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MONTE CARLO CALCULATIONS OF THE DOSE DISTRIBUTION IN TEETH DUE TO INTERNAL EXPOSURE FROM ^{90}Sr: APPLICATION TO EPR TOOTH DOSIMETRY

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Abstract — This paper addresses issues in the application of the electron paramagnetic resonance (EPR) retrospective dosimetry with dental tissues exposed by radionuclides accumulated in the dentin. A simple dosimetric model of a tooth incorporating ^{90}Sr is presented. The tooth is modelled as two concentric cylinders: the inner cylinder composed of dentin, and the outer cylindrical shell of enamel. Extensive Monte Carlo calculations were done to obtain the distributions of absorbed dose in dentin and enamel for teeth of different sizes. The results were used to calculate the mean absorbed doses in enamel that are directly measurable by EPR. A relationship between such measured doses and the specific activity of ^{90}Sr in dentin was derived based on a simple model of ^{90}Sr accumulation. The roles of different tooth tissues as dose detectors are analysed, and the importance of dentin as a dosimetric material for internal exposure is pointed out.

INTRODUCTION

Electron paramagnetic resonance (EPR) dosimetry with teeth has proved to be a reliable technique of retrospective dose reconstruction. The method is based on measurements of concentrations of stable free radicals produced by radiation in the mineral component of the dental calcified tissues, namely, hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$. The principles of this method and results of its application have been described in many publications (see, e.g., References 1–8). EPR dosimetry with tooth enamel has been applied to reconstruction of doses from the atomic bomb explosions in Hiroshima and Nagasaki[1,9], from the Chernobyl accident[10], and from workplace exposures of South Urals nuclear workers[3]. A number of blind intercomparisons[11–14] have demonstrated that absorbed doses in tooth enamel can, in most cases, be accurately measured by EPR.

Until recently, EPR tooth dosimetry has been applied primarily to the relatively simple case of external high energy irradiation. The rather uniform radiation fields typically associated with such irradiations, combined with the negligible attenuation of the radiation by body tissues, results in a fairly uniform dose and the radical concentration throughout the tooth enamel. Similar conditions are reproduced in additional, controlled laboratory irradiations that can provide an accurate assessment of the initial dose using the back-extrapolation technique. External high energy irradiation provides roughly the same doses in teeth as in other, more important, organs, including bone marrow. Therefore, doses in tooth enamel measured with EPR can be used by radiation biologists and epidemiologists in a fairly straightforward way.

The problem of dose reconstruction becomes far more difficult when the irradiation is to a significant extent or exclusively from emitters internal to the body and the radiation energy is not very high. A typical example of this is internal irradiation from ^{90}Sr, which is accumulated in bones and dentin and emits beta particles with a penetration range in tooth enamel of just 1–2 mm (see Table 4), comparable to the enamel thickness. In such cases, the distribution of absorbed dose in the tooth enamel (as well as in the dentin) is not uniform, and its specific pattern depends on the sizes and shapes of the dentin and enamel constituents, as well as on the radiation energy. Accordingly, the concentration of radicals producing the EPR signal is also non-uniform, and application of the usual techniques of sample preparation results in a difficult-to-estimate degree of dilution of the highly irradiated enamel parts with the enamel that received much lower doses. As a result of these complications, doses estimated directly from the average EPR signal in the standard way are not very meaningful. Thus doses reconstructed from tooth enamel of two different-size teeth of the same person may be considerably different, and, even when these values are close to each other, they cannot be converted to the dose to more important organs, such as bone marrow, as easily as in the case of an external high energy irradiation. For this reason, dose reconstructions with EPR in cases of internal radiation have been rather limited so far[4,15].

Strontium-90 is one of the most hazardous radionuclides for humans among those released from anthropogenic sources because of the combination of the fol-

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lowing three factors: (i) a significant decay energy, (ii) a long lifetime in the human body (its biological half-life in the body is about 20 y), and (iii) rapid accumulation in the body's calcified tissues from the contaminated environment. The accumulation is very effective because ^{90}Sr is chemically similar to calcium, and substitution occurs within tissues in the human body (bone and teeth). This radionuclide in the environment is especially dangerous in adolescence, when the skeleton rapidly consumes a lot of calcium to increase the bone mass. Strontium-90 can be presented to the body from a number of sources, including intentional releases by nuclear plants, radiation accidents and weapon test fallout.

One of the most interesting cohorts in the world from the viewpoint of radiation epidemiology is the population of the Techa riverside in Russia, who received large radiation doses (over 1 Gy in some cases) due to continual consumption of the river water that contained highly radioactive releases from the first Soviet nuclear plant Mayak[16]. For many of these people, the doses received are mostly due to long-lived ^{90}Sr. A comprehensive review of the available information on ^{90}Sr content in teeth and skeletons for the Techa riverside population has been made recently by Tolstykh and coworkers[17]. At present, doses from the internal ^{90}Sr irradiation are estimated mostly from the results of whole-body counting; however, this method has certain weaknesses discussed below. Therefore, development of an alternative technique for retrospective dosimetry for this case would be very helpful. The study reported in this paper was motivated by the need to interpret the results of an EPR dose reconstruction for the population of the lower and middle Techa riverside performed earlier[4,15] and of an EPR study of calcified tissues from a dog injected with ^{90}Sr[18]. Recently results of the model calculations described in the present paper were applied to the correction of the radiation doses measured by EPR in tooth-enamel samples prepared from the teeth of near 100 Techa riverside residents[19], where they reduced or eliminated some serious inconsistencies in the experimental results.

TOOTH AS AN EPR DOSIMETRIC SYSTEM

Reconstruction of doses from internal or mixed irradiation requires a deeper insight into the anatomy and physiology of a tooth than was sufficient for reconstructing external doses. This section provides a summary of such information compiled from the books by Bhaskar[20], Driessens and Verbeeck,[21] and Graber[22].

Anatomically the tooth consists of two parts: the crown (the upper part of the tooth covered with enamel) and the root (the lower part providing attachment of the tooth to the gum and jawbone) (Figure 1). The root is covered with cementum. There is a cavity called the pulp channel inside the tooth where the soft tissue pulp is located.

From the EPR dosimetric viewpoint, the important components of a tooth are its calcified tissues, namely, tooth enamel, dentin, and cementum. Because of the differences in their chemical compositions and the associated metabolic processes, these three dental tissues accumulate different dosimetric information, and they have different scales and fields of application in EPR retrospective dosimetry. From the chemical point of view, all the calcified tissues are basically compositions of the same three components, mineral hydroxyapatite, water, and organic matter, although their relative concentrations vary significantly. Hydroxyapatite, the component in which the stable free radicals accumulate and that stores the information on the absorbed dose, constitutes 95–97% of tooth enamel, 70–75% of dentin, and 50–60% of cementum.

Tooth enamel is composed of hydroxyapatite needle crystallites about 0.5–0.6 μm long dispersed in an aqueous-organic gel. This is the only human tissue without a cellular structure. Due to this, metabolism in mature tooth enamel is extremely weak, and the chemical composition of the enamel is very stable.

In contrast to tooth enamel, dentin has a cellular structure and, therefore, participates in metabolism to a much larger degree. The organic component of dentin consists of collagenous fibrils and a ground substance of mucopolysaccharides. Hydroxyapatite crystals (about 0.04 μm) cover the individual collagen fibres. The cellular structure of dentin is quite specific: the dentin cells (odonoblasts) are located outside of dentin, on its pulpal surface (Figure 1). Every odonoblast has one branch (cytoplasmic extension), the so-called tubule, which traverses the entire dentin layer to terminate at the junction with the enamel or cementum. In the mature tooth, all living processes occur in the dentinal tubules. Deposition of dentin continues throughout the human life, although this process is much slower after the tooth eruption. The parts of dentin formed after eruption are

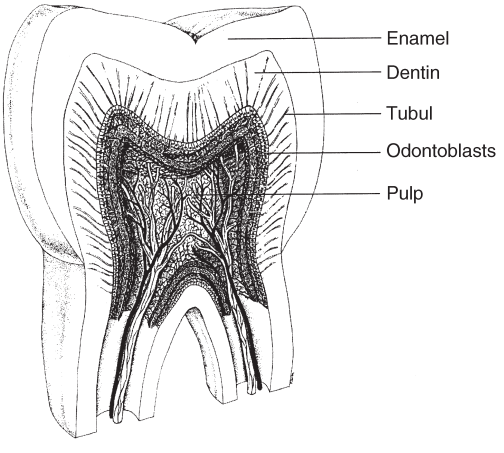

Figure 1. Schematic of a human tooth. Reproduced with permission from Reference 20.

often called secondary dentin, and, in cross sections, they are separated from that previously formed primary dentin by a dark stained line. Secondary dentin is deposited on the entire pulpal surface, and it is best observable in premolars and molars. In the pulpal chambers of these teeth, deposits of the secondary dentin on the ceiling are much larger than on the walls. The growth of dentin can be thought of roughly as a process similar to development of tree rings. However, unlike tree rings, the largest 'core' portion of dentin is the initial primary dentin with a low mineral turnover. This part of dentin loses virtually none of the accumulated calcium. Bone-seeking radionuclides supplied to the body after the tooth is erupted are accumulated primarily in the secondary dentin with only minute absorption in the primary dentin near the tubules.

The third calcified tissue of tooth is cementum. This connective tissue serves as a membrane between the gum and the tooth root. The portion of organic matter in this tissue, the highest as compared with tooth enamel and dentin, reaches 50%. The mineral turnover in cementum is relatively high.

The differences among the calcified tissues of teeth in the degree of the involvement in metabolism are of great importance for EPR dosimetry. Tooth enamel is hardly involved, and, thus, is not able to absorb bone-seeking radionuclides to any noticeable degree, unless their supply into the body coincides with the relatively short period of the enamel formation. Hence, it can be irradiated only from outside, in particular, by radionuclides residing in the other parts of the tooth. From internal irradiation from osteotropic radionuclides with limited depth of penetration, absorbed doses in tooth enamel are usually lower than the absorbed doses in the other calcified tissues. Dentin participates in metabolism to a much greater extent, and, therefore, can absorb ^{90}Sr coming into the body not only in the period of its pre-eruptive formation, but also when the tooth is in the mature state. However, new supplies are presumably accommodated mostly in the secondary dentin. Therefore, ^{90}Sr-containing dentin irradiates both itself and the neighbouring tissues, including enamel. The dentin dose from bone-seeking radionuclides is typically higher than to the enamel. Root dentin has the highest absorbed dose, because the growth of the secondary dentin in the root is more extensive than in the crown and, additionally, the root gets significant external irradiation from the adjacent bone. The high chemical turnover in cementum makes this tissue unsuitable for reconstructing doses received long ago, but, in terms of radionuclide accommodation and geometry of irradiation, it behaves rather like compact bone. Thus, the differences between enamel, crown dentin, root dentin, and cementum in terms of their accessibility for radionuclides, the degree of radionuclide turnover, spatial distribution of the radionuclides, and the resulting differences in the intensity of EPR signals are very important factors to consider in selecting an appropriate tissue for dose reconstruction in each particular case.

An important issue regarding biokinetics in teeth and bone was studied in the extensive experimental work of Goldman *et al*[23,24], based on more than 500 beagles reared for 1.5 years on diets containing ^{90}Sr and subsequently followed over a period of 12 years. Their results showed that while the skeleton exhibited a considerable reduction in retained ^{90}Sr after discontinuing ^{90}Sr ingestion, due to bone remodelling, the teeth had a very small change in ^{90}Sr content. This suggests the nearly exclusive suitability of teeth for the reconstruction of previous ^{90}Sr intake.

The other important aspect is the difference in the EPR signals of the tooth components. Qualitatively, the EPR spectra of irradiated tooth enamel, dentin, and cementum are similar. In all these cases, the useful, dose-dependent signal is due mainly to the extremely stable ion radicals CO_2^-[25] that are produced by radiation from the diamagnetic carbonate ions occurring in hydroxyapatite as impurities. The interfering, radiation-irrelevant, background signal comes mainly from the organic components of the calcified tissues[26]. However, there are significant quantitative differences.

As expected, the relative usefulness of the three calcified tissues for EPR dosimetry depends on the relative amounts of hydroxyapatite and the organic matter in these tissues, as well as on the concentration of the carbonate precursors in hydroxyapatite. The average carbonate contents of hydroxyapatite in tooth enamel, dentin, and cementum are 3.2% (dry weight), 4.6% (dry weight), and 6–10%, respectively[21]. However, because the concentration of the organic matter in tooth enamel is the lowest (about 1%), and the concentration of hydroxyapatite is the highest, this material would seem to offer the best opportunity for dose reconstruction: the background signal is the weakest in this case, and the resolution of the two signals in question is, therefore, the best. As a result, the detection limit achievable with tooth enamel is the lowest among the calcified tissues: a recent direct experimental estimate produced the value of 29 mGy at 95% confidence level[27]. Dentin and cementum, with their much higher organic matter concentrations, exhibit roughly 10-fold stronger native signals, which hampers their use in reconstructing doses lower than a few gray without special chemical treatment to dissolve the organic component[28,29]. One has to take these important differences into account when the anatomical and physiological properties discussed above suggest that a non-enamel material would, in principle, provide better information on the internally received dose than would tooth enamel.

In summary, for the case of internal irradiation, the tooth represents a somewhat complex system for retrospective EPR dosimetry. The complexity stems from both the spatial and the chronological non-uniformity. In addition to the possibly (and most probably) varying supply of a radionuclide into the teeth during its life-

time, there is the simultaneous partial removal from the teeth due to turnover. The removal rate in each particular microscopic area of a material may change in time, for example, as a result of dentin growth. At any moment, the distribution of a radionuclide within the tooth as a whole and even within a selected constituent is not uniform. If the energy of radiation (and, hence, its penetration depth) is not very high, the dose distribution is non-uniform even if the radionuclide is distributed uniformly over one of the calcified tissues, e.g. dentin.

Obviously, the problem of such a degree of complexity cannot be solved completely, and simplified approaches based on idealised models are inevitable. In this particular work, we largely ignore the temporal factors and focus mostly on the spatial non-uniformity. The goal is to develop procedures for relating the absorbed doses in enamel and in dentin to more meaningful 'normalised' characteristics that would then be comparable for different teeth of the same or different persons. If successful, such procedures would be useful in future models relating doses in dental tissues to doses in other organs.

To achieve this goal, we need quantitative information on dose profiles in tooth enamel. We have obtained such profiles for a simplified model of a tooth using Monte Carlo calculations. Similar problems for different geometries that are typical for EPR dating were addressed by Grün *et al*[30], Brennan *et al*[31], and Yang *et al*[32].

MONTE CARLO MODEL

The tooth was modelled as two concentric cylinders: the inner cylinder composed of dentin, and the outer cylindrical shell composed of enamel (Figure 2). Accordingly, only crown dentin and enamel are taken into consideration; root dentin and cementum are ignored in this model. The dimensions of the dentin cylinder were associated with representative dimensions of crown dentin in various tooth positions (Table 1). Such a very simplified model of the tooth does not fully take into account the rather more complicated morphology of dental tissues discussed above. However, it allows one to take advantage of the cylindrical symmetry, which makes the calculations much more efficient. Therefore, the results obtained are applicable mainly to teeth whose shapes are similar to cylinders, such as molars and premolars. This does not seem a serious limitation as front teeth are rarely used in EPR tooth dosimetry both because of sun exposure[33] and because of the relatively small amount of available tooth enamel. Some estimates of the uncertainties in our results due to the deviation of teeth from cylinders are given later.

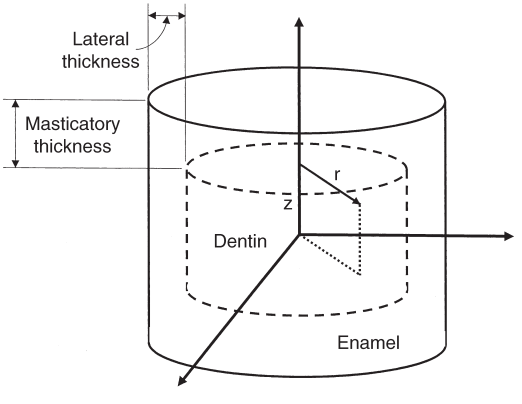

Figure 2. Simplified model of the tooth, composed of an inner cylinder of dentin and an outer concentric cylindrical shell of enamel.

A uniform, isotropic source of electron emission from $^{90}Sr/^{90}Y$ decay was assumed in the dentin cylinder. Thus, it was assumed that the radionuclide uniformly occupies only the dentin volume so that the emitted radiation must cross into the enamel shell to deposit energy there. No other sources of radiation were taken into account. These assumptions appear founded for the case of the residents of the middle and lower Techa riverside, who were irradiated mostly internally from radionuclides consumed from the river water[4,15]. From the composition of the radioactive waste released into the river (Table 2) it follows that most of the irradiation over the years was provided by $^{90}Sr/^{90}Y$, and that the primary location of the parent bone-seeking ^{90}Sr, from which enamel was irradiated, was dentin.

The assumed composition of the dental tissues used in the calculations is given in Table 3. Estimates are given in Table 4 of the radial distances from a point source of $^{90}Sr/^{90}Y$ (assumed in secular equilibrium) within which various fractions of the decay energy are absorbed in such materials. Results are based on beta spectra calculated from the LOGFT program[34] in conjunction with the Evaluated Nuclear Structure Data File from the National Nuclear Data Center, Brookhaven National Laboratory. The spectra are consistent with those given by Cross *et al*[35] and in ICRU Report 56[36]. Some characteristic parameters used for $^{90}Sr/^{90}Y$ decay are given in Table 5.

The Monte Carlo calculations of the transport of electrons and secondary photons were done with the CYLTRAN code from the Integrated Tiger Series (ITS), version 3.0[37]. The ITS transport physics and cross sections are based on the ETRAN code for coupled electron–photon transport[38–40], and take into account in a rather accurate way the diffusion and slowing down of all radiations in the electron–photon cascade established in the media. A straightforward code change was made in CYLTRAN to enable sampling from the source assumed in the chosen model. A cylindrical shell of enamel assumed to extend 2 mm beyond the dentin cylinder was found to capture nearly all of the resultant absorbed dose (Table 4). The absorbed dose was scored

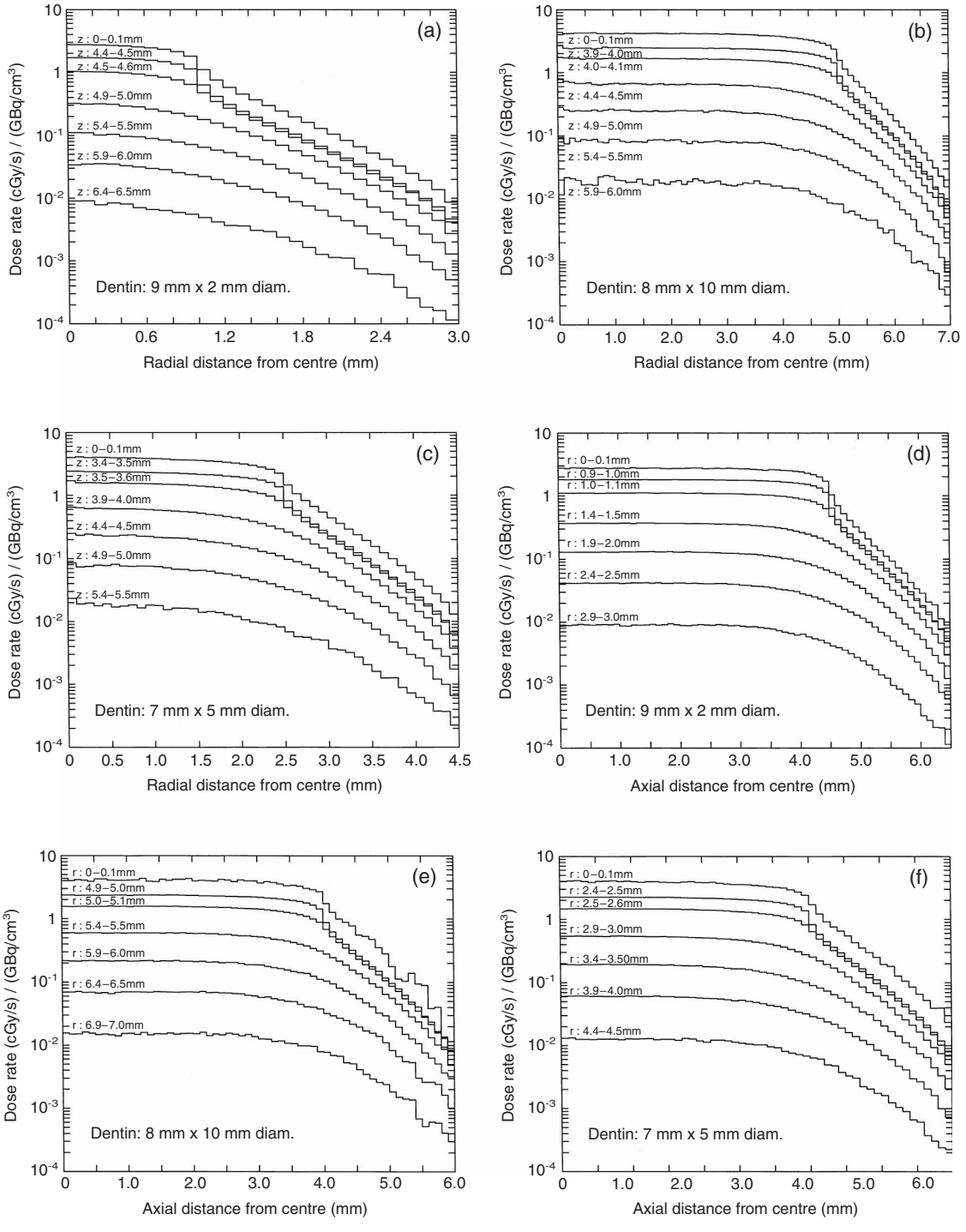

Figure 3. Spatial distributions of absorbed dose rate in tooth tissue, for an assumed uniform distribution of $^{90}Sr/^{90}Y$ in the dentin. (a) Radial distribution for a 9 mm × 2 mm diameter dentin cylinder. (b) Radial distribution for a 8 mm × 10 mm diameter dentin cylinder. (c) Radial distribution for a 7 mm × 5 mm diameter dentin cylinder. (d) Axial distribution for a 9 mm × 2 mm diameter dentin cylinder. (e) Axial distribution for a 8 mm × 10 mm diameter dentin cylinder. (f) Axial distribution for a 7 mm × 5 mm diameter dentin cylinder.

throughout the double cylinder in annular rings of 0.1 mm in height and 0.1 mm in radial thickness. Although each calculation had to be made for specific dimensions of the dentin, it is assumed that the distribution of absorbed dose in an enamel layer less than 2 mm thick would not be greatly affected by the presence of a real boundary. This assumption is perhaps justified to the extent of the only modest effect (see Figures 5(a) and (b)) apparent in the absorbed-dose distribution near the enamel/vacuum interface at 2 mm. An actual tooth would likely have tissue or the enamel of other teeth in close proximity in many directions, at least partially mitigating enamel/vacuum interface effects (note, however, that the presence of high-Z restorations and structures could introduce other, more severe, interface effects).

Calculations were performed for 16 different dentin cylinder dimensions whose heights and diameters ranged from 2 to 10 mm. All results are based on a sample of 15M histories of emitted beta particles. Because of the geometry assumed for the calculation, the

Table 1. Representative dimensions of human teeth.

Tooth position	Crown dentin dimensions h×d (mm)	Enamel thickness (mm)	
		Lateral surface	Masticatory surface
Upper jaw			
4 (1st premolar)	7×6	0.5	0.6
5 (2nd premolar)	7×5	0.6	0.5
6 (1st molar)	5×4	1.3	2.0
7 (2nd molar)	6×10	0.65	0.70
8 (3rd molar)	5×9	0.60	0.75
Lower Jaw			
4 (1st premolar)	8×4	0.5	0.5
5 (2nd premolar)	7×6	0.7	0.7
6 (1st molar)	5×5	1.2	1.5
7 (2nd molar)	8×10	0.6	0.75
8 (3rd molar)	8×10	0.6	0.75

Table 2. Composition of radioactive wastes released into the Techa river.

Radioisotope	Radioisotope abundance (%)
^{90}Sr	11.6
^{89}Sr	8.8
^{137}Cs	12.2
^{95}Zr, ^{95}Nb	13.6
^{103}Ru, ^{106}Ru	25.9
Rare-earth elements	26.9

Table 3. Assumed composition of dental tissues.

Element	Atomic number	Fraction by weight	
		Dentin	Enamel
H	1	0.030773	0.009788
C	6	0.113246	0.014743
N	7	0.025240	0.001298
O	8	0.361391	0.419226
F	9	0.000170	0.000130
Na	11	0.002000	0.006000
Mg	12	0.011000	0.004000
Si	14	0	0.000030
P	15	0.150000	0.175000
Cl	17	0.000300	0.002500
K	19	0.000700	0.003000
Ca	20	0.305000	0.364000
Fe	26	0	0.000025
Cu	29	0	0.000100
Zn	30	0.000180	0.000160
Density, ρ (g.cm^{-3})		2.14	2.95

Table 4. Estimated percentile radial distances, in mm, in dental tissues within which various percentages of the decay energy of a point source of ^{90}Sr/^{90}Y are absorbed.

Percentage (%)	Percentile distance (mm)	
	Dentin	Enamel
10	0.1	0.1
30	0.4	0.3
50	0.8	0.6
70	1.4	1.0
90	2.3	1.6
95	2.7	1.9
98	3.2	2.3

Table 5. Parameters of ^{90}Sr and ^{90}Y beta decay. E_{max} is the end-point energy of the emitted beta spectrum; E_{av} is the average beta energy emitted; and the probabilities per disintegration are calculated for ^{90}Sr and ^{90}Y assumed to be in secular equilibrium.

Nuclide	Physical half-life, $T_{1/2}$	E_{max} (MeV)	E_{av} (MeV)	Probability (dis^{-1})
^{90}Sr	29.12 y	0.546	0.1958	0.49994
^{90}Y	64.1 d	2.279	0.9326	0.49998*
^{90}Sr/^{90}Y	29.12 y	2.279	0.5642	0.99992*

*This result reflects the neglect of a low energy beta transition that occurs in 0.016% of ^{90}Y decays.

absorbed dose distribution is a function only of the radius r and the height z in the cylinders, and is symmetric about a plane bisecting the axis of the cylinders (see Figure 2). Thus, the results could be averaged over corresponding positive and negative axial distances z, measured from the centre of the cylinders. Complete information on the distribution of absorbed dose in the dentin and in the enamel is rather voluminous, so only illustrative and summary information will be given here.

CALCULATED RESULTS

Beta particles emitted in the dentin of course will deposit energy in the dentin itself and in the neighbouring regions of enamel. The resultant absorbed dose distribution is expected to be non-uniform in both materials: in the dentin near the dentin/enamel interface because of the net leakage of energy into the enamel, and in the enamel because of the increasing attenuation with increasing distance from the interface. In Figures 3(a–f) are shown the calculated distributions of absorbed dose rate in the tooth model for three of the assumed dentin sizes. There are marked differences in the distributions of absorbed dose at the dentin/enamel interfaces, while the distributions away from the interfaces tend to have similar shapes. All results are given in terms of the absorbed dose rate per unit specific activity, and so represent the absorbed dose distributions for a fixed concentration of ^{90}Sr/^{90}Y in dentin. Thus we will use absorbed dose rate and absorbed dose interchangeably when there is little possibility of confusion.

Uncertainties in the basic Monte Carlo calculations, aside from those associated with the assumed compositions and the applicability of the results to real teeth, include an estimated 3–4% associated with the accuracy of cross sections and of algorithms, along with statistical uncertainties associated with the scored results. For example, the results shown in Figures 3(a–f) of the spatial distribution of absorbed dose throughout the tooth have standard deviations from about 1% to about 20%, depending on the magnitude of the dose in the small annular scoring volumes (the uncertainty increases as the dose decreases). However, averages over these distributions have far smaller statistical uncertainties. Thus the doses averaged over the entire dentin region have statistical uncertainties of a small fraction of one per cent, and doses averaged over large annular or disc regions (as given in Table 6) have statistical uncertainties also of less than 1%.

When a dose is reconstructed from the complete dentin, the original signal (i.e. the signal measured before any additional irradiations) represents the average concentration of free radicals, which corresponds to the mean absorbed dose in dentin. Although the mean dose rate seemingly depends in a complex way on the cylinder diameter and height, it turns out that the mean absorbed dose rates in the various dentin cylinders tend to form a rather smooth curve if plotted as a function of a particular scale length for the cylinders. We have chosen the scale length x_s as the mean chord length for an external uniform field of straight lines*, which from Cauchy's theorem is simply $x_s = 4V/A$ (see, e.g. Kellerer[41]), where V is the volume and A the surface area of the cylinder. The results are shown in Figure 4, where we have plotted the reciprocal of the mean dose rate as a function of the reciprocal of the scale length. The use of reciprocals allows inclusion of the result for an infinite volume plotted at $1/x_s = 0$. The mean dose rate for the infinite volume is simply E_{av}/ρ_{dentin}, which for ^{90}Sr/^{90}Y decay is 4.22 cGy.s^{-1}.GBq^{-1}.cm^3. The dashed line in Figure 4 fits the data to within less than 1% and is a simple 2nd order polynomial:

$$\dot{D}^{-1}_{dentin} = a_0 + a_1 x_s^{-1} + a_2 x_s^{-2} \quad (1)$$

whose coefficients are $a_0 = 0.2366$, $a_1 = 0.2618$, and $a_2 = 0.2124$. This scaling thus appears to cover any dentin size with scale lengths from 1.8 mm to infinity, with the mean dose rate a function only of the ratio of volume to surface area. For example, the same mean dose rate can be expected for dentin cylinders of such different dimensions as h = d = 5 mm and h = 10 mm, d = 4 mm. Indeed, the direct Monte Carlo calculations for these sizes give mean dose rates in the dentin within ~1% of each other. The combination of the limited variation (a) of scale lengths among typical tooth dimensions, and (b) of the mean dose rate on the scale length, is fortunate for tooth dosimetry because it renders the mean dose rate in dentin only weakly dependent on the tooth type, particularly among molars and premolars.

In our model, the tooth enamel does not contain any emitters and thus can only absorb radiation from the dentin that it surrounds. The absorption gives rise to distributions of absorbed dose in the enamel that exhibit large gradients, with the absorbed dose falling to negligible values at distances greater than the ~2 mm range of ^{90}Sr/^{90}Y beta particles. For EPR dosimetry, the quantity of practical interest is the *mean* absorbed dose in an enamel sample. Information on the mean absorbed dose in enamel was generated by averaging over the calculated distributions of absorbed-dose rate in the following way. For the mean absorbed dose as a function of radial (lateral) thickness, the absorbed dose rate in the enamel was averaged over axial distances z up to the height of the dentin cylinder and radial distances out to the thickness of interest. For the mean absorbed dose

* For the more appropriate interior radiator randomness, the actual mean chord length is related to the adopted exterior radiator mean chord length, but by a more complicated quantity not in general obtainable in analytic form. For the right circular cylinders of dimensions considered here, the interior radiator results are ~5–10% larger than the simpler adopted scale lengths[42]. However, the finite range of the beta particles would reduce the mean chord length. Regardless of any consideration of theoretical justification, the adopted scale length can be considered simply as an empirical parameter.

Table 6(a). Mean absorbed dose in enamel as a function of radial thickness measured from the surface of the dentin. Results are for an enamel annulus of height equal to that of the dentin, and are given for various dimensions of a dentin cylinder. Dentin dimensions are given as height (mm) × diameter (mm). Values of the mean absorbed dose in the enamel are given as fractions of the mean absorbed dose in the dentin listed in units of (cGy/s)/(GBq/cm^3).

Dentin dimension	9×2	4×3	5×4	8×4	9×4	10×4	5×5	7×5	8×5	9×5	7×6	5×9	6×8	6×10	7×9	8×10
Scale length (mm)	1.800	2.181	2.857	3.200	3.273	3.333	3.333	3.684	3.810	3.913	4.200	4.737	4.800	5.455	5.478	6.154
Mean dose in dentin	2.228	2.510	2.832	2.937	2.957	2.971	3.004	3.093	3.122	3.145	3.220	3.327	3.337	3.432	3.435	3.512
Enamel radial thickness (mm)	Mean absorbed dose in enamel (as fraction of mean absorbed dose in dentin)															
0.1	0.469	0.454	0.445	0.449	0.449	0.450	0.435	0.437	0.438	0.439	0.431	0.415	0.421	0.414	0.417	0.416
0.2	0.390	0.382	0.377	0.382	0.383	0.384	0.371	0.373	0.374	0.375	0.368	0.356	0.361	0.355	0.358	0.358
0.3	0.336	0.331	0.330	0.335	0.335	0.336	0.325	0.328	0.329	0.330	0.324	0.314	0.318	0.314	0.317	0.316
0.4	0.295	0.293	0.293	0.298	0.299	0.300	0.290	0.293	0.293	0.295	0.290	0.281	0.285	0.282	0.284	0.284
0.5	0.262	0.262	0.263	0.268	0.268	0.269	0.261	0.264	0.264	0.266	0.262	0.254	0.258	0.255	0.257	0.257
0.6	0.235	0.235	0.238	0.243	0.243	0.244	0.237	0.239	0.240	0.241	0.238	0.232	0.235	0.233	0.234	0.235
0.7	0.211	0.213	0.216	0.221	0.221	0.222	0.215	0.218	0.219	0.219	0.217	0.212	0.215	0.213	0.214	0.215
0.8	0.191	0.194	0.197	0.201	0.202	0.202	0.197	0.199	0.200	0.201	0.199	0.195	0.197	0.196	0.197	0.198
0.9	0.174	0.176	0.181	0.184	0.185	0.185	0.181	0.183	0.183	0.184	0.183	0.180	0.181	0.181	0.182	0.182
1.0	0.158	0.161	0.166	0.169	0.169	0.170	0.166	0.168	0.169	0.170	0.168	0.166	0.168	0.167	0.168	0.169
1.1	0.144	0.148	0.152	0.156	0.156	0.157	0.153	0.155	0.156	0.156	0.155	0.154	0.155	0.155	0.156	0.156
1.2	0.132	0.136	0.141	0.144	0.144	0.144	0.142	0.144	0.144	0.145	0.144	0.143	0.144	0.144	0.145	0.145
1.3	0.121	0.125	0.130	0.133	0.133	0.134	0.131	0.133	0.133	0.134	0.134	0.133	0.134	0.134	0.135	0.136
1.4	0.111	0.116	0.120	0.123	0.123	0.124	0.122	0.124	0.124	0.124	0.124	0.124	0.125	0.126	0.126	0.127
1.5	0.102	0.107	0.112	0.114	0.114	0.115	0.113	0.115	0.115	0.116	0.116	0.116	0.117	0.117	0.118	0.118
1.6	0.094	0.099	0.104	0.106	0.106	0.107	0.106	0.107	0.108	0.108	0.108	0.109	0.109	0.110	0.110	0.111
1.7	0.087	0.092	0.097	0.099	0.099	0.100	0.099	0.100	0.100	0.101	0.101	0.102	0.103	0.103	0.104	0.104
1.8	0.081	0.086	0.090	0.092	0.093	0.093	0.092	0.094	0.094	0.094	0.095	0.096	0.096	0.097	0.097	0.098
1.9	0.075	0.080	0.085	0.087	0.087	0.087	0.087	0.088	0.088	0.089	0.089	0.091	0.091	0.092	0.092	0.093
2.0	0.070	0.075	0.079	0.081	0.081	0.082	0.081	0.082	0.083	0.083	0.084	0.085	0.086	0.087	0.087	0.088

Table 6(b). Mean absorbed dose in enamel as a function of axial thickness measured from the surface of the dentin. Results are for an enamel disc of diameter equal to that of the dentin, and are given for various dimensions of a dentin cylinder. Dentin dimensions are given as height (mm) × diameter (mm). Values of the mean absorbed dose in the enamel are given as fractions of the mean absorbed dose in the dentin listed in units of (cGy/s)/(GBq/cm^3).

Dentin dimension	9×2	4×3	5×4	8×4	9×4	10×4	5×5	7×5	8×5	9×5	7×6	5×9	6×8	6×10	7×9	8×10
Scale length (mm)	1.800	2.181	2.857	3.200	3.273	3.333	3.333	3.684	3.810	3.913	4.200	4.737	4.800	5.455	5.478	6.154
Mean dose in dentin	2.228	2.510	2.832	2.937	2.957	2.971	3.004	3.093	3.122	3.145	3.220	3.327	3.337	3.432	3.435	3.512
Enamel axial thickness (mm)	Mean absorbed dose in enamel (as fraction of mean absorbed dose in dentin)															
0.1	0.380	0.423	0.423	0.408	0.405	0.402	0.428	0.416	0.412	0.410	0.419	0.436	0.428	0.429	0.423	0.419
0.2	0.314	0.357	0.361	0.348	0.345	0.343	0.367	0.356	0.353	0.351	0.360	0.377	0.369	0.371	0.365	0.362
0.3	0.271	0.312	0.318	0.306	0.304	0.302	0.325	0.315	0.312	0.310	0.318	0.335	0.327	0.329	0.324	0.321
0.4	0.239	0.278	0.285	0.274	0.273	0.271	0.292	0.283	0.280	0.278	0.286	0.302	0.295	0.297	0.292	0.290
0.5	0.214	0.251	0.258	0.249	0.247	0.246	0.265	0.257	0.255	0.253	0.260	0.275	0.269	0.271	0.266	0.264
0.6	0.194	0.229	0.236	0.227	0.226	0.224	0.242	0.235	0.233	0.231	0.238	0.252	0.246	0.248	0.244	0.242
0.7	0.177	0.210	0.217	0.209	0.208	0.206	0.223	0.216	0.214	0.212	0.219	0.232	0.227	0.229	0.225	0.223
0.8	0.162	0.194	0.200	0.193	0.192	0.190	0.206	0.200	0.198	0.196	0.203	0.215	0.210	0.212	0.208	0.207
0.9	0.150	0.179	0.186	0.179	0.178	0.177	0.191	0.185	0.184	0.182	0.188	0.199	0.195	0.197	0.193	0.192
1.0	0.139	0.166	0.173	0.166	0.165	0.164	0.178	0.172	0.171	0.169	0.175	0.186	0.182	0.183	0.180	0.179
1.1	0.129	0.155	0.161	0.155	0.154	0.153	0.166	0.161	0.160	0.158	0.164	0.174	0.170	0.171	0.168	0.167
1.2	0.120	0.145	0.151	0.145	0.144	0.143	0.155	0.151	0.149	0.148	0.153	0.163	0.159	0.160	0.157	0.156
1.3	0.113	0.136	0.141	0.136	0.135	0.134	0.146	0.141	0.140	0.139	0.144	0.153	0.149	0.150	0.148	0.147
1.4	0.106	0.128	0.133	0.128	0.127	0.126	0.137	0.133	0.132	0.131	0.135	0.144	0.140	0.142	0.139	0.138
1.5	0.100	0.120	0.125	0.121	0.120	0.119	0.129	0.125	0.124	0.123	0.127	0.135	0.132	0.133	0.131	0.130
1.6	0.094	0.114	0.118	0.114	0.113	0.113	0.122	0.118	0.117	0.116	0.120	0.128	0.125	0.126	0.124	0.123
1.7	0.089	0.108	0.112	0.108	0.107	0.107	0.116	0.112	0.111	0.110	0.114	0.131	0.118	0.119	0.117	0.117
1.8	0.084	0.102	0.106	0.102	0.102	0.101	0.110	0.106	0.105	0.105	0.108	0.115	0.112	0.113	0.111	0.111
1.9	0.080	0.097	0.101	0.097	0.097	0.096	0.104	0.101	0.100	0.099	0.103	0.109	0.107	0.108	0.106	0.105
2.0	0.076	0.092	0.096	0.093	0.092	0.091	0.099	0.096	0.095	0.095	0.098	0.104	0.102	0.103	0.101	0.100

as a function of axial or masticatory thickness, the absorbed dose rate in the enamel was averaged over radial distances r up to the radius of the dentin cylinder and axial distances out to the masticatory thickness of interest. In both cases, the results were normalised to the mean absorbed dose rate in the dentin cylinder and so expressed as fractions of the mean absorbed dose in the dentin. The results are given in Tables 6(a) and 6(b), for all of the 16 dentin cylinders used in our calculations; the columns are arranged in order of increasing scale length of the cylinders. The fractional mean absorbed dose is plotted as a function of enamel thickness also in Figures 5a and b. The data for all the tooth models tend to form a single distribution, perhaps less so for the axial case, particularly for the more asymmetrical 9 mm × 2 mm diameter dentin cylinder. The curve in both Figures 5(a) and 5(b) is from a least-squares fit:

$$\ln\left(\frac{\dot{D}(t)}{\dot{D}_{dentin}}\right) = \sum_{i=0}^{4} b_i t^i \qquad (2)$$

where t is the enamel thickness and $b_0 = -0.7496$, $b_1 = -2.9292$, $b_2 = 1.1868$, $b_3 = -0.5335$, and $b_4 = 0.02906$. The results of the fit are within ~10–15% of the data, except for the 9 mm × 2 mm diameter dentin cylinder for which the data are ~30–40% below the results of the fit.

Current EPR measurements make use of the total available amount of enamel from the whole tooth (or from half of it), both the lateral and masticatory enamel. Our summary results are, in principle, inadequate for this because they do not include the absorbed dose in the 'corner' region, i.e. the annulus for which *both* r and z are outside those of the dentin cylinder. An approximation has been found that seems largely to overcome this difficulty and allows one to estimate the total enamel dose using the summary results in Tables 6(a) and (b), without recourse to the basic Monte Carlo data. The approximation is illustrated in the following recipe and applies to the assumption that the masticatory and lateral enamel layers form a cylindrical 'cap' whose sides extend down to the bottom of the crown dentin cylinder. For the assumed lateral enamel thickness, t_r, calculate the volume V_r of the annulus surrounding the full height of the dentin cylinder. For the assumed masticatory enamel thickness, t_a, calculate the volume V_a of a disc whose radius equals that of the dentin. Then calculate the volume V_c of the corner annulus that extends

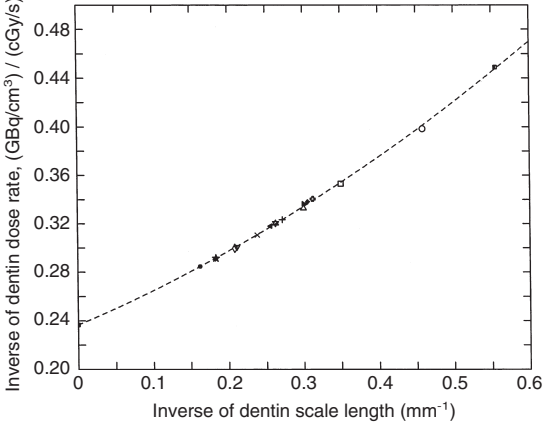

Figure 4. Mean absorbed dose rate in dentin. Results are given in terms of the absorbed dose rate in dentin per unit specific activity in the dentin, as a function of the scale length for the dentin volume.

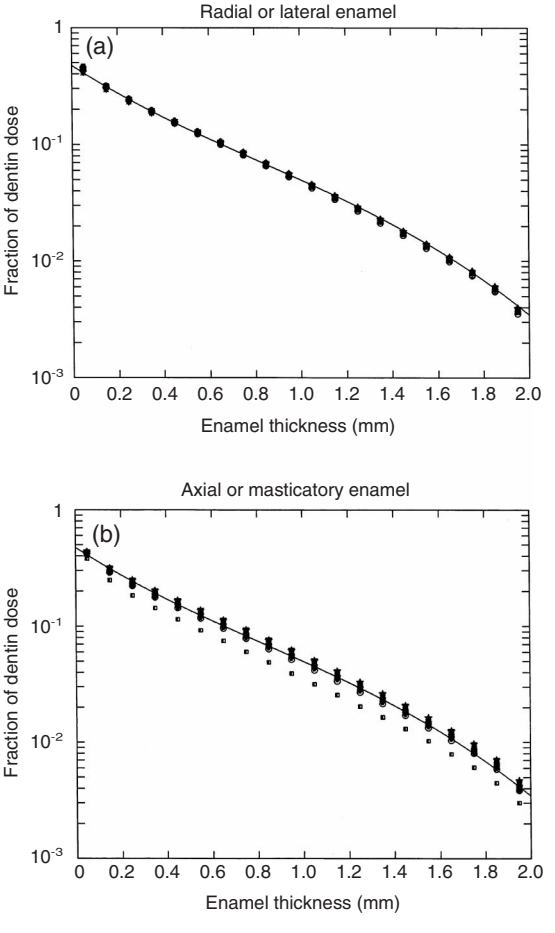

Figure 5. Mean absorbed dose rate in the contiguous enamel expressed as a fraction of the mean absorbed dose rate in the dentin. (a) Radial, or lateral, enamel. The results, averaged over the thickness of the enamel annulus extending from the bottom to the top of the dentin cylinder, are given as a function of the enamel thickness. (b) Axial, or masticatory, enamel. The results, averaged over the thickness of the enamel disc whose radius is that of the dentin cylinder, are given as a function of the enamel thickness.

from the top of the dentin to the top of the masticatory surface and from the dentin radius to that of the lateral enamel. The relative weights, ω_r, ω_a, and ω_c, are simply the respective volumes divided by the total enamel volume. The fractional dose rate in the enamel is then

$$\frac{\dot{D}}{\dot{D}_{dentin}} \approx \omega_r \left(\frac{\dot{D}(t_r)}{\dot{D}_{dentin}}\right)_r + \omega_a \left(\frac{\dot{D}(t_a)}{\dot{D}_{dentin}}\right)_a + \frac{\omega_c}{5}\left(\frac{\dot{D}(t_r)}{\dot{D}_{dentin}}\right)_r \quad (3)$$

where

$$\left(\frac{\dot{D}(t_r)}{\dot{D}_{dentin}}\right)_r \text{ and } \left(\frac{\dot{D}(t_a)}{\dot{D}_{dentin}}\right)_a$$

are from Table 6(a) and 6(b), respectively. The last term of Equation 3 represents the approximation. Justification for the use of one-fifth of the mean radial dose rate is strictly empirical. For lateral enamel thicknesses from 0.3 to 1.7 mm and for masticatory enamel thicknesses from 0.3 to 2.0 mm, Equation 3 gives results within ~1–2% of that from the appropriate sum of the basic Monte Carlo data for the 16 dentin sizes considered. Extension to other sizes could be done using Equation 3 in conjunction with Equations 1 and 2, but with the much larger errors associated with the global fits. For a sample taken from enamel layers not contiguous with the dentin surface (e.g. in cases where chemical etching was applied after dentin removal), the mean absorbed dose can be obtained from the differences between appropriate values in Tables 6(a) and (b).

RELATIONSHIPS BETWEEN RECONSTRUCTED DOSES AND INCORPORATED ^{90}Sr ACTIVITIES

The ultimate goal of dose reconstruction from the viewpoint of radiation biology and epidemiology is to determine doses to certain critical organs, such as bone marrow. This is not easy in the case of low energy emitters whose distribution over the body is not uniform. The dose to tooth enamel, which can be reconstructed with EPR, generally is not equal to the dose to bone marrow, although these values are related in some complicated way. Finding this relationship is a task outside the scope of this paper, but a solution can perhaps be facilitated with our results.

The dose from ^{90}Sr to bone marrow will probably be easier to relate to the ^{90}Sr activity (or concentration) in dentin than to the absorbed dose in tooth enamel. The activity in dentin is obviously related to mean absorbed dose in the dentin (and to the corresponding mean absorbed dose in the enamel) and can be determined from these experimentally measurable characteristics, provided that the time course of the radionuclide accumulation in dentin is known and assuming that the accumulation results in a uniform increase of the ^{90}Sr concentration over the whole dentin volume. Results in this paper have been given in terms proportional to $(\dot{D}/\lambda N)$, where $\dot{D}$ where is the absorbed dose rate and N is the total activity of ^{90}Sr + ^{90}Y in the dentin, assumed in secular equilibrium. In this case, then, $N_{Sr} = 0.4985$ N. If we assume a continuous incorporation of activity at a constant rate c into the dentin over a time 0 to T_c, then the integrated dose at some time T later than T_c is

$$D(T) = \left(\frac{\dot{D}}{N}\right)\frac{c}{\lambda}\left[T_c - \frac{1}{\lambda}e^{-\lambda(T-T_c)}\left(1 - e^{-\lambda T_c}\right)\right] \quad (4)$$

where λ ($= \ln 2/T_{1/2}$) is the decay constant* of ^{90}Sr. If $T >> T_c$ and $\lambda T_c << 1$,

$$D(T) = \left(\frac{\dot{D}}{N}\right)\frac{cT_c}{\lambda}\left(1 - e^{-\lambda T}\right) \quad (5)$$

Note that cT_c is the total activity introduced in the dentin. In terms of current activity N(T),

$$D(T) = \left(\frac{\dot{D}}{N}\right)\frac{N(T)}{\lambda}\left[\frac{\lambda T_c}{1 - e^{-\lambda T_c}}e^{\lambda(T-T_c)} - 1\right] \quad (6)$$

or

$$D(T) \approx \left(\frac{\dot{D}}{N}\right)\frac{N(T)}{\lambda}\left(e^{\lambda T} - 1\right) \quad (7)$$

for $T >> T_c$ and $\lambda T_c << 1$.

As an example, consider $T_c = 1.5$ y and $T - T_c = 47$ y. For $\lambda = \ln 2/29.12$ y^{-1}, evaluation of Equation 6 using the mean absorbed dose rate in dentin, per unit specific activity, from Table 6 gives the estimates found in Table 8 of the ratio of mean absorbed dose in dentin to ^{90}Sr activity measured at T. (If one assumed a shorter biological half-life of, say 25 y, the results in Table 8 would be larger by about 12%.)

Thus, using Tables 6(a) and 6(b), one can determine the mean dose to dentin from the experimentally reconstructed dose in tooth enamel, and then, using Equation 6 or 7, calculate the activity of ^{90}Sr in dentin at the time of the dose reconstruction.

DISCUSSION

Some experience in using these Monte Carlo results to analyse EPR measurements in our laboratory indicates their usefulness and suggests some conclusions. First, they provide a link between the mean absorbed doses in enamel to the mean absorbed dose in dentin. This appears to be a more significant quantity because, for the same specific activity of the radionuclides in dentin, the absorbed dose in dentin depends on the tooth type (size) to a much smaller extent than does the absorbed dose in the enamel. This theoretical conclusion

* It would seem more appropriate to use the biological half life of the ^{90}Sr in the dentin, rather than the physical half life.

Table 7. Variation of the mean absorbed dose in enamel.

(a) **Results typical for a 3rd molar. Dentin dimensions: h = 5 mm, d = 9 mm; enamel layer thicknesses: masticatory 0.8 mm, and lateral 0.6 mm.**

Fractional absorbed dose				Deviation from nominal value			
Masticatory thickness (mm)	Lateral thickness (mm)			Masticatory thickness (mm)	Lateral thickness (mm)		
	0.5	**0.6**	0.7		0.5	**0.6**	0.7
0.7	0.233	0.218	0.205	0.7	10.4%	3.3%	−2.8%
0.8	0.224	**0.211**	0.199	**0.8**	6.2%	**0.0%**	−5.7%
0.9	0.216	0.204	0.192	0.9	2.4%	−3.3%	−9.0%

(b) **Results typical for a 1st molar. Dentin dimensions: h = 5 mm, d = 5 mm; enamel thicknesses: masticatory 1.5 mm, and lateral 1.2 mm.**

Fractional absorbed dose				Deviation from nominal value			
Masticatory thickness (mm)	Lateral thickness (mm)			Masticatory thickness (mm)	Lateral thickness (mm)		
	1.0	**1.2**	1.4		1.0	**1.2**	1.4
1.3	0.141	0.123	0.108	1.3	19.5%	4.2%	−8.5%
1.5	0.134	**0.118**	0.104	**1.5**	13.6%	**0.0%**	−11.9%
1.7	0.128	0.113	0.100	1.7	8.5%	−4.2%	−15.3%

Table 8. Estimates of the ratio of the mean absorbed dose in dentin to the ^{90}Sr activity as measured 47 y after incorporation of activity at a constant rate for 1.5 y. A half-life for ^{90}Sr of 29.12 y was assumed. Results are given for dentin dimensions, given as height × diameter, assuming a density for dentin of ρ = 2.14 g.cm^{-3}.

Dentin dimensions (mm)	Dentin volume, V_d (cm^3)	Scale length, $x_s = 4V_d/A_d$ (mm)	$D(T)/[\lambda N_{Sr}(T)]$ (cGy/Bq)	$\rho V_d D(T)/[\lambda N_{Sr}(T)]$ (cGy/(Bq/g))
9 × 2	0.02827	1.800	442	26.7
4 × 3	0.02827	2.181	498	30.1
5 × 4	0.06283	2.857	253	34.0
8 × 4	0.10053	3.200	164	35.3
9 × 4	0.11310	3.273	147	35.5
10 × 4	0.12566	3.333	133	35.7
5 × 5	0.09817	3.333	172	36.1
7 × 5	0.13744	3.684	126	37.1
8 × 5	0.15708	3.810	112	37.5
9 × 5	0.17671	3.913	99.8	37.8
7 × 6	0.19792	4.200	91.3	38.7
5 × 9	0.31809	4.737	58.7	39.9
6 × 8	0.30159	4.800	62.1	40.1
6 × 10	0.47124	5.455	40.9	41.2
7 × 9	0.44532	5.478	43.3	41.2
8 × 10	0.62832	6.154	31.4	42.2

is consistent with the recent experimental findings for different calcified tissues of a dog that was injected with ^{90}Sr[18]. Thus, the enamel measurements are mapped onto more of a universal scale, which makes it far easier to compare absorbed dose in teeth of different types. This can help resolve previously inexplicable discrepancies between doses reconstructed from the same person, and to make more meaningful comparisons of doses reconstructed from teeth of different people. Note that applying the Monte Carlo results at this level are, so far, free of assumptions on the regimen of radionuclide intake into the body.

However, the geometric assumptions are still made: our shapes are assumed to be strictly cylindrical with known dimensions, with the radionuclide distributed uniformly in the dentin cylinder. Obviously, this is not true. Although it is not easy to estimate the uncertainty due to the non-uniformity of the radionuclide distribution in dentin (mainly due to lack of information on its actual distribution), it is possible to get an idea of possible uncertainties due to irregularities in shape. Because it is more difficult to calculate dose profiles for irregular shapes, the easiest way to estimate the uncertainty is to compare mean absorbed doses for cylinders slightly differing in dimensions.

As follows from Figure 4, the average absorbed dose in dentin is rather insensitive to the cylinder dimensions and, consequently, to irregularities in its shape. Simple calculations show that, even if the errors in both the diameter and the height of the cylinder reach 1 mm each, the relative error in the mean absorbed dose will always be within 5.5%. The situation for tooth enamel is not as favourable. Tables 7 show that errors of 0.1 mm in the lateral and masticatory thicknesses may result in errors of up to 10%. Errors of 0.2 mm may lead in some cases (for specific types of teeth and particular combinations of errors in the lateral and masticatory thicknesses) to an error of 30–40%. Therefore, errors of this magnitude in the enamel mean dose might be expected to arise due to irregularities in the shapes of dentin and tooth enamel. If such errors are largely unavoidable, the global fit given by Equation 2 could be used in conjunction with Equation 1 to approximate by superposition the results for some irregular shapes and non-uniform distributions of activity in dentin.

The reason why the errors are larger in the enamel is easy to understand. For a given specific activity, a change in the dimensions of a dentin cylinder results in only a marginal change in the net energy leakage into the enamel. However, the very strong attenuation of the beta particles in the enamel makes the mean absorbed dose quite sensitive to the uncertainties associated with the volume over which it is averaged. In view of this difference in the uncertainties, it is reasonable to reconsider the relative suitability of dentin and enamel for dose reconstruction. At present, dentin is practically unused in EPR dosimetry (the only exception being the recent EPR study of middle and lower Techa riverside population[19]). Although dentin is a considerably more difficult material to use in EPR dosimetry and the lower limit for detection is several times higher than for the enamel, the uncertainty in the dose reconstructed directly from dentin is about one order of magnitude lower than that achieved by way of determining the mean dose in dentin through the measured dose in enamel. For internal irradiation by ^{90}Sr, the doses in dentin is typically higher than the dose in enamel of the same tooth. Thus, for Techa riverside residents with a high ^{90}Sr body burden, ratios of these doses range from 3 to 6[4,15,19]. Hence, the inferior detection limit for dentin is largely compensated by the higher doses presented for measurement. Dentin as a dosimetric material will be even more important in reconstructing internal doses from alpha emitters. Because of the very small penetration depth of alpha particles, their contribution to the dose to enamel will be negligible. These factors advocate using crown and root dentin as the primary dosimetric materials in reconstruction of internal doses.

Calculating the radionuclide activity in dentin from the EPR-reconstructed dose is based on additional assumptions that contribute significant additional uncertainties. However, such a calculation appears to be a necessary link in any effort to relate the relatively easily measurable enamel or dentin doses to the absorbed dose in organs such as bone marrow. The assumptions fall into two categories: the regimen of the radionuclide accumulation and retention in dentin and the radiation source. Moderate errors in the geometrical model of the tooth lead to relatively small errors in the dentin dose. But failure to assign an accurate time course for the accumulation and retention of the radionuclide could lead to large errors in the conversion of this dose to estimated activities.

The results given here are relevant to ^{90}Sr, one of the most important sources of internal irradiation. Similar calculations can be performed for different emitters. The use only of our ^{90}Sr results assumes there are neither other radionuclides incorporated in the dentin (or in the enamel) nor significant contributions from external sources to the measured enamel or dentin doses. The experimental reconstruction of the doses in both dentin and the enamel of the same tooth thus should reveal failures in the model assumptions. In simple cases (such as internal irradiation from ^{90}Sr in dentin plus uniform high energy external irradiation), it might even be possible to separate the contributions. However, this depends on the validity of all the other assumptions in the model.

The methodology and data described here open the possibility of using EPR tooth dosimetry in the reconstruction of doses received internally from ^{90}Sr. Such information is presently obtained mostly with two methods: model calculations of doses based on the level of the ^{90}Sr environmental contamination, and whole-body counter (WBC) measurements of the ^{90}Sr body burden. Unfortunately, the former method needs

to be verified against independent dose assessments based, for example, on individual WBC measurements. There are significant difficulties in interpreting WBC measurements[43]. In addition, whole-body counting is based on the measurements of current radioactivity, which of course decays over time, making the determination of doses received long ago rather difficult. A typical lower limit for detection of ^{90}Sr is 1–2 kBq in the whole body, so, application of WBC is limited to cases with relatively high environmental contamination. In contrast, the EPR tooth dosimetry signal increases with time, and would appear to offer an alternative method for evaluating internal doses from ^{90}Sr. Although EPR tooth dosimetry rests on its own important assumptions, these assumptions are different from those of WBC measurements, and the two methods can perhaps compliment and verify each other.

In summary, some practical conclusions are apparent:

(1) *Importance of tooth geometry (shape and size).* In the case of low energy internal exposure, the results of EPR tooth enamel dose reconstruction will substantially depend on the shape and dimensions of the tooth. This makes it imperative to convert the measured mean absorbed dose in enamel to a more meaningful value, such as the mean absorbed dose in dentin. Such a conversion can be made using the results given in this paper. It is also important to document the tooth shape in detail before destruction for possible reevaluation of the reconstructed dose using future models that take into account more complexities.

(2) *Importance of dentin as a dosimetric material.* Dentin should be used more extensively in tooth dosimetry for a number of reasons. A tooth with a high dose in dentin compared with the dose in enamel clearly indicates internal exposure and signals the need for the type of analysis described above. Such an analysis of the EPR dosimetry results for internal exposure is more precise when based on the dentin dose rather than the enamel dose. The radiation-induced signal from dentin is often more pronounced than that from enamel of the same tooth because of the significantly higher dose in dentin from internal irradiation. The dentin dose is more directly related to the strontium burden of dentin than is the enamel dose. Potentially, the strontium burden of dentin can be related to the strontium burden of other organs and of the whole body. That would give a direct link between results of EPR dosimetry, results of whole-body counter measurements, and doses in organs other than teeth.

(3) *Importance of distinguishing between crown and root dentin.* Because the geometry and metabolism of dentin in these two locations are very different, it is expedient to separate crown dentin from root dentin and perform dose reconstruction for each separately. From the dosimetric point of view, the ^{90}Sr deposited in crown dentin should serve as the main source for the irradiation of the tooth enamel. Therefore, if the doses measured in the tooth enamel and the crown dentin are consistent with the results given in Tables 6(a) and 6(b), it would clearly indicate a considerable (or predominant) internal ^{90}Sr contribution to the dose received by the tooth donor (for practical examples, see also Romanyukha *et al*[19]). In contrast, the absorbed dose in the root dentin was found to be close to the absorbed dose in the cortical jaw bone and in sinciput bones[18]. Thus the absorbed dose in root dentin can help in conversion of EPR-reconstructed doses to the absorbed dose in more important organs, such as bone marrow.

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