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ScienceDirect
Radiation Measurements 42 (2007) 1089–1093
Radiation Measurements
www.elsevier.com/locate/radmeas

Radiation dose reconstruction from L-band *in vivo* EPR spectroscopy of intact teeth: Comparison of methods

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Abstract

In vivo EPR tooth dosimetry is a more challenging problem than *in vitro* EPR dosimetry because of several potential additional sources of variation associated with measurements that are made in the mouth of a living subject. For *in vivo* measurement a lower RF frequency is used and, unlike in the *in vitro* studies, the tooth cannot be processed to optimize the amount and configuration of the enamel that is measured. Additional factors involved with *in vivo* measurements include the reproducibility of positioning the resonator on the surface of the tooth in the mouth, irregular tooth geometry, and the possible influence of environmental noise. Consequently, in addition to using the theoretical and empirical models developed for analyzing data from measurements of teeth *in vitro*, other unconventional and more robust methods of dose reconstruction may be needed. The experimental parameter of interest is the peak-to-peak amplitude of the spectrum, which is correlated to the radiation dose through a calibration curve to derive the reconstructed dose. In this study we describe and compare the results from seven types of computations to measure the peak-to-peak amplitude for estimation of the radiation-induced signal. The data utilized were from three sets of *in vivo* measurements of irradiated teeth. Six different teeth with different doses were placed in the mouth of a volunteer *in situ* and measurements of each tooth were carried out on three different days. The standard error of prediction (SEP) is used as a figure of merit for quantifying precision of the reconstruction. We found that many of the methods gave fairly similar results, with the best error of prediction resulting from a computation based on a Lorentzian line model whose center field corresponds to the known parameter of the radiation-induced EPR spectra of teeth, with corrections from a standard sample that was measured as part of the data acquisition scheme. When the results from the three days of measurement were pooled, the SEP decreased dramatically, which suggests that one of the principal sources of variation in the data is the ability to precisely standardize the measurement conditions within the mouth. There are very plausible ways to accomplish improvements in the existing procedures.

Keywords: Electron paramagnetic resonance; Inverse regression; Standard error of prediction; Statistical methods

1. Introduction

Electron paramagnetic resonance (EPR) tooth dosimetry is a very promising method for after-the-fact determination of radiation dose. Initially such measurements were done with isolated teeth, usually obtained after natural loss of teeth, but in at least one case the teeth were actively extracted (Rossi et al., 2000). Most of the work has been done using X-band (~ 9 GHz) EPR *in vitro* with a technique that involves mechanical isolation of the enamel of the tooth (enamel is the site of most of the radiation-induced EPR signals in irradiated teeth). Recent references are by Tieliewuhan et al. (2006), Wieser et al. (2006), and Skvortsov et al. (2006). *In vitro* measurements using lower frequency (1.2 GHz, or L-Band) EPR also have been reported using intact teeth (Zdravkova et al., 2003).

The ability to make measurements in the mouth without the need to extract teeth is very attractive (*in vivo* tooth dosimetry), but this is a more challenging task. There are many factors that can affect measurements that are made in the mouth of a patient and it is necessary to use less sensitive lower frequency EPR spectrometers (typically 1.2 GHz). In addition to the background/native signal that also must be considered with measurements *in vitro*, several other sources of variation emerge: the challenge of exact positioning the resonator in the mouth; the effects of adjacent tissues that non-resonantly attenuate the

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doi:10.1016/j.radmeas.2007.05.025

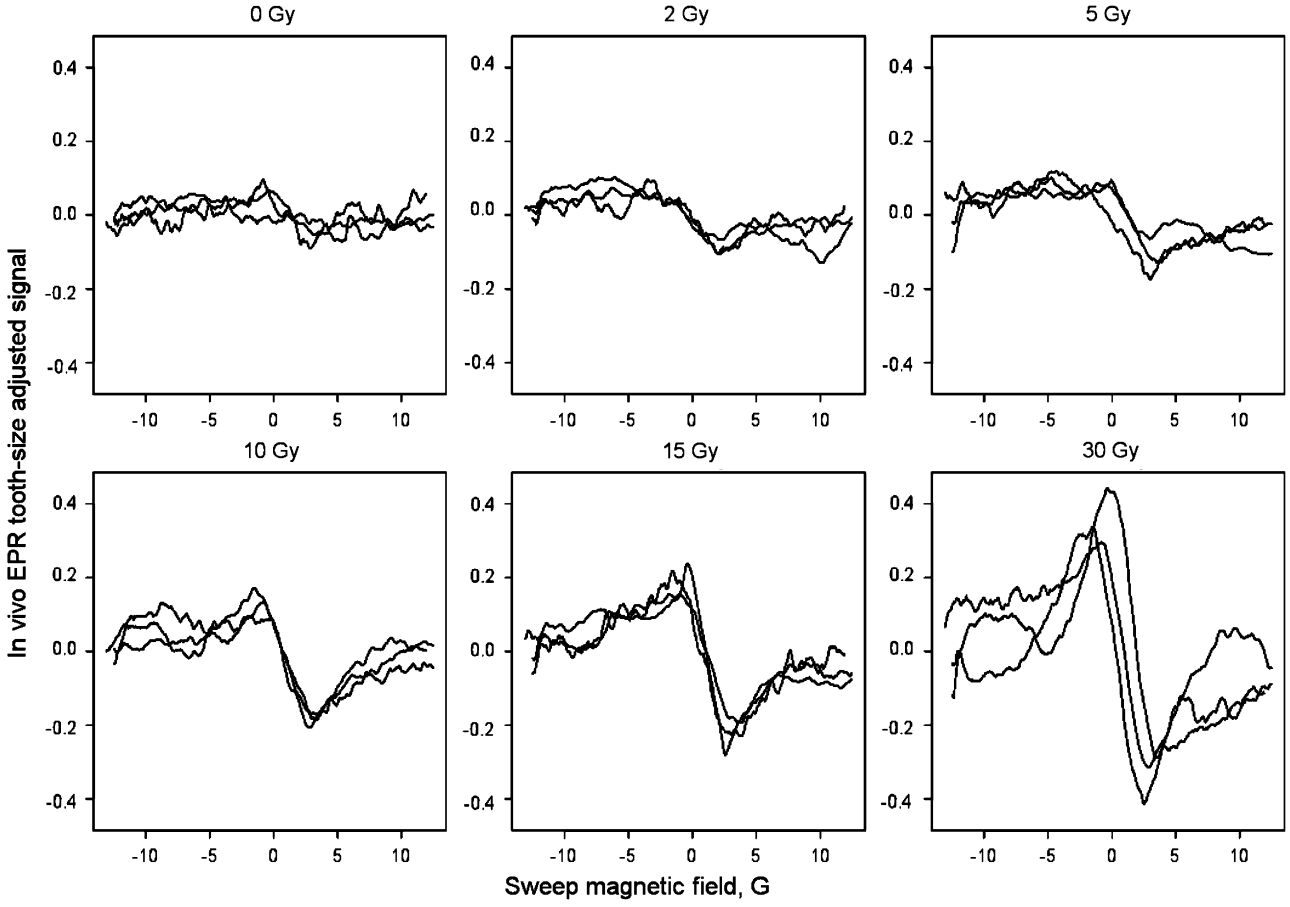

Fig. 1. Eighteen tooth-size adjusted EPR spectra *in vivo* with six teeth that received 0, 2, 5, 10, 15 and 30 Gy radiation. The irradiated teeth were inserted into a gap in the dentition of a volunteer. Measurements were repeated on three days with identical instrumental settings, as described in the text.

microwave frequencies used for the measurement; differences in the size of teeth; irregular geometry of the tooth surface; and the constraints on shielding from unwanted microwave sources when a subject needs to be positioned within the magnet. These complications require that we modify our approaches to dose reconstruction and need to apply spectral models that are sufficient for fitting the radiation-induced EPR spectra for *in vivo* data. The goal of the present communication is to compare several methods of the dose reconstruction that we are exploring for analyzing data obtained *in vivo*. We use the standard error of prediction as the figure of merit to compare the methods. This research is ongoing and the methods are under continuous attempts to improve them, but the results that already are obtained provide some very useful insights and indicate that the challenges are likely to be overcome.

2. Materials and methods

Six previously extracted teeth were irradiated with 0, 2, 5, 10, 15, and 30 Gy. These teeth we placed in a gap in the dentition in the mouth of a volunteer and sets of EPR spectra were acquired on three days. All measurements were done with a clinical 1.2 GHz spectrometer at the EPR center at Dartmouth (Swartz et al., 2006) with 1024 points recorded for each EPR spectrum. On each day, spectra for all six teeth were acquired using the same acquisition parameters. Typically these were: scan range 25 Gauss (10 G = 1 mT), scan time 3 s, 30–90 scans that were averaged (more scans were used for low dose spectra), modulation amplitude 4 Gauss, modulation frequency 24.5 kHz, incident radio frequency (RF) power 100 mW. The $N = 6 \times 3 = 18$ EPR spectra are shown in Fig. 1. The spectra were adjusted for tooth-size, by measurements of the surface of the teeth in two orthogonal directions (D_1 and D_2) and each original signal was divided by $(D_1 D_2)/100$. This provides the amplitude of the EPR signal per 100 square millimeters of the surface of the tooth.

The reconstructed dose is derived from a calibration curve that is traditionally obtained as a linear regression of the peak-to-peak (P2P) amplitude on the radiation dose given. The method of abscissa prediction using regression analysis is called an *inverse regression* (Draper and Smith, 1998). To compare various methods of the dose reconstruction a precision measure should be used. We used an intuitively appealing standard error of prediction (SEP) as the measure of precision computed as

$$\mathrm{SEP} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\widehat{D}_i - D_i)^2},$$