FLEXIBLE, WIRELESS, INDUCTIVELY COUPLED SURFACE COIL RESONATOR FOR EPR TOOTH DOSIMETRY

Wilson Schreiber^{1,*}, Sergey V. Petryakov¹, Maciej M. Kmiec¹, Matthew A. Feldman^{1,†}, Paul M. Meaney^{1,2,†}, Victoria A. Wood¹, Holly K. Boyle^{1,†}, Ann Barry Flood¹, Benjamin B. Williams¹ and Harold M. Swartz¹

¹Department of Radiology, EPR Center for the Study of Viable Systems, Geisel School of Medicine at Dartmouth, Hanover, NH 03755, USA

²Thayer School of Engineering at Dartmouth, Hanover, NH 03755, USA

*Corresponding author: Wilson.Schreiber@dartmouth.edu

Managing radiation injuries following a catastrophic event where large numbers of people may have been exposed to life-threatening doses of ionizing radiation relies on the availability of biodosimetry to assess whether individuals need to be triaged for care. Electron Paramagnetic Resonance (EPR) tooth dosimetry is a viable method to accurately estimate the amount of ionizing radiation to which an individual has been exposed. In the intended measurement conditions and scenario, it is essential that the measurement process be fast, straightforward and provides meaningful and accurate dose estimations for individuals in the expected measurement conditions. The sensing component of a conventional L-band EPR spectrometer used for tooth dosimetry typically consists of a surface coil resonator that is rigidly, physically attached to the coupler. This design can result in cumbersome operation, limitations in teeth geometries that may be measured and hinder the overall utility of the dosimeter. A novel surface coil resonator has been developed for the currently existing L-band (1.15 GHz) EPR tooth dosimeter for the intended use as a point of care device by minimally trained operators. This resonator development provides further utility to the dosimeter, and increases the usability of the dosimeter by non-expert operators in the intended use scenario.

INTRODUCTION

A variety of resonators for Electron Paramagnetic Resonance (EPR) have been constructed over the years to provide high sensitivity to the absolute number of detectable spins in a given sample. These resonators have been designed in various shapes and sizes, but very seldom allow for high sensitivity measurements *in vivo*, and even fewer allow for practical measurements to be made *in vivo*. Given the intended measurement conditions, scenarios and specifications that dosimetry must meet^(1–4), it is essential that the resonator (and subsequently the EPR dosimeter as a whole) balances the tradeoffs between measurement feasibility, sensitivity, practicality and usability in order to provide a robust measurement setting to ensure sufficient results for those in need of dosimetry.

The intended use of the EPR dosimeter will entail several-hundred to several-thousand individual dosimeters being used in the event of a large-scale event⁽⁵⁾, each measuring thousands of subjects over the course of the response. Many cities/locations will likely need to stockpile the dosimeters and the subsequent supplies. These dosimeters will also need to be used and operated by minimally trained personnel.

Given this general summary of the intended measurement conditions and scenario, the ideal resonator would have the following characteristics:

- Sufficient performance
 - High dosimetric sensitivity
 - Low dependence of position of the resonator on the tooth on the estimated dose
 - Low baseline distortion
 - High coupling capability
 - Low variance across individual resonators
- Sufficient usability and operability
 - Easy to use
 - Hygienic via single-use/disposable components
 - Minimally invasive
 - Use on either left/right upper incisor
 - Comfortable
- Other desirable aspects
 - Mass/repeatable/low-cost manufacturability
 - Minimal preparation, assembly and testing
 - Stable over time

The sensing component of a conventional L-band (1.2 GHz) EPR spectrometer typically consists of a surface coil resonator with a coupler that is rigidly, physically attached to the other components of the EPR spectrometer^(6–9), which can result in bulky and cumbersome operation, limitations in samples and sites that can be measured, reduction in sensitivity and hinder the overall performance and utility of the spectrometer. Other EPR resonators for measuring

[†]Performed research for this paper while at the EPR Center at Dartmouth, but are currently no longer with the Center.

human teeth also have physical dimensions that hinder proper *in vivo* measurements^(10, 11).

This resonator eliminates the need for the measurement sample (in the case of EPR tooth dosimetry: the measurement subject and their tooth) to be physically and electrically connected to the coupler of the EPR spectrometer. This wireless resonator is adhered to the tooth, and inductively coupled to an EPR bridge and spectrometer through the use of an antenna coupler. The coupler has been specifically designed and optimized to transmit power to resonant structures at a given frequency in the presence of lossy materials (materials having significant water content); similar to lossy tissues found in a human mouth. The device has been designed on a low-loss (for 1.15 GHz), flexible substrate (TeflonTM) with a low dielectric constant in order to conform to a wide variety of sizes, shapes and contours of an incisor tooth of a given individual measurement subject. This device has subsequently been designed to be made hygienic and disposable for the given intent of use. These refinements further enable the use of the device in conjunction with an EPR dosimeter by minimally trained operators by removing the significant burden on the operator of the EPR dosimeter (Figure 2).

Wireless is used in this context to indicate that the resonator is not galvanically or physically connected to

the radio frequency (RF) source and detection circuitry of the EPR dosimeter. The resonator is inductively coupled to the rest of the dosimeter through a loop of a neighboring coupling antenna. This facilitates rapid placement of the resonator by a novice operator and the increased flexibility of the resonator allows it to be placed reliably on the tooth with accommodation for a range of natural variation in pitch, curvature or twisted positions of incisor teeth in the mouth.

This novel resonator (Figure 1) reduces the weight and size of the resonator assembly, increases the manufacturability of the resonator, enables single-use disposable sensors/resonators (highly desirable for a medical device, such as this), increases the potential efficiency of the dosimeter, reduces the skill and time required for accurate placement, allows for the placement on most incisor teeth size or geometry and increases the ease of use for minimally trained operators of the EPR spectrometer without compromising the accuracy of the dose estimate, as compared with the ~ 0.05 -Gy dosimetric precision of the conventional rigid loop resonator⁽¹²⁾.

This technology can also easily be adapted for EPR tooth dosimetry at higher frequencies⁽¹²⁾, as well as other EPR applications for viable systems, such as *in-vivo* EPR oximetry or other EPR measurements where resonator flexibility and physical/electrical isolation are desired. This can be

Figure 1. Model of wireless resonator and antenna coupler indicating the various components of the device.

Figure 2. A wireless resonator being placed on an incisor tooth. The bite block is mounted to the magnet and held in the mouth of the subject to facilitate retraction of the lips, and docking into the EPR tooth dosimeter for a measurement.

Figure 3. Ideal resonance circuit consisting of an ideal inductor and capacitor in two configurations (a) showing the simplest configuration and (b) showing an alternative, but equivalent configuration, which is used in the construction of the wireless resonator.

accomplished via straightforward changes in the geometry of the resonant structure in order to accommodate the desired frequency of the EPR spectrometer.

DESIGN OF THE RESONANT STRUCTURE

The ideal resonant circuit comprises an ideal inductor and an ideal capacitor (ideal referring to no electrical resistance) which exchanges energy from one component to another. This resonant circuit is depicted in Figure 3a.

As the design will mimic previously developed surface coil resonators, the initial design for the inductor will consist of a single turn with a total length of $< \frac{1}{4}\lambda$ (λ defined as wavelength in millimeters of the signal in a given sensing medium (air); $\frac{1}{4}\lambda$ is ~ 65 mm). Inductor wire length $< \frac{1}{4}\lambda$ is used as a general rule when designing these types of surface coil resonators in order to ensure that the phase of the energy delivered to the coil does not reverse the effective phase of the energy delivered to the sample, and therefore destructively interfere with the magnetic fields generated by the coil. The coil diameter of the resonators previously developed by Dartmouth⁽⁹⁾ is approximately 10 mm (center-to-center, circular) in

Figure 4. Preliminary design concept for wireless resonator and the relationship to the ideal resonance circuit.

diameter, and was used as a starting point for the design of the resonator. The 10-mm dimension was chosen specifically to match the average width of the upper central incisor teeth⁽¹³⁾. These teeth are known as T8 and T9 in reference to the dental notation ‘Universal numbering system’ in the USA.

In previously designed surface coil resonators⁽⁶⁾, the capacitor of the resonance circuit is either purchased as an off-the-shelf component or tailored from a dielectric material (copper-plated Teflon from Polyflon Co. of Norwalk, CT was used in the past), and soldered onto the resonator. This extra manufacturing step, which is typically done by expert hands, should be removed for the sake of mass manufacturing, minimizing contamination on the resonator that could cause baseline distortion (BLD) or unwanted EPR signals and overall repeatability across resonators. Given that the resonator will be designed on a flexible substrate, the design can also effectively use this substrate as a dielectric in the construction of a capacitor. The resulting design concept can be seen in Figure 4.

A magnetic field is created about the inductor (L) with its resonant frequency dictated by the capacitive divider network (C) at the base of the resonator. The combined, isolated components shown in Figure 3 create an LC-resonance circuit. These two equal capacitors can be treated as one combined element, whose physical lengths, widths and thickness of the dielectric substrate can be varied in order to create the desired LC resonance to stimulate the electron spins within a given sample (such as teeth for tooth dosimetry). For our L-band tooth dosimetry and EPR spectrometers, this frequency is $1.15 \text{ GHz} \pm 15 \text{ MHz}$ (dictated by the bandwidth of the bridge) when the resonator is applied to the tooth, inside a living human mouth.

Several materials were identified as a suitable flexible dielectric material, including KaptonTM (polyamide film), Taconic fastFilmTM, Ultralam[®] and TeflonTM (polytetrafluoroethylene). Due to EPR signals inherent to the other materials (primarily), cost and dielectric/material stability of the substrates, TeflonTM was chosen as the material for the wireless resonator. Teflon also has an advantage of being a

low-loss substrate commonly used in printed circuit board (PCB) industry. Teflon is also known in the medical industry for its biocompatibility⁽¹⁴⁾. The resonator utilizes PCB technology developed for manufacturing microwave circuit (Polyflon of Norwalk, CT), which utilizes a thin, homogenous dielectric substrate (Teflon™) covered with oxygen-free copper on either side. The profile of the resonator, seen in Figure 4, is etched into the copper substrate, and the excess material is removed. This is then coated with a layer of silver, with thickness equal to or greater than the skin depth of the frequency of the EPR resonance condition. For 1.15-GHz L-band, this skin depth equates to $8\text{ }\mu\text{m}$ ⁽¹⁵⁾. Oxygen-free copper and silver plating was used for this design in order to eliminate magnetic components used near/on the resonant structure. This reduces the potential of unwanted spectral BLDs, as well as unwanted paramagnetic centers (which produce an EPR signal), from entering the resonators, which may potentially confound dosimetric estimations. These materials have allowed for the wireless resonator to be conformable to a variety of surfaces, which makes this particularly applicable for tooth dosimetry, where previous rigid designs have suffered from their inability to physically adapt to the highly variable geometry of human incisor teeth.

These materials were also selected as to provide adequate means of cleaning the substrates of contaminants that would otherwise confound dosimetric estimates. Given that many manufacturers are not concerned as to whether or not their materials/processes produce unwanted BLDs for highly-sensitive EPR spectroscopy, we wanted to select materials that could be easily/commercially preventatively cleaned and stored long term for use many years later in the event of an unplanned nuclear incident⁽⁴⁾.

The frequency of the resonator was then optimized to match the center frequency and bandwidth of the bridge to the shifts in resonance frequencies we could expect in the presence of lossy and conductive material. To accomplish this, simulations were performed using a finite element computer simulation software package: Ansoft High Frequency Structure Simulator (HFSS) (Ansys of Cecil Township, PA). The frequency was adjusted by varying the height and width of the capacitor divider network at the base of the resonator, as shown in Figure 4. This can be plotted as S-parameters, showing the resonance characteristics of the circuit, as shown in Figure 5.

The resonance frequency as a function of capacitor dimensions, as seen in Figure 6, can also be plotted to generate a 'tuning curve' which can guide engineering decisions when looking to refine the resonance frequency of the resonator in design iterations.

The maximum magnetic field is generated about the inductor (loop of the resonator, which is what

Figure 5. S-parameter plots showing the effect of changing the capacitor area on the resonator. Each color/shade is a different capacitor dimension, and the dimension of the inductor (coil/loop) is held constant at 10 mm (center-to-center). It should be noted that there are very minute differences in the resonance response across the various frequencies. This indicates that capacitor value can be varied to obtain desired resonance frequency without affecting resonance characteristics, within the bandwidth of the bridge.

Figure 6. Results of parametric sweep of capacitor width indicating the versatility and tune-ability of the resonator design. Any frequency, within the range of the bandwidth of the bridge ($1.15\text{ GHz} \pm 15\text{ MHz}$) can be achieved with the current design, as indicated by the simulation. The fitted (solid) line represents the best fit to the LCR resonance of the circuit.

stimulates the spins in the sample). The electric field, which is primarily contained between the plates of the capacitive elements, is intended to be far away from the loop. The reason for this is that the electric

field is greatly perturbed by the presence of water (lossy human tissue), and can hinder resonator performance (sensitivity to detecting spins) if there is a significant amount of lossy tissue in close proximity to the capacitor. This decrease in performance due to the presence of lossy tissue is referred to a reduction in the quality factor (Q) of the resonator. To compensate for the reduction in Q , the loop circumference was decreased to be less than $\lambda/4$ but kept large enough to provide a sufficient filling factor (intensity of the magnetic field generated at the loop)⁽¹⁶⁾. We have also reduced the Q in favor of a larger filling factor due to a lower- Q resonator being less susceptible to ambient electromagnetic and acoustic noise in a given environment. This has been observed in previous resonator designs for *in vivo* applications at Dartmouth.

Simulations in HFSS verify that the resonator design is sufficient to stimulate the spins, and generate an EPR signal⁽¹⁷⁾, over a large volume of enamel of a human tooth, as shown in Figure 7. These simulations indicate that we are achieving an EPR signal from the tooth, as indicated by the blue-green gradient shown in the top-most graphics of Figure 7. These simulations also provide an estimation of the spatial distribution of where 90% of our EPR signal amplitude originates, which are indicated by the three bottom-most graphics of Figure 7. Each highlighted voxel represents enamel that contributes one arbitrary unit to the EPR signal amplitude. The tooth used for the HFSS model is of an extracted human tooth, which was generated by computed tomography. This allowed the anatomy of the tooth (dentin, pulp and enamel) to be modeled accurately. Material properties were then assigned accordingly

in order to ensure more accurate simulations. The 3D geometry of the resonator was also varied along the surface of the tooth in order to provide a more accurate representation of how the resonator would be applied, and conformed on to the tooth during a dosimetry measurement, and whether we can expect significant changes in EPR signal amplitude.

DESIGN OF THE COUPLER

One of the main goals of the design and use of the wireless resonator is to enable use of the resonator on either the left or right upper incisor (T8 and T9, respectively), and also reduce and simplify the steps that the operator of the dosimeter takes in order to place the resonator and/or coupler on the subjects tooth. For this reason, it is desirable to have a coupler (antenna coupler) that can function independently of which tooth is chosen, and with minimal changes to the setup and/or positioning of the coupler by the operator to facilitate the measurement on a given tooth.

The antenna coupler, depicted in Figure 2, comprises four fundamental components: (1) an ‘antenna loop’ that magnetically/wirelessly transfers RF power into the wireless resonator; (2) a $\frac{1}{4}\lambda$ 100 ohm balun with lengths adjusted to match the desired frequency (1.15 GHz); (3) a variable shunt capacitor used to adjust the coupling of the coupler to the bridge in the EPR spectrometer; and (4) a $\frac{3}{4}\lambda$ 50-ohm transmission line with a SubMiniature version A (SMA) connector that allows the coupler to be connected to the RF bridge of the EPR spectrometer. It should be noted that the characteristic impedance of the RF bridge is 50 ohms, and that the range of the variable capacitor will dictate the coupling capability of the overall device.

The antenna loop comprises silver-coated (to at least one skin depth) copper wire in order to provide low electrical series resistance at our given frequency. The shape of the loop is approximately that of an oval in order to span the width of both upper central incisor teeth. The intent is that the antenna coupler will be able to magnetically couple to a wireless resonator if the wireless resonator is within the projected area of the antenna loop and proximity of the antenna loop. The total length of the wire of the antenna loop must be less than $\frac{1}{4}\lambda$ in the medium through which the coupler is exposed to in order to minimize the effect of phase rotation canceling the coupling effect⁽¹⁸⁾. This limits the overall effective length of the antenna loop wire to approximately 45–50 mm, which still allows the oval shape of the antenna loop to sufficiently cover both upper incisors, as shown in Figure 8. The diameter of this antenna loop wire is also significantly smaller (100–200× smaller) than the $\frac{1}{4}\lambda$ of the working frequency

Figure 7. HFSS simulations indicating the magnetic field generated by the resonator superimposed on the enamel of the tooth (left-most graphics), and the corresponding spatial distribution indicating where 90% of the EPR signal (highlighted voxels) originate from for our dose estimations.

Figure 8. Simplified depiction of the wireless resonator placed on a graphic of human teeth. The projection of the antenna loop is shown and designed to span the overall area where the teeth, and therefore wireless resonator, are expected to be placed for a dosimetry measurement.

in order to minimize the effects of distributed capacitances to ground^(19, 20).

The 100-ohm balun acts as an impedance matching system that facilitates critical coupling of the RF power from the bridge of the EPR spectrometer into the resonant circuit. Conventionally, 50-ohm transmission lines are used to transmit power to a resonant surface coil^(8, 9), whereas 100-ohm transmission lines are used in this design. These transmission lines were custom made to match the outer diameter and attenuation of standard RG401 cable, and manufactured by Coax Co., Ltd of Hokkaido, Japan. The intent of this is to double the impedance of the EPR spectrometer to minimize reflected power at the point where the coupler is connected to the spectrometer, and to eliminate standing waves, which result in resonances within the coupler. These standing waves reduce the overall efficiency of the coupler, and can result in tuning difficulties if the resonances within the coupler are near (in the frequency domain) the expected resonances of the wireless resonators to be measured. The coupler should ideally deliver all RF energy to the resonance circuit that is detecting the spins, and not deliver energy to resonances that do not. Doubling the characteristic impedance at this point also allows the coupler to perform optimally at the frequency that the balun is tuned to, rather than conventional couplers, which typically only provide limited bandwidths.

A mechanical trimmer capacitor (Voltronics NMP8BE) was used as the variable capacitor, which effectively allows the coupler to transfer the most RF power to the resonance circuit (critically coupled). In previously designed resonators^(8, 9), electronic coupling in the form of varicaps or varactors are used as voltage-controlled tunable capacitors, which provide excellent automated control of the coupling property of the resonator. In practice, we have observed very unstable baselines and offsets due to the presence of varactors in resonators that are not completely and properly shielded from the modulation field used for conventional continuous-wave EPR, which stimulates the spins in the permanent magnetic field. It is hypothesized that the unstable baselines and offsets

are caused by the active component(s) in the resonator (varactors) rectifying the modulation field, which is then observed by the bridge as reflected power at our modulation frequency, thus causing the phase sensitive detector of the EPR spectrometer to observe a signal that is not stimulated by the spins. This feature is very detrimental to the detection of small numbers of spins, especially *in vivo*; and therefore, mechanical capacitors were used simply because there are no active or magnetic components in these devices.

A $\frac{3}{4}\lambda$ 50-ohm transmission line with a female SMA connector was placed as an input port to the coupler in order to (1) provide a convenient place to attach/detach an RF cable connecting the coupler to the EPR spectrometer, and (2) provide the ability to attach further matching capabilities, if necessary. The 50-ohm transmission line matches that of the rest of the bridge, and the fixed $\frac{3}{4}\lambda$ distance from the primary coupling element (variable capacitor) allows us to add another coupling element (either variable or fixed) to provide further coupling, as needed without disassembling and the coupler.

HFSS models and simulations were also utilized to provide insight into the relative performance characteristics of the wireless resonator compared with the conventional, rigid loop resonator that is currently used in the *in vivo* EPR tooth dosimeters at Dartmouth. One of the goals of this resonator design was to ensure that the resonator remains in stable contact with the tooth, which can be addressed by using a mild medical/dental grade adhesive on the wireless resonator. This still leaves the possibility of the antenna loop of the coupler moving during a measurement; therefore, we wanted to see the impact on the EPR signal amplitude as the antenna loop moves away from the tooth. The results of this parametric study performed in HFSS, shown in Figure 9, indicate that while the antenna coupler moves away from the tooth, this resonator design can still reliably estimate the EPR radiation induced signal (RIS) amplitude, as long as the antenna coupler remains critically coupled (or close to critically coupled, within reason). The calculation of the EPR signal amplitude in HFSS⁽¹⁷⁾ was performed identically to the simulation shown in Figure 7. This is a clear advantage over the rigid loop resonator. These calculations also provide an indication that the wireless resonator is more sensitive to the absolute number of spins, although these results are only intended to show a relative difference between these two resonators, and the resulting relative trends as the rigid loop or antenna coupler is moved away from the tooth.

BENCH TESTING, PREPARATION AND DOSIMETRIC TESTING OF MANUFACTURED RESONATORS

The wireless resonators were made using commercial microwave substrate processing techniques (via

Figure 9. HFSS results demonstrating the relative loss in EPR signal amplitude as either the antenna coupler, or conventional rigid loop resonator, is translated away from the tooth.

Polyflon of Norwalk, CT), and are likely to have discrepancies between the design and actual resonant frequencies of each of the wireless resonators. The resonance frequency for each wireless resonator was measured using a balanced detection coil connected to an Agilent Technologies® E5071C ENA Series Network Analyzer, and compared with simulation, as shown in Figure 10.

The wireless resonators (and EPR resonators in general) are also expected to have some level of contamination that could contribute to unwanted BLD, if they are not properly cleaned. While the mechanism of this unwanted BLD is not fully understood, evidence suggests that cleaning resonators in diluted hydrochloric acid (~5–10% by volume) for approximately 20 min (longer periods of time have the potential of degrading the silver/copper traces), and rinsing with a solvent (methanol or HPLC-grade isopropanol) for some time remove a majority of the BLD that contributes to significant dosimetric errors.

Using data acquisition parameters previously used for *in vivo* EPR tooth dosimetry⁽¹²⁾, EPR spectra were collected based on measurements of 0 and 10 Gy irradiated extracted human incisors (samples of these spectra are shown in Figure 11). We found that the standard deviation of dose estimates is 0.5–0.6 Gy, independent of the true dose of the tooth. The dosimetric errors across individual wireless resonators are also on the order of 0.5–0.6 Gy, which are comparable to that of the conventional rigid loop resonator.

IN VIVO AND ERGONOMIC TESTING

To test and evaluate the wireless resonators for use *in vivo*, we focused on human factor considerations and evaluated the instrument–user interfaces to

Figure 10. Comparison of simulated and measured resonance frequencies of the wireless resonator. The error in measured frequencies and the simulated frequencies is found to be <1% of each other, across all capacitor width values shown, which provide an indication of a valid simulation. Data from Figure 5 (simulated) are also included.

determine how best to facilitate the usability of the resonator for the operator while maintaining the comfort of the subject.

The *in vivo* wireless resonator was adhered to the front surface of the tooth using double-coated adhesive (3M™ 1577 Double Coated Medical Tape). An applicator structure was designed to facilitate placement of the wireless resonator on the tooth. This applicator comprises a 10-mm diameter, 1/8" Volara® foam dot attached to an applicator rod. It is adhered to the wireless resonator sensor using another piece of the same 3M adhesive. By applying the foam tipped applicator to the back (non-tooth) surface of the wireless resonator, the operator is able to easily apply the resonator sensor to the surface of either tooth (regardless of geometry), lightly conform (using the cushion of the foam) along all edges, and then gently twist off the applicator to remove it for a measurement.

A safety line made of coated nylon thread is attached to a click lock pin that fits securely in a hole on the bite block used to position the subject and teeth within the magnet for measurement (as shown in Figure 12). This safety line acts as a means of both preventing subjects from inadvertently swallowing the resonator (by firmly attaching it to the bite block mounted in the dosimeter), and allowing the quick removal of the wireless resonator by gently peeling the sensor and adhesive off the subject's tooth as they exit the dosimeter. To prevent possible confounders in our data, all of the aforementioned components (3M adhesive, Volara foam, applicator,

Figure 11. Comparison of spectra measured under baseline conditions (no added dose, left) and with 10 Gy added dose (right). Each data set (individual measurement) is fit to a spectral model, where tooth peak-to-peak amplitudes (proportional to dose) are estimated. In the right figure, the EPR signal centered at ~ 413 gauss is the radiation-induced signal in the enamel, and the EPR signal located at ~ 423 gauss is an EPR reference standard (15N-PDT) used to mark the absolute field.

Figure 12. *In vivo* wireless resonator assembly. Shown is the wireless resonator with adhesive on tooth-side (not visible), applicator assembly and safety line attached to a bite block.

etc.) were screened to determine whether or not there was an intrinsic EPR signal in each material, both at X-band and at L-band. None of the materials used had a distinguishable EPR signal. The entire *in vivo* assembly can be seen in Figure 12.

These human factor components allow for decreased resonator application time, greater ease-of-use, increased work flow, the potential for fewer operators and minimal operator training without compromising the accuracy of the dose estimate.

CONCLUSION

This novel resonator has been proven to have sufficient dosimetric precision to be useful in a Point of Care device for detecting meaningful doses⁽²²⁾. The

precision of dose estimation of 0.5–0.6 Gy has been shown to be comparable to that of the rigid loop resonator^(12, 21), which indicates that this novel resonator design could replace the rigid loop resonator without sacrificing dosimetric performance of the EPR dosimeter. This resonator also provides the potential to reduce the overall complexity of the measurement, reduces the weight and size, increases the manufacturability and enables single-use disposable sensors (highly desirable for a medical device). These advancements further provide potential to increase the throughput of the dosimeter, and increase the utility of the EPR spectrometer as a dosimeter to be used by minimally trained operators.

ACKNOWLEDGEMENTS

The authors are grateful to Selaka Bulumulla and his team at GE Global Research for their assistance in the early design stages and material identifications; Hiroshi Hirata for identifying Coax Co. Ltd as a manufacturer of the 100-ohm coaxial cable; Kevin Rychert, formerly of the EPR Center, for his assistance in data processing of the RIS for irradiated teeth; Spencer Brugger, formerly of the EPR Center, for his assistance in computer aided drawing and carrying out testing procedures; Mike Melkers and Roger McWilliams of Lyme Dental; Farm Design Inc., and Paul Calderone, consultants for the

EPR Center, for their assistance in developing ergonomic components of this technology.

FUNDING

This work was performed as part of contract HHSO201100024C with the Biomedical Advanced Research and Development Authority (BARDA), within the Office of the Assistant Secretary for Preparedness and Response, US Department of Health and Human Services.

REFERENCES

- Buddemeier, B. and Dillon, M. *Key Response Planning Factors for the Aftermath of Nuclear Terrorism*. (Livermore, CA: Lawrence Livermore National Laboratory (LLNL)) (2009).
- Gougelet, R. M., Rea, M. E., Nicolalde, R. J., Geiling, J. A. and Swartz, H. M. *The view from the trenches: part 1: emergency medical response plans and the need for EPR screening*. *Health Phys.* **98**(2), 118–127 (2010).
- Grace, M. B., Moyer, B. R., Prasher, J., Cliffer, K. D., Ramakrishnan, N., Kaminski, J., Coleman, C. N., Manning, R. G., Maidment, B. W. and Hatchett, R. *Rapid radiation dose assessment for radiological public health emergencies: roles of NIAID and BARDA*. *Health Phys.* **98**(2), 172–178 (2010).
- Waselenko, J. K., MacVittie, T. J., Blakely, W. F., Pesik, N., Wiley, A. L., Dickerson, W. E., Tsu, H., Confer, D. L., Coleman, C. N. and Seed, T. *et al. Strategic National Stockpile Radiation Working Group. Medical management of the acute radiation syndrome: recommendations of the Strategic National Stockpile Radiation Working Group*. *Ann. Intern. Med.* **140**(12), 1037–1051 (2004).
- Flood, A. B., Boyle, H. K., Du, G., Demidenko, E., Nicolalde, R. J., Williams, B. B. and Swartz, H. M. *Advances in a framework to compare bio-dosimetry methods for triage in large-scale radiation events*. *Radiat. Prot. Dosim.* **159**(1–4), 77–86 (2014).
- Sugawara, H., Hirata, H., Petryakov, S., Lesniewski, P., Williams, B. B., Flood, A. B. and Swartz, H. M. *Design and evaluation of a 1.1-GHz surface coil resonator for electron paramagnetic resonance-based tooth dosimetry*. *IEEE Trans. Biomed. Eng.* **61**(6), 1894–1901 (2014).
- Williams, B. B. *et al. A deployable in vivo EPR tooth dosimeter for triage after a radiation event involving large populations*. *Radiat. Meas.* **46**(9), 772–777 (2011).
- Hirata, H., Walczak, T. and Swartz, H. M. *Electronically tunable surface-coil-type resonator for L-band EPR spectroscopy*. *J. Magn. Reson.* **142**(1), 159–167 (2000).
- Salikhov, I., Hirata, H., Walczak, T. and Swartz, H. M. *An improved external loop resonator for in vivo L-band EPR spectroscopy*. *J. Magn. Reson.* **164**(1), 54–59 (2003).
- Sirota, K., Twig, Y. and Blank, A. *Pulsed electron spin resonance ex situ probe for tooth biodosimetry*. *Appl. Magn. Reson.* **44**(6), 671–689 (2013).
- Junwang, G., Qingguan, Y., Jianbo, C., Lei, M., Guofu, D., Goushan, Y. and Ke, W. *New developed cylindrical TM010 mode EPR cavity for X-band in vivo tooth dosimetry*. *PLoS One.* **9**(9), e106587 (2014).
- Williams, B. B., Flood, A. B., Salikhov, I. K., Kobayashi, K., Dong, R., Rychert, K., Du, G., Schreiber, W. and Swartz, H. M. *In vivo EPR tooth dosimetry for triage after a radiation event involving large populations*. *Radiat. Environ. Biophys.* **53**(2), 335–346 (2014).
- Ash, M. M. and Nelsn, S. J. *Dental Anatomy, Physiology, and Occlusion*. (Philadelphia, PA, USA: Saunders-Elsevier Health Sciences) (2003).
- Stanley, H. R. *Toxicity Testing of Dental Materials*. (Miami, FL, USA: CRC Press) (1985).
- Aeroflex Inc. *Microwave Datamate: Introduction to RF Signal Jamming*. (Plainfield, New York, USA: Aeroflex Inc.) (2011).
- Eaton, G. R., Eaton, S. S., Barr, D. P. and Weber, R. T. *Quantitative EPR*. (Germany: Springer-Verlag/Wein) (2010).
- Pollock, J. D., Williams, B. B., Sidabras, J. W., Grinberg, O., Salikhov, I., Lesniewski, P., Kmiec, M. and Swartz, H. M. *Surface loop resonator design for in vivo EPR tooth dosimetry using finite element analysis*. *Health Phys.* **98**(2), 339–344 (2010).
- Petryakov, S., Samouilov, A., Kesselring, E., Wasowicz, T., Caia, G. L. and Zweier, J. L. *Single loop - multi gap resonator for whole body epr imaging of mice at 1.2 ghz*. *J. Magn. Reson.* **188**(1), 68–73 (2007).
- Schelkunoff, S. A. and Friis, H. T. *Antennas: Theory and Practice*. (New York, NY, USA: John Wiley and Sons) (1952).
- Wadell, B. C. *Transmission Line Design Handbook*. (Norwood, MA, USA: Artech House Inc.) pp. 386 (1991).
- Williams, B. B., Dong, R., Nicolalde, R. J., Matthews, T. P., Gladstone, D. J., Demidenko, E., Zaki, B. I., Salikhov, I. K., Lesniewski, P. N. and Swartz, H. M. *Physically-based biodosimetry using in vivo EPR of teeth in patients undergoing total body irradiation*. *Int. J. Radiat. Biol.* **87**(8), 766–775 (2011).
- Swartz, H. M., Flood, A. B., Williams, B. B., Dong, R., Swarts, S. G., He, X., Grinberg, O., Sidabras, J., Demidenko, E. and Gui, J. *et al. Electron paramagnetic resonance dosimetry for a large-scale radiation incident*. *Health Phys.* **103**(3), 255–267 (2012).