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The development and establishment of in-vivo electron paramagnetic resonance tooth dosimetry system for triage after radiation emergency

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1. Introduction

An unexpected radiation emergency causes to radiation damage where large numbers of public members may have been exposed to a large amount of doses of ionizing radiation. Rapid emergency response for disaster will depend on sufficient availability of fast reliable biodosimetry methods [1]. The most critical factor of emergency response depends on triage process rate of identifying accumulated dose and distributing for individuals who have exposed doses above 2 Gy where acute medical treatment would affect survival rate for efficient radiation emergency [2].

In-vivo electron paramagnetic (EPR) tooth dosimetry has the ability to take non-invasive measurements without damaging teeth, could enable rapid triage of response for radiation emergency. The EPR tooth dosimeter would eliminate the additional steps and special human resource such as dentists in the emergency situation for triage purpose.

We developed the in-vivo EPR tooth dosimetry system and the established relation between EPR signal and dose response curve for demonstrating the feasibility of providing accurate dose estimation for individuals investigated with the established system. We also investigated the effect of the volume of teeth for improvement of accurate dose estimation with finite element analysis software.

2. Methods and Results

2.1 EPR tooth dosimetry instrumentation

EPR tooth dosimetry uses magnetic resonance phenomena, where the influence of an applied external magnetic field. The absorption of microwave energy by radiation-induced radicals in enamel of teeth is measured and estimated as absorbed dose.

We have established prototype of a continuous-wave EPR tooth dosimeter with an operating frequency of 1.15 GHz. The in-vivo EPR dosimeter consists of magnet generation part, a microwave bridge circuit, a surface coil resonator for signal detection, and appropriate immobilizer to provide support and positioning capabilities necessary for measurements [2-4].

This dosimeter utilizes about 30 kg permanent dipole magnets generating static magnetic field of 41.5 mT with a 17 cm gap manufactured by Resonance Research, Inc. (Billerica, MA, USA). Surface coil resonator is employed to detect the generated radicals in the enamel of teeth. The resonator is designed of silver wire with thickness of 1.0 mm and an outer diameter of 10 mm. Brass shield was covered to inner circuit to protect from modulated field signal. The produced resonator was shown in figure 1(a). This resonator resonates at 1.15 GHz and high frequency selectivity at the frequency.

The field sweeping and EPR detection electronic circuits are contained in a rack. The microwave bridge circuit is built within our laboratory to achieve efficient signal transmission based on previous design [2].

The data acquisition process and the dosimeter are controlled using software designed by LabVIEW. This software also controls parameter settings for the bridge circuit, lock-in amplifier, and sweep and modulation field systems. The developed resonator is based on the conventional design [4-5].

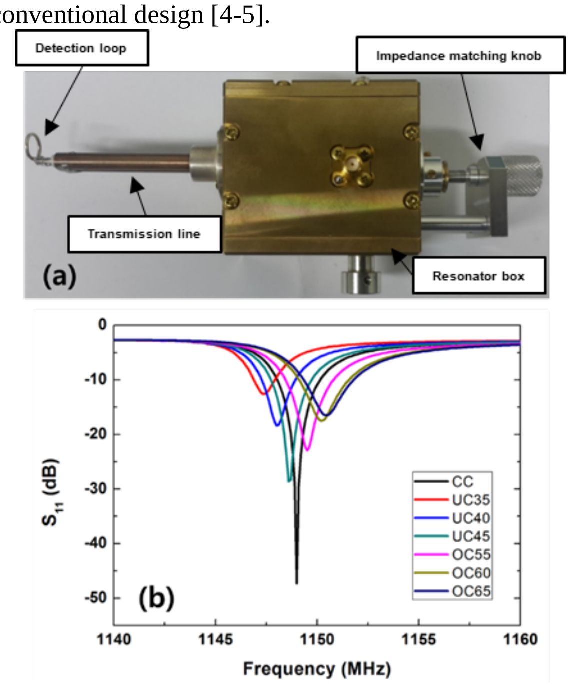

Fig. 1. (a) The resonator of EPR tooth dosimetry. The key components of the resonator are described. The detection surface coil is located on the teeth and transmission line connects the inductively coupling loops in the resonator box. The gap of the inductively coupling coils is adjusted to achieve the critical coupling in the measurement setup. (b) The variation of S_{11} of resonator was described in figure, which is the reflection characteristic of the resonance system. When critical coupling (CC) was achieved, this resonator shows the best S_{11} value at 1.15 GHz.

2.2 Measurement procedures

We used three intact human teeth donated by local dentist by Korean subjects. The selected teeth had no dental cavities or metal fillings. Before irradiation, the teeth were measured individually using an EPR tooth dosimeter to measure the background signal. Each tooth was then irradiated with 120 kVp X-rays to accumulated doses of 2, 5, 10 Gy and was measured after each dose. Irradiation was performed using X-RAD 320 (Precision X-Ray, Inc., North Branford, CT). The Farmer chamber was used to calibrate dose. The EPR spectrum was measured using our EPR tooth dosimeter.

As shown in figure 2, each tooth was positioned precisely using a custom-made frame that positioned each tooth within the central region of the magnet. Each tooth sample was placed in a dental putty mold to ease both handling and positioning within the measurement frame.

For each tooth and at each dose, measurements were obtained with the detection loop placed at the center of the middle region of teeth. The coil of the resonator was placed so that the magnetic field generated at the center of the detection coil was perpendicular to the static magnetic field, and the plane of the coil was parallel to the surface of the tooth. The coil placements were consistently maintained during measurements. The EPR spectrum was acquired using standard parameters (scan range, mT; scan time, 10 s; average scans, 10; modulation amplitude, 0.4 mT). This process was iteratively performed for ten data sets for each dose. A Teflon tube was made with containing a solution of 0.1 mM 4-oxo-2,2,6,6,-tetramethylpiperidine-d16-1-15N-1oxyl(^{15}N-PDT) was placed in close proximity to the surface loop and was used as a reference standard which also be used as the validation for magnitude of the magnetic field described as point of x-axis.

The spectra from the collected data sets were analyzed using nonlinear least-squares fitting to estimate the peak-to-peak signal amplitude of the radiation-induced signals. These acquired data were then averaged to obtain the mean amplitude for each tooth at each dose point [6].

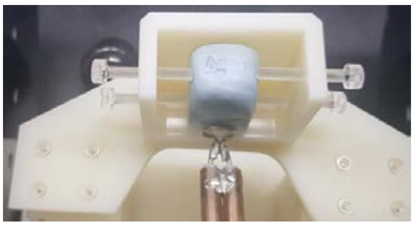

Fig. 2. The teeth phantom was position at surface coil of resonator. The phantom was inserted into custom-made immobilization frame made of non-magnetic material polycarbonate which is non-magnetic material.

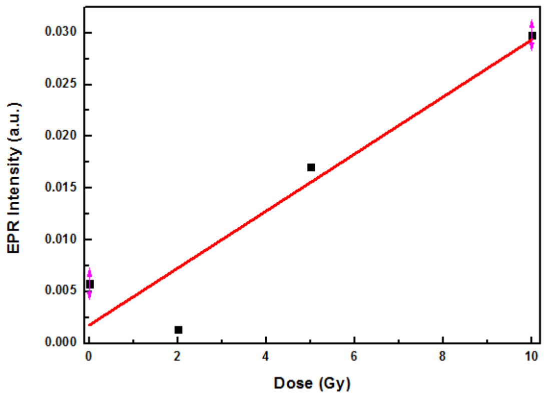

Fig. 3. The established calibration curve between the irradiated dose and EPR intensity. The R-square value was 0.89 within investigated dose range.

2.4 Simulation of the EPR tooth dosimeter

The EPR signal intensity (S) is proportional to the product of the quality factor (Q) of resonator with the η of the resonator [7]. It can be expressed as follows

$$S \propto x\eta Q\sqrt{P_{in}}$$

Where “x” is the magnetic susceptibility of the sample, and P_{in} is the incident microwave power. The filling factor μ is equal to the ratio of the magnetic energy of the radio frequency in the teeth to the total magnetic energy in the resonator system. A 3D model of the surface coil resonator was modeled and validated. Then, electromagnetic fields were calculated at 1.15 GHz using an ANSYS HFSSTM 3D full-wave model microwave filed simulator (ver. 17.0.0; Ansys Inc., Canonsburg, PA, USA). Teeth model from micro CT for simulations of the magnetic fields as shown in figure 4.

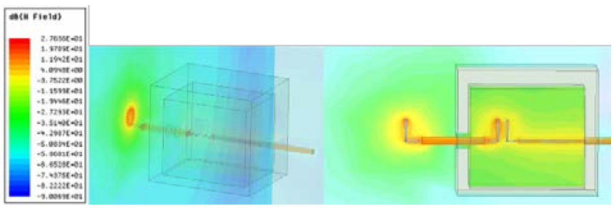

Fig. 4. The magnetic energy distribution of modeled resonator. The resonator was modeled and simulated to mimic the measurement environment in terms of critical coupling, which is the status for the best measurement performance. The magnetic energy was mainly stored within the surface coil of resonator.

To understand the variation of the EPR intensities along the depth (thickness direction of enamel), we performed simulations with the variation of depth. We used the simulation parameters based on the previous article [8]. For the enamel region of teeth, the dielectric constant ε_r was 7.625, and the dielectric loss tangent tan δ was 0.0656. The simulation results were described in figure 5. The EPR intensity was dramatically decreased with depth.

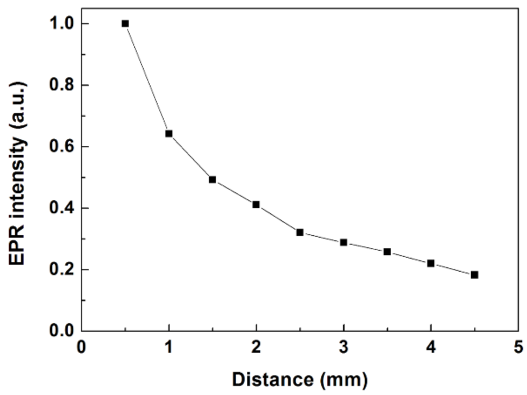

Fig. 5. The relative EPR intensity was decreased along the depth.

The energy distribution in a sample affects the filling factor and the sensitivity of EPR measurement. The energy density of magnetic fields is proportional to the square of magnetic field intensity. The RF magnetic energy in an enamel can be calculated as the integral of the energy density over the enamel region of teeth. The spatial profile of the magnetic energy in enamel was obtained from the magnetic energy in the enamel of teeth of the simulated model. As shown in figure 6, we investigated three types of teeth, which are the incisor, premolar and molar teeth to understand variations of EPR intensity among the type and volume of tooth.

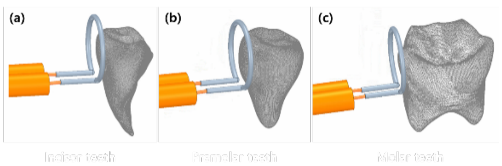

Fig. 6. The modeled teeth with resonator on the ANSYS HFSS software (a) incisor teeth (b) premolar teeth, (c) molar teeth.

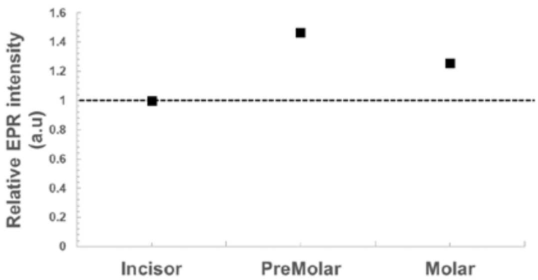

Fig. 7. The results of relative EPR intensity. The relative EPR intensity of Premolar shows approximately 40% higher than incisor teeth. The relative EPR intensity of molar shows approximately 20% higher than incisor.

2.5 In-vivo dosimetry

EPR measurement was performed over the course of total body irradiation patient using the EPR tooth dosimeter and the standard EPR acquisition parameters under agreement from patient (scan range, mT; scan time, 5 s; average scans, 5; modulation amplitude, 0.4 mT). The standard error of inverse prediction (SEIP) was 2.11 Gy from our dose response curve. The dose was prescribed of 12 Gy to the midline at the umbilicus. The predicted dose was 17.6 Gy calculated from our dosimeter.

3. Conclusions

We developed EPR spectroscopy for in-vivo tooth dosimetry called as EPR tooth dosimeter. We also established dose response curve for dose estimation. The amplitude of the EPR is dependent on the thickness of the underlying enamel. The SEIP would be decreased with additional measurements with in-vivo volunteer and patients for the establishment of the dose response curve.

In the future study, we will implement the automatic frequency control circuit to compensate the movement of subjects. We are also developing automatic matching control system to minimize the variation of coupling status during the measurements. Finally, we will finish the establishment of accurate in vivo tooth dosimetry system for triage the end of this year.

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