THE APPLICATION AND DISTRIBUTION OF MAGNETIC FIELD MODULATION IN THE DETECTION APERTURES OF X-BAND EPR CAVITIES FOR *IN VIVO* TOOTH DOSIMETRY

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In vivo electron paramagnetic resonance tooth dosimetry could be a practical and ideal tool for quick mass triage of victims in the rescue following a disaster event involving irradiation radiation. Magnetic field modulation is an important issue to improve the sensitivity of X-band *in vivo* tooth dosimetry. We designed a couple of trapezoidal modulation coil sets fixed on the magnet poles that could be used to apply sufficient magnet field modulation into the detection aperture of the resonant cavity. Measurements of irradiated teeth with such coil sets demonstrated significant radiation-induced signals. The modulation generation efficiencies and magnetic field distributions in apertures with different cavity geometries were analytically calculated, simulated by a finite element method and evaluated by measurements of a free radical point sample to study the influences caused by the geometries of the apertures and other factors.

INTRODUCTION

Electron Paramagnetic Resonance (EPR) tooth dosimetry has been long recognized as a method for assessment of individual absorbed ionizing dose following a large disaster event involving ionizing radiation^(1–3). Traditional EPR spectrometry offers precise detection of tooth samples but is not appropriate for *in vivo* tooth detection. The feasibility of EPR *in vivo* dosimetry was proposed a few years ago^(4–6). Since then an L-band *in vivo* EPR spectrometer has been developed and described in practical use^(7–15).

Beyond L-band, there are several fundamental advantages associated with increases in radio frequency (RF) frequency and magnetic field strength for *in vivo* EPR tooth dosimetry. The signal-to-noise ratio is predicted to increase in proportion to RF frequency; this has been supported experimentally by comparing L-band and S-band EPR spectrometers that showed improvement of the detection sensitivity when working at higher RF frequency⁽⁸⁾. Our recently developed cavities for an X-band *in vivo* EPR dosimeter indicated that X-band *in vivo* tooth dosimetry could be feasible in practice^(16–18).

Magnetic field modulation is an important factor for improving the detection sensitivity of X-band *in vivo* dosimetry. Conventional EPR uses a modulated magnetic field to enable narrow bandwidth phase-sensitive detection to be performed with associated improvements in the signal to noise. Traditional magnetic field modulation is commonly achieved by placing small Helmholtz coils on each side of the

cavity along the axis of the static field. The modulation field electromagnetic wave has to penetrate through the thin conductive layers of the cavity walls.

X-band EPR *in vivo* tooth dosimetry utilizes specially designed cavities. In this case, the detection area is the cavity ‘aperture’ which is an air gap surrounded by metal cavity walls. The thickness of the cavity wall is normally >1.5 mm and is thicker than the skin depth for common modulation frequency. Therefore, trapezoidal coil sets were designed to generate sufficient magnetic field modulation. In order to meet the requirement of *in vivo* measurement for people, the coils were designed to be distant from the cavity to simplify the structure of the cavity and leave more space for *in vivo* operation in the narrow space of the magnet gap.

In our previous work, we studied the microwave distribution features around the cavity aperture^(16–18). The microwave leaking efficiency in the aperture area was dependent on the aperture geometry. In a subsequent experiment, we found that the relationship between the geometry and the field modulation efficiency in the aperture area was another important issue for improving the detection sensitivity of the cavity design. Therefore, in the work reported here, the generation efficiency and field distribution of magnetic field modulation under different aperture geometries or frequencies was analytically calculated and simulated by a finite element method to study the influence of the geometry of the aperture, and to thereby obtain a constructive reference for further cavity designs. The parameters included the structure of coil sets, the geometry of detection aperture and the RF frequency.

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MATERIALS AND METHODS

X-band *in vivo* tooth EPR dosimeter

The homemade EPR spectrometer included a magnet that had a relatively large gap for *in vivo* measurements, a resonant cavity with a detection aperture, an alternating current power amplifier for modulation, a signal receiver and a data processing unit and other relevant equipment. Figure 1a shows a sketch of the structure of the dosimeter. This dosimeter has been used in some *in vitro* and *in vivo* experiments and showed it could measure radiation-induced signals from irradiated teeth. The static magnet field and scan magnet field were applied using a C-shape magnet, composed of static magnet poles combined with electromagnet coils. The tapered magnet poles had a relatively larger air gap than a conventional EPR spectrometer. Therefore, it could comfortably encompass the chin of a human subject.

Figure 1b shows a view of the outer surface of the resonant cavity, which was specially designed for *in vivo* tooth detection and had a detection aperture in the metal cavity wall where human teeth can bite into when being measured. The detection aperture was a rectangular slot in the xy plane and penetrating along the z -axis of the cavity structure. The scanning magnet field and modulation field could penetrate into the aperture, and the microwave electromagnetic field could leak into the aperture to fulfill the EPR detection conditions. The modulated magnetic field was applied by a couple of coil sets separated from the cavity and combined with the static magnet poles. The direction of the modulated field was the same as the static magnet direction. The coil sets were driven by a matched alternating current power amplifier.

The coil sets for magnetic field modulation

Figure 2 shows the cross-section drawing of the coil sets for magnetic field modulation. The coils were placed on a plastic base support of a circular truncated cone with diameters of 20 mm at the top and 60 mm at bottom. Each coil set had three layers, and each layer had 30 loops for a total of 90 loops on one coil set.

In single layer, the radius R of the n th loop and horizontal distance, $x(n)$, from the n th loop center to the magnet gap center was

$$\begin{cases} R(n) = 0.01 + d(n) \\ x(n) = 0.04 + 0.25 \times d(n) \\ d(n) = 0.0007 \times n, n = 0 - 29 \end{cases} \quad (1)$$

As the wire diameters of the coils were quite small compared with the coil set diameter and magnet gap distance, the loops in different layers were regarded at the same position in the following calculations. According to the Biot–Savart law, the magnetic flux $\mathbf{B}$ induced by current element $d\mathbf{l}$ at point P was

$$d\mathbf{B} = \frac{\mu_0 I d\mathbf{l} \times \mathbf{a}}{4\pi r^3} \quad (2)$$

where I was current intensity in the wire, $\mathbf{a}$ was unit vector point from $d\mathbf{l}$ to P , r was distance from $d\mathbf{l}$ to P and μ_0 was magnetic permittivity in a vacuum.

If P was a point on the central axis (defined in Figure 2), the magnetic flux intensity $\mathbf{B}$ induced by a single loop was

Figure 1. The scheme of the X-band EPR spectrometer for *in vivo* dosimetry (a) and the resonant cavity with detection aperture (b).

Figure 2. The cross-section drawing of the coil sets for magnetic field modulation.

$$\vec{B} = \frac{\mu_0 R^2 I}{2(R^2 + x^2)^{3/2}} \vec{a} \quad (3)$$

where R was the loop radius, x was the distance between the coil center and the point P and $\vec{a}$ was the unit normal vector through the circle center of the coil loop.

Considering all the coils of the sets, the magnetic flux intensity B_m at center point P (defined in Figure 2) was

$$\vec{B}_m = 2 \times \sum_{i=1}^3 \sum_{n=0}^{29} \frac{\mu_0 R(n)^2 I}{2(R(n)^2 + x(n)^2)^{3/2}} \vec{a} \quad (4)$$

After calculation, the result was

$$|B_m| \approx I \times 4.2 \times 10^{-4} T \quad (5)$$

The generation efficiency of modulation amplitude, k_0 , was

$$\begin{cases} |B_m| = k_0 I \\ k_0 = 4.2 \times 10^{-4} T/A \end{cases} \quad (6)$$

The magnetic flux intensity at any point on the axis was

$$\begin{aligned} |\vec{B}_m| = 3 \times & \left(\sum_{n=0}^{29} \frac{\mu_0 \times R(n)^2 I}{2 \times (R(n)^2 + (x(n) + x')^2)^{3/2}} \right. \\ & \left. + \sum_{n=0}^{29} \frac{\mu_0 \times R(n)^2 I}{2 \times (R(n)^2 + (x(n) - x')^2)^{3/2}} \right) \end{aligned} \quad (7)$$

where x' was the distance between the measurement point and the center point P .

The aperture geometry of the cavity

The modulation efficiency and distribution had close relationships with the geometry of the cavity aperture. A rectangular cavity for *in vivo* EPR dosimetry in TE₁₀₁ mode was used in the calculations and experiments. The electromagnetic field of the TE₁₀₁ cavity along the x -axis (the coordinate system was defined in Figure 1b) was uniform, so that the magnetic field modulation effect along the x -axis could be studied separately. The detection aperture was open through the cavity's metal wall for sample detection.

In order to investigate the efficiency and distribution of magnetic field modulation under different aperture geometries, the aperture was defined with different sizes and geometries, which are described in Figure 3a: (1) rectangular, width 3 mm, (2) rectangular, width 2 mm, (3) rectangular width 4 mm, (4) trapezoidal, expanded to outside, (5) trapezoidal, expanded to inside. We observed that 2 mm was the smallest width possible for incisor cusp insertion and the resonant quality factor Q would decrease significantly if the width was >4 mm.

The finite elements simulation

The finite element calculation method used the following parameters: edge current on the coil sets, 1 A; frequency, 100 and 10 kHz for comparison; major element type, tetrahedral and triangular elements; maximum element size, 7.66 mm; minimum element size, 0.0766 mm, number of elements, $\sim 1000\ 000$; RAM cost, ~ 40 GB, computer platform: DELL server T620, Software: COMSOL Multiphysics.

The simulation was designed with six variations of the magnetic field distribution: (1) the magnetic field distribution when generated by the coil sets in empty space (without cavity structure between coils), then the magnetic field distribution varying by type of cavity aperture, i.e. with (2) a rectangular aperture of 3 mm in width (regarded as the standard condition, Figure 3a(1)), (3) a rectangular aperture of 2 mm in width (narrow aperture, Figure 3a(2)), (4) a rectangular aperture of 4 mm in width (wide aperture Figure 3a(3)), (5) a trapezoid aperture expanded to inside (Figure 3a(4)) and (6) a trapezoid aperture expanded to the outside (Figure 3a(5)).

Free radical point sample and measurement

A DPPH (1,1-Diphenyl-2-picrylhydrazyl radical 2,2-Diphenyl-1-(2,4,6-trinitrophenyl) hydrazyl) sample was used as a standard free radical point sample for a system check and calibration of the signal intensity. DPPH powder was inserted into a quartz capillary, 1 mm in length and 1 mm in diameter. The DPPH sample was fixed in the cavity's aperture. Typical experimental parameters were microwave power 1 mW, scan time 10 s, time constant 0.03 s,

Figure 3. (a) The geometry of the aperture; (b) y - z cross section of the cavity; (c) x - y cross section of the cavity. The geometry of the aperture: (1) rectangular, width 3 mm; (2) rectangular, width 2 mm; (3) rectangular, width 4 mm; (4) trapezoid, expanded to outside; (5) trapezoid, expanded to inside. The coordinate system was defined in Figure 1b.

scan width 10 mT, center field 0.34 T and modulation amplitude 0–2 mT.

Tooth sample measurement

One human incisor that had no significant dental cavities, metal fillings or history of endodontic treatment was selected for this work. The tooth was irradiated by a ^{60}Co radiation source with a dose of 6 Gy and was immersed in physiologic saline to simulate the *in vivo* environment after exposure. The tooth was wiped dry and fixed in a gum model when measured. Only the incisal edge of the incisor was inserted into the cavity's aperture to ensure that the enamel was the main part of the tooth detected. The EPR measurement parameters were scan time, 100 s; scan width, 10 mT; microwave frequency, 9.6 GHz; microwave power, 20 mW; time constant, 0.03 s; specified modulation amplitude 0.5 mT.

RESULTS

Magnetic field modulation distribution by analytical calculation and finite element simulation

Figure 4a compares the modulation amplitude along the axis estimated by analytical calculation and by finite element simulation. The calculation result showed the modulation amplitude (norm of the magnetic flux intensity) along the x -axis from -50 to 50 mm (0 mm was the center of the aperture) by analytical calculation using equation (7). The results were (1) the modulation amplitude varied obviously along the axis and reached the strongest near the coils and lowest in the center area and (2) the non-uniformity was $<2\%$ from -5 to 5 mm. The close congruence between the simulation and calculation results provided mutual verification of each other.

The simulation result was lower than analytical calculation by $\sim 3.5\%$. This loss was probably related with the modeling precision during processing.

Figure 4b shows the modulation amplitude before and after the cavity was placed between the coil sets. In the simulation, the detection aperture was a rectangular slot in the xy plane and penetrating along the z -axis of the cavity body. The results indicated that (1) the change in field distribution was obvious in the aperture area when surrounded by the metal wall, (2) the modulation became quite nonuniform in the aperture area ($3.9\text{--}9 \times 10^{-4}\text{T}$), (3) the magnetic field modulation amplitude was slightly lower (4.5%) in the center point and (4) the modulation amplitude was remarkably enhanced in the edge of the aperture induced by the metal wall.

Figure 4c compares the modulation amplitude when the aperture width changed. The results indicated that when the aperture width was narrower: (1) the modulation amplitude was lower in the center point (14.6% when 2 against 4 mm), (2) the modulation was more nonuniform in the aperture area and (3) the modulation amplitude was more enhanced near the edge of the aperture ($\sim 16.8\%$ when 2 against 4 mm).

Figure 4d shows the change of modulation amplitude when the aperture geometry changed. The results indicated that (1) the modulation amplitude is slightly reduced at the center point and became more nonuniform when the aperture changed from rectangular to trapezoid and expanded to the outside and (2) the modulation amplitude is slightly enhanced at the center point and becomes less nonuniform when the aperture is changed from rectangular to trapezoid and expanded to the inside.

Figure 4e compares the modulation amplitude when the frequency is changed. The results indicated

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Figure 4. The magnetic field modulation amplitude along the axis generated by the coil sets driven by alternating current of 1 A in amplitude. (a), the modulation amplitude without cavity by analytical calculation and finite element simulation; (b), the modulation amplitude simulation without cavity and with cavity of 3 mm width aperture; (c), the modulation amplitude by simulation when the widths of the aperture of the cavity were 2 , 3 and 4 mm; (d), the modulation amplitude by simulation result when the geometry of the aperture changed; (e), the modulation amplitude when the frequency changed; (f), the simulation results of modulation inhomogeneity in z-axis. The 0 point in x-axis and z-axis was the center of the aperture and at the boundary between the inner cavity and the metal body.

that: (1) the modulation amplitude was about the same when the frequency changed, (2) the modulation was less nonuniform when the frequency was lower and (3) the modulation amplitude was more enhanced near the aperture edge when the frequency was higher (9.8% when 100 against 10 kHz).

Figure 4f indicates the simulation results of modulation inhomogeneity in z -axis. The results indicated that (1) the modulation amplitude decreased when the aperture was ‘deeper’ and (2) it varied from 3.8 to 5×10^{-4} T in the aperture center area ($-2 \sim 0$ mm in z -axis).

Apply magnetic field modulation in DPPH and irradiated tooth measurement

Figure 5a shows a batch of EPR spectra acquired from DPPH measurements under gradually increasing modulation amplitude. The line intensity change and line width increase implied sufficient modulation amplitude was applied into the aperture of the cavity. Figure 5b shows a spectrum of a 6 Gy tooth, clearly showing the radiation-induced signal, providing evidence that this device could be used for tooth dose assessment.

Modulation efficiency by the coil sets

Figure 6a shows the spectral amplitude of free radical point sample (DPPH) measurement against increasing modulation amplitude on a calibrated spectrometer (Bruker A-300), and Figure 6c shows the spectral amplitude against increasing driven current I in the modulation coil sets on the homemade

spectrometer. The spectral amplitude first increased linearly with modulation amplitude $|B_m|$, then reached a maximum and finally decreased slowly. However, long before the line amplitude reached a maximum, the observed line width increased significantly. The line amplitude reached a maximum when the $|B_m|$ was 0.55 mT in Figure 6a, while it reached maximum when the I was 1.40 A in Figure 6c. So the modulation efficiency k_1 was roughly estimated to be

$$\begin{cases} |B_m| = k_1 I \\ k_1 = 3.9 \times 10^{-4} \text{ T/A} \end{cases} \quad (8)$$

This result was close to the calculation result ($k_0 = 4.27$).

Figure 6b and 6d compares the line width against increasing modulation amplitude or driven current I from a calibrated spectrometer (Bruker A-300) and the homemade *in vivo* spectrometer. If the curve was fitted using a linear model, for Figure 6b, the line width W was

$$W = 0.85 \times |B_m| \times 10^4 + 0.40 \quad (9)$$

For Figure 6d, the line width W was

$$W = 2.90 \times I \times 10^4 + 0.34 \quad (10)$$

So the modulation efficiency k_2 was estimated to be

Figure 5. The EPR spectra acquired from DPPH measurements under gradually increasing modulation amplitude (a) and the spectrum acquired from a 6 Gy irradiated tooth (b).

Figure 6. Modulation amplitude response of free radical point sample measurement; (a) and (b), the spectral intensity and line width against increasing modulation amplitude acquired from the Bruker A-300; (c) and (d), the spectral intensity and line width acquired from the homemade spectrometer.

$$\begin{cases} |B_m| = k_2 I \\ k_2 \geq 3.4 \times 10^{-4} T/A \end{cases} \quad (11)$$

The average modulation efficiency k of k_1 and k_2 was

$$\begin{cases} k = (k_1 + k_2)/2 \\ k \approx 3.7 \times 10^{-4} T/A \end{cases} \quad (12)$$

Modulation distribution in the aperture by free radical point sample measurement

Figure 7 shows the spectral amplitude in DPPH measured when the sample was placed at different positions on the x -axis in the aperture. The signal intensity was the lowest when the sample was placed in the center and gradually increased when the sample was gradually moved to the edge of the aperture. This tendency was in accord with the

modulation distribution from simulation results in Figure 4c.

However, the simulations and experimental result of inhomogeneity along the x -axis are substantially different in magnitude, potentially related to the fact that the simulation result was based only on the magnetic field, but the experimental result was affected by both the modulation and microwave field in the aperture at the same time. This suggests that the microwave field in the aperture might have some inhomogeneity. In addition, the size of the DPPH sample (1 mm in diameter and 1 mm in length) used for the experimental measurements was another factor that should be considered because the modulation magnet field in the aperture was quite non-uniform ($4-9 \times 10^{-5}$ in 5 mm) according to Figure 4c.

DISCUSSION

As the cavity structure and modulation method changed in the schema of our X-band *in vivo* EPR dosimeter, there was a concern whether sufficient

Figure 7. The spectral amplitude from free radical point sample measured when the sample was placed at different positions on the x -axis in the aperture.

magnetic field modulation could be applied at the aperture due to attenuation caused by the metal cavity metal since the skin depth in copper was only ~ 0.25 mm at 100 kHz, which was much thinner than the thickness of cavity wall. The simulations and experiments in this work showed that sufficient magnetic field modulation could be generated at the aperture and the scheme of the cavity and coil sets was practical in applications, even though the magnetic modulation was inhomogeneously distributed in the aperture.

The homogeneity of the magnetic field modulation would be unsuitable for some analytic spectroscopy applications, but for dosimetry the prime concern is the signal intensity, and some line distortion can be tolerated. The $|B_m|$ should be increased until a maximum derivative amplitude is obtained⁽¹⁸⁾. Based on our experimental results, the field inhomogeneity caused line distortion but did not remarkably hinder the acquisition of the radiation-induced signal. In fact appropriate excessive modulation amplitude improved the signal-to-noise ratio in tooth measurements according to the experimental results.

The coil sets were separated from the cavity, which allowed the structure of the cavity to be simplified. This allowed the volume of the cavity to be reduced and as a consequence more space for *in vivo* application was available. This design helped to improve quality factor Q of the cavity and the detection sensitivity.

The simulation and point sample measurements showed the regular pattern of how magnetic field modulation is distributed in the aperture area, i.e. (1) the simulation result was approximately equal to the analytical result of the magnetic field modulation amplitude at the center point along the x -axis, (2) the efficiency of the magnetic field modulation was

~ 0.37 mT, driven by unit alternating current (100 kHz, 1 ampere) in the center area of the cavity aperture by this coil sets, (3) the modulation amplitude became quite nonuniform in the aperture area, induced by the metal wall of the cavity and it was lowest in the center point and enhanced near the edge of the aperture and (4) a change of geometry and frequency would cause changes of amplitude and uniformity, but not significantly.

To optimize the efficiency and uniformity of the magnetic field modulation, the geometric design of the cavity, especially the aperture, is another major factor besides of the design of the coil sets. This work offers a constructive reference for the future design of X-band cavities and modulation devices for *in vivo* dosimetry. In order to improve the modulation efficiency and homogeneity, the distance between coil sets should be as close to the coil diameter as possible, with a wider and longer aperture and lower frequency to improve toward achieving homogeneity.

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