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High resolution mapping of 1D and 2D dose distributions using X-band electron paramagnetic resonance imaging

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Abstract

EPR imaging (EPRI) was performed to visualize 2D dose distributions of homogeneously irradiated potassium dithionate tablets and to demonstrate determination of 1D dose profiles along the height of the tablets. Mathematical correction was applied for each relative dose profile in order to take into account the inhomogeneous response of the resonator using X-band EPRI. The dose profiles are presented with the spatial resolution of 0.6 mm from the acquired 2D images; this value is limited by pixel size, and 1D dose profiles from 1D imaging with spatial resolution of 0.3 mm limited by the intrinsic linewidth of potassium dithionate. In this paper we focus on dose profiles from 2D reconstructed EPR images using the Xepr software package by Bruker. The conclusion is that using potassium dithionate the resolution 0.3 mm is sufficient for

mapping steep dose gradients if the dosimeters are covering only ± 2 mm to 3 mm around the centre of the resonator.

Introduction

Different computational algorithms for calculation of two or three dimensional (2D or 3D) absorbed dose distributions play an important role in the treatment planning for radiation therapy. Because of approximations needed to save calculation time for the dose distributions predicted by treatment planning systems experimental validation is sometimes necessary. Dosimetry of brachytherapy needs the use of a 3D analysis method. In brachytherapy the need of validation is high; in interstitial brachytherapy, the effects of source-to-source shielding (1,2) should be considered and shielded applicators in intracavitary brachytherapy are used the dose distributions should be validated (3). Several dosimetry systems have been used to perform accurate dose measurements. Radiochromic films are widely used in practice and can produce high resolution 2D dose distributions in the submillimeter range. The dose response is however nonlinear and saturation effects can occur at high dose rates. Gel dosimeters have been developed as a 3D dosimeter with a resolution around 1 mm (4).

In the field of EPR dosimetry many different materials have been tested since alanine was applied for dosimetry (5,6). Polycrystalline formates and dithionates have been used as new suitable materials for EPR dosimetry (7,8). One of the proposed materials for dosimetric purpose is potassium dithionate. While EPR dosimetry can determine the mean absorbed dose from whole irradiated phantom, the spatial distribution of radicals related to the dose distributions along two dimensions can be shown by electron paramagnetic resonance imaging (EPRI).

The theoretical spatial resolution, which represents the shortest distance (d) between two points that can be resolved in an EPR image, was calculated as follows: $d = LW/G$, where LW (mT) is the linewidth of an EPR signal from used material and G (mT/m) is the magnitude of the magnetic field gradient (9).

Experimental determinations of 1D and 2D dose distributions performed by using various EPRI methods are found in the literature (10-13). We have used homogeneously irradiated potassium dithionate tablets and an additional mathematical method necessary to achieve the measurements and analyses in our EPRI technique, and our procedure can be adapted for tissue equivalent materials to perform 1D and 2D relative dose measurements for specific clinical dosimetry tasks, for example, in the brachytherapy field. Potassium dithionate was chosen because of its narrow line width. Clinical applications of the EPRI dosimetry tool is lacking due to following reasons: the cost of the scanning tool, for example, EPR imager, absence of an accurate analysis software available for dosimetric purpose, and a necessity to perform routinely 2D visualization of delivered dose distributions.

The aim of this work is to explore the feasibility of X-band EPR imaging (approach) to determine dose distributions by using homogeneously irradiated potassium dithionate tablets and using the Xepr software package (Bruker GmbH, Rheinstetten, Germany) for image reconstructions. In this paper we will focus on dose profiles from 2D reconstructed EPR images.

Materials and methods.

Potassium dithionate dosimeters.

Potassium dithionate was synthesised using the following method; Barium dithionate was synthesized according to standard methods. Potassium dithionate was synthesized using barium dithionate and prepared by mixing potassium sulphate and barium dithionate in water solutions. The filtered solution was kept at room temperature until the water had evaporated to obtain a crystalline precipitate of potassium dithionate. Potassium dithionate was crushed in a mortar and sieved to grain size $90\text{ }\mu\text{m} < d < 180\text{ }\mu\text{m}$ using an Endecotts MINOR test sieve shaker. Potassium dithionate powder was pressed to the tablets (4.5 mm in diameter and 5 or 2.5 mm in height) using a manual tablet press.

Irradiation of tablets.

The pellets were irradiated at the ^{60}Co irradiation facility at the Swedish Secondary Standards Dosimetry Laboratory, SSM, to 600 Gy, dose to water. The irradiation was performed at 100 cm distance from the source with 2 cm PMMA build up along the dosimeters that were turned 180° after half the irradiation time to ensure a homogenous irradiation.

Experimental setup for EPRI measurements.

We used a specific 5 mm diameter quartz tube filled up to the total length of 20 mm, i.e. 4x5 mm with irradiated or/and non-irradiated potassium dithionate tablets of different combinations to handle that stack together inside resonator for different measurements. We paid special attention to position the center of the pellets exactly in the center of the resonator in order to obtain the highest sensitivity and the biggest signals from each combination.

EPRI measurements.

EPRI measurements were performed with a Bruker Elexsys E540 X-Band EPR/EPRI spectrometer equipped with 2D field gradients, 1700 mT/m along the direction of the sample tube and with a resonator of type TMHS operating at 9.8 GHz. The EPRI acquisition parameters were: applied modulation frequency of 100 kHz, modulation amplitude of 0.5 mT, time constant of 20.48 ms, sweep time of 40.42 s, sweep width of 51 mT, 6 scans and 1024 sampling points, the field of view of 20 mm, pixel size of 0.625 mm. All imaging parameters were kept constant for all the irradiated tablets. For the intensity measurements of DPPH the microwave power was 5 mW, the modulation amplitude 0.2 mT, time constant 10 ms and for sufficient accuracy 3 sweeps of 20s with a sweep width of 4 mT. The measurements were repeated in order to check the reproducibility of obtained experimental results.

2D image reconstruction.

EPR spectra were obtained for all combinations of tablets both without gradient and with a gradient of 1700 mT/m. The data of collected EPR spectra were imported using the Easyspin toolbox (14). 2D EPRI measurements were performed with a Bruker Elexsys E540 X-Band EPR/EPRI spectrometer equipped with 2D field gradients, 1700 mT/m along the direction of the sample tube and with a resonator of type TMHS operating at 9.8 GHz. 2D images were reconstructed by filtered backprojection using a Shepp–Logan filter; standard in the Bruker Xepr software. The algorithm used in Xepr is a Fourier Transform method, where, instead of deconvolution in the spectral domain, division in the Fourier domain is applied, and the filtering of the data by multiplication with a Gaussian window function to avoid artifacts caused by division by very small values (15). The deconvolution parameters, including the maximum cut-

off frequency and the width of the Gaussian window function was chosen to achieve sufficient noise reduction without affecting the resolution too much. Spectral deconvolution and filtered backprojection were performed using the Xepr software package (Bruker GmbH, Rheinstetten, Germany).

Correction for inhomogeneous resonator response.

In order to find the response of TMHS resonator, the signal intensity (amplitude) from a DPPH grain inserted in a quartz tube at each mm along the vertical axis of the resonator was obtained. Reconstructed dose profiles were divided with the experimentally obtained resonator response curve in order to take into account the inhomogeneous response.

Spatial resolution determination.

The spatial resolution was estimated from the edge response from the reconstructed dose profiles. The distance of the edge response to rise from 10% to 90% was used to estimate the resolution. The 10% to 90% distance is a robust parameter even if the edge response does not have a symmetric profile (16).

Results.

Each reconstructed 2D EPR image reflects the known diameter and height of tablets. The color code directly depicts the dose distribution, as shown on Fig 1a and 1b. 2D EPRI data sets were collected and repeated for each combination of pellets with 1 or 2 irradiated tablets surrounded by non-irradiated ones. These data were used to analyze the relative dose distributions along the total length of irradiated and non-irradiated tablets. The dose

measurements were made across the line profile from the center of the tablet in 0.3125 mm steps due to the performed algorithm in the Bruker software for image reconstruction.

The result for the resonator response used in these experiments is presented in Fig.2 and 3, where signal intensity is plotted as a function of the distance in the millimeter scale. The dependence was approximated by a second order polynomial. The dose profile on Fig.2 shows that the response of the resonator is homogeneous within ± 2 mm from the center. Fig.3 shows the uncorrected dose distribution for one irradiated potassium dithionate tablet placed between -2 and -7 mm from the centre of the resonator together with the resonator response. Corrected and non-corrected dose profiles of the same tablet position are compared in Fig 4. The deviations of the dose profile from the response curve at the edges of tablet are clear.

Fig.5 shows a dose profile extracted from 2D reconstructed images for 4 irradiated potassium tablets stacked together and placed slightly off the centre of the resonator.

The spatial resolution obtained from the 10% to 90% distance method agreed very well with that obtained from the theoretical value 0.625 mm as it is shown on Fig 6.

Discussion.

We observed that the resonator sensitivity is approximately homogeneous only within ± 2 mm from the centre of the resonator. However, even if the tablet is situated in the center of the cavity, see Fig 1 a minor slope along the whole distribution in the image is observed. This discrepancy from a constant dose over the tablet is unexplained, since the radical density should be constant over the whole tablet. It is probably an artefact and similar tendencies are found in 2D figures published by Leveque et al 2009. The two tablets in Fig 1b were placed from position

-3 to +7 mm and hence most of the difference in intensity in the upper part of the stack is due to not being corrected for intensity variations in the cavity.

When a correction for the change in sensitivity of resonator response along the vertical axis was applied for distances from -3 to +2 mm from the centre the dose distribution of a tablet is almost homogenous as shown in figure 2. We developed a method in order to perform a division of dose profiles on resonator response curve for distances from -5 to 5 mm. However, corrected results show an overestimation at distances larger than 5 mm from the center of the resonator as illustrated by placing the irradiated tablet 4 mm off center. This might be because the response curve is obtained with another load in the cavity compared to the profile measurements when 20 mm of the tube is filled with dosimeter material. As a further development the cavity response will be experimentally determined by help of an unirradiated tablet 2.5 mm height and 4.5 mm diameter with a grain of DPPH in the middle. This tablet will be placed at different positions between unirradiated tablets giving measured points at every 2.5 mm from about -19 to + 19 mm along the cavity.

When stacks of irradiated tablets are visualized as shown in figure 5 an incomplete compensation of the spectral information causes pronounced dips in the spatial information. This has to be regarded as artefacts. .

The line width of potassium dithionate is 0.5 mT, therefore, the theoretical spatial resolution of potassium dithionate is 0.3 mm. For potassium dithionate, the experimentally deduced resolution from the 10% to 90% distance method was 0.3 mm for 1D dose profiles and 0.612-0.625 mm for 2D EPR images due to the pixel size. Without further filtering and post processing the present resolution was found to be optimal. Different filtering techniques are

suggested by Anton and Selbach (18) followed by an iterative fitting to a Monte Carlo calculated dose distribution convolved with a Gaussian function. Hereby they achieved a high resolution of dose gradients in electron irradiated alanine phantoms.

Conclusion.

The present study represents a method for determination of dose distributions by using EPRI technique and homogeneously irradiated potassium dithionate tablets. The Bruker Xepr reconstruction software was used together with a correction for the inhomogeneity in the resonator for dose distributions obtained across the line profile of the 2D images from the center of the tablet. This correction resulted in approximately homogenous dose distributions only if a 5 mm dosimeter was placed exactly in the center. For corrections up to 10 mm from the center the sensitivity in the cavity correction will be determined by means of a grain of DPPH inserted at different positions in a stack of unirradiated tablets. Experimental determination of the spatial resolution was found to be optimal without further post processing; 0.3 mm for 1D dose distributions and 0.6 mm for 2D images of irradiated potassium dithionate tablets and X-band EPR imaging with maximal magnetic field gradient.

Such technique with this spatial resolution can be useful for dose distribution verification in the brachytherapy field where spatial dose gradients are steep, but corrections for the artefacts are needed.

We conclude that using the Bruker Xepr reconstruction software is sufficient for visualizing differences in radical concentrations in for instance biological species but for mapping dose distributions more sophisticated methods are needed.

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Figure captions

Fig.1. (a) Reconstructed 2D EPR image of an irradiated potassium dithionate tablet. (b). Experimental setup and 2D EPR image of 2 homogeneously irradiated potassium dithionate tablets. The positions in the sample tube are shown to the left and the normalized intensity scale to the right for both figures.

Fig.2. Resonator response curve (squares); dose distribution for one homogeneously irradiated potassium dithionate tablet in the centre of the resonator (diamonds).

Fig.3. Resonator response (squares), dose distribution for one irradiated potassium dithionate tablet without corrections (diamonds), the tablet is placed off-center in the cavity.

Fig.4. Corrected dose profile (diamonds) for one homogeneously irradiated potassium tablet placed off-center in the cavity together with the dose distribution without correction (filled squares).

Fig.5. Dose distribution for 4 homogeneously irradiated potassium tablets without correction.

Fig.6. Edge response along a vertical direction for a homogeneously irradiated potassium dithionate tablet. The distance of the edge response to rise from 10% to 90% is indicated.

Fig.1a.

Fig 1b

Fig 2

Fig 3

Fig 5

Fig 4

Fig 6