DIELECTRIC-BACKED APERTURE RESONATORS FOR X-BAND *IN VIVO* EPR NAIL DOSIMETRY

Oleg Grinberg¹, Jason W. Sidabras², Dmitriy S. Tipikin¹, Vladimir Krymov¹, Michael Mariani¹, Matthew M. Feldman¹, Maciej M. Kmiec¹, Sergey V. Petryakov¹, Spencer Brugger¹, Brandon Carr¹, Wilson Schreiber¹, Steven G. Swartz³ and Harold M. Swartz^{1,*}

¹Geisel School of Medicine at Dartmouth, Hanover, NH 03755, USA

²Department of Biophysics, Medical College of Wisconsin, Milwaukee, WI 53211, USA

³Department of Radiation Oncology, University of Florida, Gainesville, FL 32610, USA

*Corresponding author: Harold.M.Swartz@dartmouth.edu

A new resonator for X-band *in vivo* EPR nail dosimetry, the dielectric-backed aperture resonator (DAR), is developed based on rectangular TE₁₀₂ geometry. This novel geometry for surface spectroscopy improves at least a factor of 20 compared to a traditional non-backed aperture resonator. Such an increase in EPR sensitivity is achieved by using a non-resonant dielectric slab, placed on the aperture inside the cavity. The dielectric slab provides an increased magnetic field at the aperture and sample, while minimizing sensitive aperture resonance conditions. This work also introduces a DAR semi-spherical (SS)-TE₀₁₁ geometry. The SS-TE₀₁₁ geometry is attractive due to having twice the incident magnetic field at the aperture for a fixed input power. It has been shown that DAR provides sufficient sensitivity to make biologically relevant measurements both *in vitro* and *in vivo*. Although *in vivo* tests have shown some effects of physiological motions that suggest the necessity of a more robust finger holder, equivalent dosimetry sensitivity of approximately 1.4 Gy has been demonstrated.

INTRODUCTION

There exists a need for rapid screening and ionizing radiation dose assessment of populations after an incident where it is very desirable to provide the most efficient treatments based on an individual's radiation dose in the range that could lead to acute radiation syndrome^(1–3). Dosimetry methods must provide a means of triaging large populations quickly, be minimally invasive, and identify individuals who may have received exposures of 2 Gy or more. Significant effort has been devoted to develop electron paramagnetic resonance (EPR) as a technique that would allow retrospective dosimetry screening^(4–6). Teeth, finger-nails and toenails have been demonstrated as a viable *in vitro* and *in vivo* EPR dosimetry assays, providing a linear dose estimate based on an ionizing radiation-induced signal (RIS)^(7–9). We focus this work on finger-nail and toenail assays, while the methods provided here are also feasible on tooth measurements with modification.

The technical approach of *in vitro* nail dosimetry methods is based on the use of X-band (9.5 GHz) or Q-band (35 GHz) EPR spectroscopy^(8, 10). Here, clipped nail samples are taken on-site, stored at –20°C and shipped to a facility for EPR analysis. The nails are measured and a dose estimate is predicted. However, *in vitro* nail dosimetry creates a series of mechanically induced signals (MISSs) from clipping which complicate the dose estimate process⁽¹¹⁾.

Therefore, an entirely non-invasive *in vivo* nail dosimetry approach is desired. Such an approach allows: (a) an on-site dose distribution assessments

through measurement of nails in both hands and both feet, (b) a radiation-induced EPR signal that is specific and linearly related to the dose of ionizing radiation and, in particular, is not affected by concurrent trauma or pre-existing conditions, (c) avoids any MIS generated by a clipping nails process and (d) does not involve complex sample storage.

One challenge of *in vivo* measurement is the presence of live tissue in close proximity to the nails that will cause dielectric losses of microwave radiation and degrade resonator efficiency. Current L-band (1.2 GHz) approaches minimize the dielectric losses but do not provide the desired sensitivity for nail dosimetry. By choosing an operating frequency at X-band, the EPR signal intensity is increased linearly with frequency. However, in order to diminish the losses into the surrounding tissue, *in vivo* nail dosimetry requires the development of innovative EPR probes that limit the microwave field to only within the thickness of the nail plate.

Recently a surface resonator array (SRA) geometry at X-band (9.5 GHz) was introduced as a means to limit the depth sensitivity to only the nail plate⁽¹²⁾. However, the aperture resonator, which was introduced by Ikeya and his colleagues^(13, 14) (referred to hereafter as Ikeya *et al.*) for X-band *in vivo* tooth dosimetry, is potentially an easier approach. Here novel aperture resonator geometries that significantly improve the EPR signal detection over Ikeya *et al.* geometries are the focus of this work.

The aperture resonator is described as a rectangular TE₁₀₂ cavity with an aperture, either a hole or

slot, cut in the far wall, illustrated in Figure 1A. The sample is placed on the aperture where an evanescent wave couples the spin system to the resonator. The power transmission through a thin walled aperture in a flat conducting screen has been extensively investigated many years ago by Bethe⁽¹⁵⁾ and in a series of publications by Harold Levine *et al.*^(16, 17). Although the aperture resonator described by Ikeya *et al.* looks very promising for nail *in vivo* EPR dosimetry, we have recognized during our investigations that these aperture resonators do not provide sufficient sensitivity for *in vivo* EPR nail dosimetry.

EPR signal enhancement through small apertures has received growing interest since successful experiments by T.S. Ebbesen, 1998⁽¹⁸⁾. Several different aperture modifications have been suggested to maximize magnetic field strength at the aperture^(19–21). Increase of microwave transmission through an aperture was shown in a number of studies^(22–24) by designing the aperture to operate at resonance. Such designs are challenging due to significant changes in the aperture resonance condition under various sample-loading conditions, resulting in inconsistent EPR signal intensities.

In this work, we present a new aperture resonator geometry based on Ikeya *et al.* geometry: the dielectric-backed aperture resonator (DAR), illustrated in Figure 1B. It was recognized that EPR sensitivity could be improved by increasing the effective magnetic field at the aperture by using a non-resonant dielectric slab. The dielectric slab provides an increased magnetic field at the aperture and sample, while minimizing the sensitivity of the aperture resonance to the load conditions. This work also introduces a DAR semi-spherical (SS)-TE₀₁₁ geometry, illustrated in Figure 1C. The SS-TE₀₁₁ geometry is attractive due to having twice the incident magnetic field at the aperture for a fixed input power. For clarity, illustrated in Figure 2A, is the magnetic field profile of a rectangular TE₁₀₂ aperture resonator, where the maximum magnetic field is in the center of the cavity while the aperture is on a sidewall. However, the SS-TE₀₁₁ geometry has the aperture on the SS plane where the magnetic field is

maximum, illustrated in Figure 2B. The SS-TE₀₁₁ geometry is modified by two ‘flat’ regions in order to align the magnetic field. In both configurations, the dielectric is placed over the aperture creating the DAR geometry.

METHODS

Finite-element simulations were performed with Ansys High Frequency Structure Simulator (HFSS; Version 15.0) on a Windows 7 64-bit Lenovo Think Vantage laptop. Both Eigen-mode, where the solution is based on lowest energy states, and Driven-mode, where power is coupled into a port, were used in the design process. Typical simulation time was about 30 min. A series of aperture resonator and DAR geometries have been designed, evaluated and optimized by HFSS. Designs were chosen based on the signal intensity of unsaturable samples, Su, where the signal at critical coupling is calculated at constant microwave incident power using formulas derived by Mett *et al.*⁽²⁵⁾.

Resonator construction of the SS-TE₀₁₁ cavity and rectangular TE₁₀₂ cavity has been fabricated using copper bulk in an in-house machine shop. Rectangular TE₁₀₂ cavity dimensions of 23.8 × 43.6 × 10.8 mm and SS-TE₀₁₁ of 23.1(XX-diameter) × 19.4(ZZ-dimension), mm, were chosen to provide a resonance frequency around 9.5 GHz. Design and construction of the DAR allow variation of several structural parameters such as the aperture and coupling iris dimensions, dielectric insert and tuning mechanisms.

Particular attention in fabrication of the DAR is paid to the flat aperture wall. Laser cutting (Potomac Photonics, Baltimore MD) precisely creates an aperture slit in the center walls of a 0.2 mm copper foil to couple microwave fields into the sample. A series of aperture walls with different aperture lengths (from 4 to 8 mm, 0.2 mm step) and 1 mm width were available for testing. These foils were silver plated by Specialized Plating Inc., Haverhill NH, to prevent the unwanted signal from copper oxide that was found to build in with time. Field modulation coils were matched for a Bruker spectrometer and wound using copper wire on a custom saddle

Figure 1. Resonator geometries: (A) Rectangular TE₁₀₂ based aperture resonator via Ikeya *et al.*, (B) DAR and (C) SS-TE₀₁₁ aperture resonator which also can be dielectric-backed.

Figure 2. Illustration of the magnetic field profile for two aperture resonator geometries. (A) The rectangular TE₁₀₂ and (B) SS-TE₀₁₁.

coil holder. Scotch tape is used for placement of different dielectric slabs on the aperture inside the desired cavity. Dielectric slabs of various materials, such as E2000 SERIES, Sapphire, TiO_2 and KTaO_3 , were all used for HFSS simulations and optimization. Bench tests used a $5 \times 10 \times 0.2$ mm slab of KTaO_3 ($\epsilon_r = 372$, $\tan \delta = 0.004$).

Three experimental models are used to evaluate the performance of the fabricated resonators. The first is to create an *in vitro* fingernail model made of films with singlet EPR signals backed by a tissue equivalent polyacrylamide gel block (PAA)⁽²⁶⁾. We used two DuPont (Wilmington, DE) Kapton adhesive thin films, Kapton25 (0.0025") and Kapton35 (0.0035"), with stable repeatable EPR singlets of 12.5 and 35 Gy, respectively, and equivalent RIS dosage in a nail plate. The RIS is defined here as the sum of the stable [RIS5] and quasi-stable [RIS2] RISs⁽²⁷⁾ and corrected for the background signal. The signal intensity is largely driven by the RIS2 intensity in 137-Cs gamma-irradiated nail samples used to test the *in vivo* nail resonators and calibrate the RIS dose equivalency of the Kapton film signal intensities. Experiments were performed with one or three Kapton films attached to bleached printer paper to simulate a full nail thickness of 0.8–1 mm. Secondly, depth sensitivity measurements were performed by placing a Rogers 5880 PC board material (equivalent to 90 Gy RIS signal; 0.25 mm thickness) at fixed distance with bleached paper spacers on a finger model⁽¹²⁾. Lastly, *in vivo* tests were performed using a healthy volunteer's nail with surface-attached Kapton films. The volunteer's finger was held in a custom made 3D printed holder. The thorough handwashing done 10–15 min prior to measurements made background signals in nails practically undetectable.

EPR spectra were acquired using Bruker Elexsys X-band spectrometer with a time constant of 10 ms, sweep time of 10 s, and field scans of 150 G. The amplitude of the 100 kHz field modulation, approximately 6 G, was chosen for maximum EPR signal intensity. A weak signal standard using the Bruker dosimetry reference standard ($g = 1.998$) was affixed to the aperture wall. Current configurations did not use the reference signal as an intensity standard due to the replacement of aperture walls. Instead, the standard was used to enable proper magnetic field positioning. The noise value was calculated as two standard deviations (noise SD) from the mean, which accounts for 95.45% of noise (assuming normal distribution). Noise SD was defined in off resonance of the EPR spectra chosen voluntarily by eye. To characterize resonator performance the term 'DAR sensitivity' was introduced, which in the absence of background signal in *in vivo* nail measurements illustrates minimum dose that could be detected with $\text{SNR} = 1$ for each measurement.

RESULTS

Simulation results

Five cavity geometries were simulated in order to understand the relationship between cavity magnetic field and the aperture geometry. Simulations predicted that EPR signal intensity would achieve a maximum value at a certain aperture size that reflects the optimal product of the Q-value times the filling factor, due to an increase of magnetic field when the aperture length increases, as shown in Figure 3. A Cylindrical TM_{010} with a rectangular aperture of 1 mm width and varied length ($\blacktriangle$) and Cylindrical TE_{011} with a rectangular aperture of 1 mm width and varied length ($\bullet$) were simulated and found to have a maximum EPR signal intensity of 0.25 and 0.21 V, respectively. Additionally, a rectangular TE_{102} with a circular aperture of varied diameter ($\blacksquare$) was simulated and found to have a maximum EPR signal intensity of 0.24 V. The subject of this work, a Rectangular TE_{102} with a rectangular aperture with a 1 mm width and varied length ($\circ$), was also simulated. A maximum EPR signal intensity of 0.30 V was calculated for an iris length of 4 mm. Finally, a SS- TE_{011} with a rectangular aperture with an aperture width of 1 mm and varied length (Δ) was simulated. A maximum EPR signal intensity of 0.55 V was found at an iris length of 3.5 mm.

Significant increase in EPR signal intensity was calculated by placing a dielectric slab of KTaO_3 , as shown in Figure 1B, creating the DAR from a Rectangular TE_{102} with a rectangular aperture at two slab thicknesses of 0.5 mm ($\circ$) and 1.0 mm ($\square$). The aperture lengths were then varied and plotted in

Figure 3. Simulated EPR signal intensity versus aperture length for various resonator geometries. Rectangular TE_{102} rectangular aperture 1 mm width ($\circ$), SS- TE_{011} rectangular aperture 1 mm width (Δ), Rectangular TE_{102} circular aperture ($\blacksquare$), Cylindrical TM_{010} rectangular aperture 1 mm width ($\blacktriangle$), Cylindrical TE_{011} rectangular aperture 1 mm width ($\bullet$).

Figure 4. Simulated EPR signal intensity versus aperture length for DAR Rectangular TE_{102} with aperture thickness of 0.5 mm (○) and 1.0 mm (□).

Figure 4. Two resonance peaks are shown. Experimental measurements support the simulated resonance phenomenon. However, the experimentally observed optimal aperture sizes differed slightly from simulated predictions by approximately 1 mm.

In vitro results

Using the PAA finger model and Rogers 5880 PC board material, a depth sensitivity profile was completed for an experimentally optimal DAR Rectangular TE_{102} with an aperture dimension of 1.0×6.1 mm. The PC board material was placed between 0.1 mm PTFE sheets and moved at interval steps. The EPR signal intensity was recorded and plotted in Figure 5. The EPR signal intensity was normalized at 0 mm and compared to Ansys HFSS data (solid) with resulting good agreement.

Finally, using the PAA finger model and three Kapton25 films placed on bleached copy paper (total thickness of 0.8 mm), a spectrum with an RIS equivalent signal of 45 Gy was measured and is shown in Figure 6. A signal-to-noise of 63 is calculated, which corresponds to a 1.4 Gy RIS equivalent signal sensitivity.

In vivo results

The *in vivo* results were performed by placing Kapton25 and Kapton35 films directly on the fingernails of healthy volunteers and measuring the EPR signal intensity. Using these spectra a signal-to-noise of 55 was calculated, which corresponds to a 1.2 and 1.4 Gy, respectively, RIS equivalent signal sensitivity. Results for Kapton25 and Kapton35 are shown in Figure 7A and B. The *in vivo* tests showed the influence of physiological motions (e.g. finger trembling, heartbeat, breathing) on spectra quality. A larger

Figure 5. Depth sensitivity data of a DAR Rectangular TE_{102} with an aperture dimension of 1.0×6.1 mm. Simulated (solid) and measured (dashed) depth sensitivity data are shown.

Figure 6. EPR *in vitro* measurements using the polyacrylamide finger model with three Kapton25 films and bleached printer paper for a total thickness of 0.8 mm. Signal is shown at 3285 G with Bruker standard at 3327 G.

time constant of 163.84 ms was used to partially offset the effect of these motions on the spectra.

DISCUSSION

Simulations show that placement of a slab of dielectric material ($KTaO_3$) at the aperture inside the rectangular TE_{102} cavity results in a 20-fold increase in EPR signal intensity over a non-backed aperture configuration. Such magnification of the signal arises as a result of increased magnetic field strength at the aperture. It is interesting to note that the observed increase in magnetic field strength at the aperture and sample and the minimization of sensitive aperture resonance conditions are provided by the non-resonant dielectric slab. Unfortunately, dielectric

Figure 7. EPR *in vivo* measurements on a healthy volunteer with (A) Kapton25 film (15 Gy equivalent) and (B) Kapton35 (35 Gy equivalent) film placed on a nail. Signal is shown at 3290 G with Bruker standard at 3332 G. Physiological noise is highlighted.

slabs may have paramagnetic impurities that result in unwanted EPR signals; therefore, care must be taken in selecting a pure dielectric source. Further improvements of signal-to-noise are expected by the implementation of a DAR SS-TE₀₁₁ geometry.

Variations in depth sensitivity from simulated results in Figure 5 are attributed to robust fabrication of the aperture endwall. Future designs will incorporate a thin plate geometry as opposed to copper foil.

In vivo tests have shown that physiological motions do not significantly affect signal amplitude or regular noise. However, they often create spikes in the spectrum that could not be averaged during reasonable signal accumulations, as highlighted in Figure 7.

CONCLUSIONS

DARs are a novel geometry for surface spectroscopy yielding at least a factor of 20 compared to traditional, non-backed aperture resonators. It has been shown that DAR provides a sufficient increase in detection sensitivity to make biologically relevant measurements of the RIS in both *in vitro* and *in vivo* conditions. Although *in vivo* tests have shown effects of physiological motions, equivalent dosimetry sensitivity of approximately 1.4 Gy is demonstrated in the current resonator designs.

Improved detection sensitivities can be achieved with a more robust finger holder as has been shown in preliminary *in vivo* comparisons of DAR and SRA. In these comparisons, the finger holder for the SRA had undergone more advanced finger

stabilization and ergonomic designs with the result that, while both SRA and DAR had comparable signal amplitudes, SRA was much less sensitive to human motion.

FUNDING

This work is supported by Centers for Medical Countermeasures Against Radiation (CMCR) in the National Institute of Allergy and Infectious Diseases (NIAID) in the [grant number U19AI091173]; and the National Biomedical Electron Paramagnetic Resonance Center in the National Institute of Biomedical Imaging and Bioengineering (NIBIB) [grant number P41EB001980] of the National Institute of Health.

REFERENCES

- Alexander, G. A., Swartz, H. M., Amundson, S. A., Blakely, W. F., Buddemeier, B., Gallez, B., Dainiak, N., Goans, R. E., Hayes, R. B. and Lowry, P. C. *BiodosEPR-2006 meeting: acute dosimetry consensus committee recommendations on biodosimetry applications in events involving uses of radiation by terrorists and radiation accidents*. Radiat. Meas. **42**, 972–996 (2007).
- Swartz, H. M., Williams, B. B. and Flood, A. B. *Overview of the principles and practice of biodosimetry*. Radiat. Environ. Biophys. **53**, 221–232 (2014).
- Brenner, D. J., Chao, N. J., Greenberger, J. S., Guha, C., McBride, W. H., Swartz, H. M. and Williams, J. P. *Are we ready for a radiological terrorist attack yet? Report from the centers for medical countermeasures against radiation network*. Int. J. Radiat. Oncol. **92**(3), 504–505 (2015).
- Symons, M. C. R., Chandra, H. and Wyatt, J. I. *Electron paramagnetic resonance spectra of irradiated fingernails: a possible measure of accidental exposure*. Radiat. Prot. Dosim. **58**, 11–15 (1995).
- Dalgarno, B. G. and McClymont, J. D. *Evaluation of ESR as a radiation accident dosimetry technique*. Appl. Radiat. Isot. **40**, 1013–1020 (1989).
- Romanyukha, A., Trompier, F., LeBlanc, B., Calas, C., Clairand, I., Mitchell, C. A., Smirniotopoulos, J. G. and Swartz, H. M. *EPR dosimetry in chemically treated fingernails*. Radiat. Meas. **42**, 1110–1113 (2007).
- Williams, B. B., Flood, A. B., Salikhov, I., 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).
- He, X., Swartz, S. G., Demidenko, E., Flood, A. B., Grinberg, O., Gui, J., Mariani, M., Marsh, S. D., Ruuge, A. E., Sidabras, J. W., Tipikin, D., Wilcox, D. E. and Swartz, H. M. *Development and validation of an ex vivo electron paramagnetic resonance fingernail biodosimetric method*. Radiat. Prot. Dosim. **159**(1–4), 172–181 (2014).
- Bahar, N., Roberts, K., Stabile, F., Mongillo, N., Decker, R. D., Wilson, L. D., Husain, Z., Contessa, J., Williams, B. B., Flood, A. B., Swartz, H. M. and Carlson, D. J. *SU-C-BRD-05: non-invasive in vivo*

- biodosimetry in radiotherapy patients using electron paramagnetic resonance (EPR) spectroscopy. *Med. Phys.* **42**, 3192–3193 (2015).
10. Romanyukha, A., Trompier, F., Reyes, R. A., Christensen, D. M., Iddins, C. J. and Sugarman, S. L. *Electron paramagnetic resonance radiation dose assessment in fingernails of the victim exposed to high dose as result of an accident.* *Radiat. Environ. Biophys.* **53**(4), 755–762 (2014).
 11. Marciniak, A., Ciesielski, B. and Prawdzik-Dampc, A. *The effect of dose and water treatment on EPR signals in irradiated fingernails.* *Radiat. Prot. Dosim.* **162**(1–2), 6–9 (2014).
 12. Sidabras, J. W., Varanasi, S. K., Mett, R. R., Swarts, S. G., Swartz, H. M. and Hyde, J. S. *A microwave resonator for limiting depth sensitivity for electron paramagnetic resonance spectroscopy of surfaces.* *Rev. Sci. Instrum.* **85**(10), 104707 (2014).
 13. Ikeya, M. and Furusawa, M. *A portable spectrometer for ESR microscopy, dosimetry and dating.* *Appl. Radiat. Isot.* **40**(10–12), 845–850 (1989).
 14. Ishii, H. and Ikeya, M. *An electron spin resonance system for in-vivo human tooth dosimetry.* *Jpn. J. Appl. Phys.* **29**(1–5), 871–875 (1990).
 15. Bethe, H. A. *Theory of diffraction by small holes.* *Phys. Rev.* **66**, 163–182 (1944).
 16. Levine, H. and Schwinger, J. *On the theory of diffraction by an aperture in an infinite plane screen.* *Phys. Rev.* **74**(8), 958–974 (1948).
 17. Levine, H. and Schwinger, J. *On the theory of electromagnetic wave diffraction by an aperture in an infinite plane conductive screen.* *Comm. Pure Appl. Math.* **22**(1), 355–391 (1950).
 18. Ebbesen, T. W., Lezec, H. J., Ghaemi, H. F., Thio, T. and Wolff, P. A. *Extraordinary optical transmission through sub-wavelength hole arrays.* *Nature* **391**, 667–669 (1998).
 19. Lockyear, M. J., Hibbins, A. P. and Sambles, J. R. *Transmission of microwaves through a stepped subwavelength slit.* *Appl. Phys. Lett.* **91**(25), 251106 (2007).
 20. Aydin, K., Cakmak, A. O., Sahin, L., Bilotti, Z., Li, F., Vegni, L. and Ozbay, E. *Split-ring-resonator-coupled enhanced transmission through a single sub-wavelength aperture.* *Phys. Rev. Lett.* **102**(1), 013904 (2009).
 21. Scorrano, L., Bilotti, F., Ozbay, E. and Vegni, L. *FSS-based approach for the power transmission enhancement through electrically small apertures.* *Appl. Phys. A Mater. Sci. Process.* **103**(3), 927–931 (2011).
 22. Yang, F. Z. and Sambles, J. R. *Resonant transmission of microwaves through a narrow metallic slit.* *Phys. Rev. Lett.* **89**(6), 063901 (2002).
 23. Suckling, J. R., Sambles, J. and Lawrence, C. R. *Remarkable zeroth-order resonant transmission of microwaves through a single subwavelength metal slit.* *Phys. Rev. Lett.* **95**(18), 187407 (2005).
 24. Suckling, J. R., Hibbins, A. P., Sambles, J. R. and Lawrence, C. R. *Resonant transmission of microwaves through a finite length subwavelength metallic slit.* *New. J. Phys.* **7**(250), 1–11 (2005).
 25. Hyde, J. S., Sidabras, J. W. and Mett, R. R. Ch. 5.2: Resonators for Multifrequency EPR of Spin Labels. *Multifrequency Electron Paramagnetic Resonance: Theory and Applications 2008.* In: Sushil K. Misra, Ed. (Weinheim, Germany: Wiley-VCH) pp. 229–294 (2011).
 26. Bini, M. G., Ignesti, A., Millanta, L., Olmi, R., Rubino, N. and Vanni, R. *The polyacrylamide as a phantom material for electromagnetic hyperthermia studies.* *IEEE Trans. Bio-med. Eng.* **31**(3), 317–322 (1984).
 27. Trompier, F., Romanyukha, A., Reyes, R., Vezin, H., Queinnec, F. and Gourier, D. *State of the art in nail dosimetry: free radicals identification and reaction mechanisms.* *Radiat. Environ. Biophys.* **53**(2), 291–303 (2014).