Aragno, D., El-Faramawy, N., Fattibene, P., Meckbach, R., Onori, S., Pressello, M.C., Pugliani, L., Ulanovsky, A., Zankl, M., 2002. Monte Carlo calculation and experimental verification of the photon energy response of tooth enamel in a head-size Plexiglas phantom. Radiat. Prot. Dosim. 101, 549–552.