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Dosimetry Based on EPR Spectral Analysis of Fingernail Clippings

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Abstract

Exposure of fingernails and toenails to ionizing radiation creates radicals that are stable over a relatively long period (days to weeks) and characterized by an isotropic EPR signal at $g = 2.003$ (so-called radiation-induced signal, RIS). This signal in readily obtained fingernail parings has the potential to be used in screening a population for exposure to radiation and determining individual dose to guide medical treatment. However, the mechanical harvesting of fingernail parings also creates radicals and their EPR signals (so-called mechanically-induced signals, MIS) overlap the $g \sim 2.0$ region, interfering with efforts to quantify the RIS and, therefore, the radiation dose. Careful analysis of the time evolution and power-dependence of the EPR spectra of freshly cut fingernail parings has now resolved the MIS into three major components, including one that is described for the first time. It dominates the MIS soon after cutting, but decays within the first hour, and consists of a unique doublet that can be resolved from the RIS. The MIS obtained within the first few minutes after cutting is consistent among fingernail samples and provides an opportunity to achieve the two important dosimetry objectives. First, perturbation of the initial MIS by the presence of RIS in fingernails that have received a threshold dose of radiation leads to spectral signatures that can be used for rapid screening. Second, decomposition of the EPR spectra from irradiated fingernails into MIS and RIS components can be used to isolate and thus quantify the RIS for determining individual exposure dose.

Keywords

dosimetry; EPR spectroscopy; fingernails; screening measurements

INTRODUCTION

Exposure to ionizing radiation is a well-known risk for workers in certain industrial (e.g., nuclear power plants) and medical (e.g., clinical radiation therapy) settings. This has also been a concern for military personnel, as well as civilian populations, since the development and deployment of nuclear weapons. More recently this risk has extended to civilians who may be in the proximity of certain types of terrorist activities (Alexander 2007). While individuals working with radiation and radioactive materials are required to carry dosimetry devices that

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measure their cumulative radiation dose, individuals unsuspectingly exposed to radiation would lack such information. Therefore, it is imperative that methods be developed to rapidly and accurately determine individual exposure to radiation for screening (triage) of populations and guiding medical treatment (Gonzalez 2007). An ideal method would involve equipment that can be brought to the exposed population and operated with minimal support, non-invasive sampling of individuals, and rapid accurate determination of the dose.

It has been known for some time that ionizing radiation generates free radicals in fingernails, toenails and other keratin-rich materials (i.e., hair, horn, hooves, scales, etc.), and that EPR spectroscopy can detect these species by their so-called radiation-induced signal (RIS) (Delgarno and McClymont 1989; Symons et al 1995). The amount of these radicals increases with the radiation dose and they are relatively stable in these proteinacious materials, much like the radiation-induced radicals found in tooth enamel and bone. Quantification of the RIS for after-the-fact determination of radiation exposure is the basis for fingernail EPR dosimetry.

Although fingernail parings are easily procured for ex vivo analysis, it has been known for some time that mechanical cutting of fingernails and toenails also generates EPR-detectable free radicals in these materials (Chandra and Symons, 1987). Two EPR signals from these radicals have been described, an anisotropic ($g_x = 2.000$, $g_y = 2.025$, $g_z = 2.061$) sulfur-centered signal with 8.5 G hyperfine coupling to a single proton that is most clearly observed at low temperature (77 K) and was originally designated the mechanically-induced signal, and a singlet at $g = 2.00$ that is most clearly observed at room temperature, is very similar to the RIS and was designated the background signal because it persists in cut fingernails (Symons, Chandra, Wyatt 1995). These signals originate from multiple species with different decay rates and, unfortunately, they overlap the RIS. Since ex vivo measurements of fingernail parings necessarily involve a harvesting cut, a major challenge to using these samples for EPR dosimetry is the ability to accurately determine the RIS in samples that also possess mechanically-induced signals (MIS).

One solution to this problem is the development of equipment and procedures for in situ measurement of the RIS in an intact fingernail. Not only does this eliminate complications from MIS but this method has the potential for measuring the radiation-induced radicals in a ~10 fold larger sample (1–2 cm × 1–2 cm fingernail versus 1–2 mm × 1–2 cm fingernail paring). Typically, in vivo EPR measurements are obtained at lower frequency (L band; ~1.0 GHz) to maximize the sampling depth and minimize sample heating, albeit with lower sensitivity (Swartz et al 2006). However, the low concentration of radiation-induced radicals in fingernails requires the higher sensitivity achieved at the standard X band frequency (~9.5 GHz), but the development of an X-band resonator that maximizes the EPR signal in a fingernail without heating the underlying tissue poses significant technical challenges. Nevertheless, the potential advantages of in situ fingernail EPR dosimetry make it a worthy objective.

One approach to accurately measure the RIS in fingernail parings, which necessarily have MIS, involves procedures that eliminate the latter while not affecting the former. It has been shown that soaking fingernail samples in water (Reyes et al 2008) or aqueous solutions containing various reducing agents (Romanyukha et al 2007) dramatically reduces the MIS, in some cases eliminating it completely. However, the hydration level of fingernails appears to modulate the magnitude of their RIS (Reyes et al 2008), and it has yet to be demonstrated that a MIS-eliminating treatment of irradiated nails does not affect the RIS. Since RIS and MIS radicals have a different distribution in fingernail parings (throughout the nail for the former and localized, at least initially, on the cut edge for the latter), this approach may have some potential. Nevertheless, until a strictly MIS-selective procedure has been demonstrated, any treatment of nails to remove the MIS is suspect for its impact on the RIS, which would compromise efforts to accurately determine the radiation dose.

If the properties of both the RIS and the MIS of fingernails are well understood, then it should be possible to account for each of their contributions to the EPR spectrum from the parings of irradiated fingernails. These spectra may then provide a signature of exposure to a threshold radiation dose, which would be useful for rapid screening, and the ability to accurately quantify the RIS to determine the actual radiation dose. Reported here are the results of our efforts to achieve these two goals.

MATERIALS AND METHODS

Fingernail parings were obtained from a large number of volunteers and either used immediately or stored frozen until needed. Samples were weighed prior to each experiment so that spectral data can be normalized to a constant mass. A set of preliminary measurements showed that soaking fingernail parings in de-ionized distilled water for 10 min and then drying them for 15 min removed most of the MIS from the initial harvesting cut and returned them to their initial mass. This procedure was then used on all parings to return them to a condition similar to that of intact fingernails. A ^{137}Cs source at an approved facility in the Department of Radiology at Dartmouth Medical School was used for sample irradiation. Prior to EPR measurements, and subsequent to any irradiation, each whole fingernail paring was cut into five pieces and placed in a Suprasil quartz EPR tube for spectral data collection.

EPR spectra were obtained on a Bruker EMX X-band EPR spectrometer with a high sensitivity ER 4119HS-W1 cavity. Spectral data were collected at ambient temperature with the following spectrometer settings: center field = 3500 G, sweep width = 150 G, sweep time = 20 sec, modulation frequency = 100 KHz, modulation amplitude = 5 G, time constant = 10 msec. Spectra were imported into Origin or Excel for comparison, scaling and subtraction.

RESULTS

Whole fingernail parings are typically 1–2 mm wide, 1–2 cm long and slightly curved. This shape allows them to be inserted into a standard quartz EPR tube for spectral analysis. However, as indicated in Figure 1, this places only a portion of the sample at the center of the EPR resonator where optimal sensitivity is obtained. Further, we have observed that the intensity and shape of the EPR spectrum from whole parings varies with their orientation in the EPR cavity, indicating an anisotropy of the EPR-detectable species when fingernails are in this configuration.

Reproducible EPR spectra can be obtained when fingernail parings are cut into ~five smaller pieces that pack in a random orientation at the bottom of an EPR tube. This allows the entire sample to be positioned in the region of maximum instrument sensitivity. Further, as indicated in Figure 1, the entire sample is also now located immediately adjacent to an EPR standard that is used to normalize the spectrometer response from sample to sample and has the potential to serve as a spin standard for quantitative measurements. Two EPR standards have been used in this research, the Mn^{+2} that is a dilute impurity in samples of CaO, which has two well-characterized hyperfine lines ($M_I = -1/2$ and $M_I = 1/2$) that bracket the $g = 2.00$ region of interest, and a proprietary standard provided by Bruker, which has a single feature at $g = 1.97$ that does not overlap the EPR signals from fingernails.

Since all fingernail parings have MIS from harvesting, it is important to understand this signal to account for its contribution to the EPR spectrum of irradiated fingernails. Figure 2 shows the time evolution of the EPR spectrum of two representative fingernail samples, one that had not been irradiated (top) and one that had received a 10 Gy dose of radiation (bottom). In each case the spectra were collected starting immediately after the fingernail paring was cut into 5 small pieces, which allows the entire sample to be positioned in the EPR cavity at the position

of optimal sensitivity and adjacent to the EPR standard (Mn^{+2} in CaO , in this case). Both the intensity and shape of the pure MIS spectrum (Figure 2, top) change dramatically within the first hour, evolving into a feature at $g = 2.003$ and broad weaker features at higher g value (lower field). Of particular interest in the early spectra is the high field minimum that is part of a doublet (vide infra) that decreases with time. The irradiated sample (Figure 2, bottom) has the same MIS features as the non-irradiated sample but also has a dominant symmetric feature at $g = 2.003$ that does not change with time and is attributed to the RIS. Unfortunately, the RIS is very similar to the final MIS feature at $g = 2.003$, which poses a challenge to accurately quantifying the RIS. Comparing these spectra, however, there are two regions where the MIS is unique in spectra obtained promptly after cutting. One is the high field minimum feature and the other is the low field side of the maximum, but these MIS features decay within the first ~60 min.

The transient MIS features can be isolated by subtraction of the final persistent MIS spectrum from spectra collected within the first 60 min, and results of this spectral decomposition are shown in Figure 3. The transient MIS spectrum, which we designate MIS3, is a symmetric doublet with $g = 2.007$ and $A = 17$ G. Its shape does not change as it decays, suggesting a quenching and/or migration of this radical created by mechanical cleavage of the alpha-keratin of fingernails.

The MIS spectrum that remains after decay of MIS3 has a major feature at $g = 2.003$ and additional features at lower field (higher g value). To determine if this EPR spectrum consists of multiple components, it has been measured over a range of microwave power, as shown in Figure 4. While the derivative at $g = 2.003$ is the major feature at power < 4 mW, the spectrum shifts to a broader derivative at lower field, and it and other low field features increase with increasing power. This indicates that the persistent MIS spectrum consists of at least two components with different power saturation behavior.

Since different EPR spectra dominate at lower and higher power, normalized (scaled) low and high power spectra can be subtracted from the Figure 4 EPR spectra to isolate the two components and their power dependence, as shown in Figure 5. The derivative at $g = 2.003$ that is the major feature at 1 mW saturates at higher power, as does the RIS (data not shown). The broad low-field features, however, exhibit negligible saturation over a wide range of microwave power, as does the Mn^{+2} standard. The $g = 2.003$ feature that dominates the persistent MIS spectrum at lower microwave power and that closely matches the RIS is designated MIS1, while the broad features that are a minor contribution to the persistent MIS at low power but dominate at higher power are designated MIS2.

As indicated in Figure 6, it is now possible to resolve an experimental MIS spectrum into three components, transient MIS3, which dominates shortly after cutting, MIS1, which is the major residual MIS feature at 3 mW and closely matches the RIS, and MIS2, which is broad and has a unique power saturation behavior. With this new understanding of the EPR spectral contributions from different mechanically generated radicals, it is possible to evaluate the EPR spectrum of irradiated fingernail parings for the RIS.

The first goal is to identify a spectral signature of the RIS that can be used to rapidly screen individuals for radiation exposure above a threshold dose. Because of the need to cut fingernails for optimum reproducible positioning of the sample in the EPR spectrometer, this requires a feature or features that allow the RIS to be distinguished from the three MIS signals. Figure 7 shows representative EPR spectra of irradiated (10 Gy) and non-irradiated fingernail parings taken 2, 15 and 120 min after cutting into five pieces. While the 120 min spectra are nearly indistinguishable, except for the intensity of the signal at $g = 2.003$, and the 15 min spectra are generally similar, the 2 min spectra are both qualitatively and quantitatively different. This

MIS spectrum, which consists primarily of MIS3, has two unique and promising features for this spectral analysis. First is the higher field minimum of the MIS3 doublet. Since the RIS contributes only to the lower field minimum of the doublet, the relative intensities of the two minima can indicate whether RIS is present or not. Second is the position of the maximum, which occurs at lower field for MIS3 than for RIS, causing a broadening to higher field in this spectral region and a shift in the crossover when RIS is present. Thus, perturbation of the 2 min MIS spectrum by the RIS provides features that have the potential to screen fingernail samples for the presence of radiation-induced radicals above a concentration (dose) threshold.

The second goal is to accurately determine the dose of radiation from the magnitude of the RIS. Because of the necessary presence of MIS, this requires the decomposition of the fingernail EPR spectrum into the MIS and RIS contributions, so the latter can be isolated and quantified. In contrast to the final (persistent) MIS spectrum, which consists primarily of the $g = 2.003$ MIS1 feature that is indistinguishable from the RIS, the MIS observed shortly after cutting is significantly different than the RIS, and data collected at an early time (e.g., 2 min) are more promising for this analysis. The early (transient) MIS spectrum consists predominantly of MIS3, although there are minor contributions from MIS1 and MIS2. However, MIS2 has a unique power dependence and features that are well separated to lower field, both of which can be used to subtract its minor contributions from the whole MIS spectrum at ~ 1 mW. (Note, the Mn^{+2} standard and the $g = 1.97$ proprietary Bruker standard also do not saturate at higher power and are subtracted at the same time.) The remaining MIS spectrum, which consists primarily of MIS3 with a small contribution from MIS1, which may be an intrinsic background signal, is remarkably consistent in shape from sample to sample at 2.0 min after cutting, as shown in Figure 8 (top) for fingernail samples from 11 different volunteers. Therefore, as shown in Figure 8 (bottom), an average 2 min MIS spectrum, which has the unique higher field minimum, can be scaled and used to subtract the remaining MIS contribution to the EPR spectrum of irradiated fingernails, leaving only the RIS. Comparison of the magnitude of this isolated RIS signal to that obtained from dose-response data with irradiated fingernail parings obtained under similar conditions can then be used to determine the radiation dose to which the fingernails were exposed.

DISCUSSION

For quite some time it has been recognized that fingernails, toenails and other keratin-rich biological materials exhibit EPR signals after they are exposed to ionizing radiation (Delgarno and McClymont 1989). Much like radiation-induced radicals in the inorganic matrices of teeth and bone, radicals generated in these crosslinked protein matrices have a relatively long lifetime, during which they can be detected and quantified with EPR spectroscopy. Therefore, fingernail parings, which are readily obtained with minimal inconvenience, have the potential to serve as a personal dosimeter. However, certain confounding properties of fingernails need to be well understood for this potential to be realized.

When an individual is exposed to radiation their fingernails are irradiated in situ and fresh parings can be provided for screening and diagnostic analysis. We have found (data not shown) that aged fingernail samples stored at ambient temperature do not give rise to the same mechanically-induced or radiation-induced EPR spectral properties as freshly harvested nails or nails that have been stored frozen since they were harvested, even if the aged ambient-temperature samples are re-hydrated. Humidity appears to be a significant confounding factor with fingernails, but it was not evaluated in this study, which used a consistent sample protocol to minimize differences in humidity and focus on establishing the basic EPR spectral properties of irradiated and cut fingernails. Therefore, only fresh or fresh frozen fingernail pairings were studied as models for samples from real dosimetry situations, and previous results with parings of uncertain age or storage conditions are of questionable relevance.

The most challenging problem that compromises the usefulness of fingernail parings as a dosimeter is the radicals that are generated by cutting the nail (Chandra and Symons 1987). The EPR signals from two types of radicals have been reported (Symons, Chandra, Wyatt 1995), a sulfur-centered signal with features at low field that are most prominent at low temperature and correspond to MIS2 characterized here, and the $g = 2.00$ singlet matching the radiation-induced signal (RIS) and designated the background signal, which corresponds to MIS1 characterized here. Calling the latter a background signal, however, may not be correct because the presence of an intrinsic or background EPR signal is unknown until it is possible to obtain in situ EPR spectra of fingernails. Unfortunately, both of these EPR signals, which have collectively been known as mechanically-induced signals (MIS), overlap the RIS. Thus, accurate quantification of the RIS for determination of radiation exposure requires either some treatment of the fingernail parings to eliminate the MIS radicals or a procedure to subtract their contribution from the EPR spectrum of irradiated nails.

It has been shown that treatment of fingernail parings with water (Reyes et al 2008) or various agents (Romanyukha et al 2007) reduces and, in certain cases, eliminates the MIS. Since one component of the MIS, which we designate MIS1, is indistinguishable from the RIS, it seems likely that chemical or physical treatments that eliminate MIS1 will also affect the RIS. In fact, water treatment, with or without additional agents, reduces the RIS and alters its dose-response relationship (Romanyukha et al 2007; Reyes et al 2008). Therefore, treating cut irradiated fingernail parings with water or other species introduces new variables and uncertainty associated with chemical or physical phenomena that affect the RIS.

We have approached this problem through a careful analysis of the EPR spectral properties of the radicals created by cutting fingernails. Based on the time dependence and power dependence of the EPR spectrum of freshly cut fingernails, the signal from a newly identified short-lived species designated MIS3, in addition to the two previously reported signals, that contributes to the MIS has been identified. This component dominates the initial EPR spectrum with a unique doublet that decays in the first hour after cutting. Although observed in published data (Reyes et al 2008, Figure 6A), it has not been noted or described previously. Measurements at different powers at the same time after cutting indicate that MIS3 saturates at higher power (data not shown). One of the previously identified components, which we designate MIS1, is the major $g = 2.003$ feature in the final (persistent) MIS spectrum and has the same shape and power saturation (Reyes et al 2008) as the RIS, suggesting that some of the radicals generated by cutting are identical to the radicals generated by irradiation. The other previously identified component, which we designate MIS2, is a broad signal that only contributes significantly at higher power due to its unique power dependence, which has been reported previously (Reyes et al 2008). This insight will ultimately allow the development of a spectral analysis procedure to achieve the two goals of establishing a signature of radiation exposure for rapid screening and developing a method to accurately quantify the RIS, and thereby determine the dose to guide medical intervention.

In situations where a potentially large number of individuals have been exposed to radiation, there is a need for rapid screening to identify those individuals who have received a clinically significant dose (Alexander et al 2007). This allows medical resources to be directed to those individuals most in need of care and reassures others so they do not become an unnecessary burden on the medical system. The experimental EPR spectra of freshly cut fingernail parings have features that allow this screening, as indicated in Figure 7. Such an analysis would be based on RIS perturbation of the MIS spectrum obtained shortly after fingernails are harvested and cut into small pieces for optimal placement in the EPR spectrometer. Fingernails exposed to radiation have an RIS contribution that adds to the lower field minimum of the MIS3 doublet and broadens the maximum, thereby shifting the crossover of the first derivative EPR signal. Thus, the relative depth of the two doublet minima and the position of the crossover (accurately

determined relative to the EPR standard) in the raw experimental spectrum can indicate whether RIS is present or not. The minimum radiation dose that gives a perceptible reproducible change in these two features, and thus establishes a threshold dose for screening, has not yet been determined but is less than 5 Gy, and may be in the clinically significant 1–2 Gy range.

The EPR spectra of all three MIS components overlap the RIS to some extent, but MIS1 is the most problematic for quantifying the RIS, and thus the radiation dose. However, it appears to be a small constant contribution to MIS spectra, which are dominated by MIS3 shortly after cutting (Figure 8, top). Thus, for three reasons we advocate an unorthodox approach to quantifying the RIS, one that involves cutting the fingernail paring into smaller pieces and thereby introducing *more* MIS. First, this allows the entire sample to be placed in the EPR cavity at the position of maximum signal intensity. Second, it allows accurate subtraction of the early MIS from the EPR spectrum of irradiated nails and, thereby, isolates the RIS, as shown in Figure 8 (bottom). While the EPR spectra in Figure 8 have had their MIS2 contributions subtracted by collecting a second spectrum at higher power, this is not necessary; an analysis without additional data at higher power requires only an average MIS2 spectrum at the experimental power for subtraction of its contribution based on its unique low field features. Third, by focusing on the early MIS, this procedure allows a more rapid screening and dose determination by fingernail EPR dosimetry.

We find that the EPR spectra of the three MIS components and the RIS are consistent among a large number of fingernail samples from many volunteers, but there is some intra-donor and inter-donor variability in the magnitude of the MIS and RIS signals. Since this may be due to variation in the properties of the nails (e.g., level of hydration/dryness, surface contamination, variation of the alpha-keratin and its crosslinking, etc.), statistical analysis of samples will be required to obtain the most precise determinations for fingernail EPR dosimetry. This will involve ≥ 3 samples from each donor, optimized signal intensity and signal-to-noise for each sample, and a statistically based decomposition of the EPR spectra from irradiated fingernails. The latter will involve a fitting procedure with statistical constraints that uses the best average MIS and RIS spectra (basis functions) to remove random noise from the spectra and achieve the most accurate decomposition of experimental spectra into their individual components. The results of this study describe the EPR spectral components and their properties that can serve as a basis for fingernail dosimetry protocols.

Samples obtained from individuals who have been exposed to radiation differ from samples used for laboratory experiments in one potentially significant regard. In an actual event, fingernails will have been irradiated in situ before the parings are harvested and analyzed, but parings are harvested from volunteer donors before irradiation in the laboratory. Two types of measurements can assess whether the presence of the harvesting MIS or measures taken to remove this MIS affect the RIS. The first involves laboratory measurements of longer fingernails that can be cut a second time after irradiation to simulate the harvesting cut of individuals whose nails have been exposed to radiation in situ. Preliminary data from these so-called double cut experiments do not show significant differences in either shape or amplitude relative to laboratory samples that are harvested, treated with water to remove the harvesting MIS and dried prior to irradiation. The second involves measurements of fingernail parings from individuals after they have undergone radiation therapy, particularly those receiving total body irradiation (TBI) as part of bone marrow transplant procedures. The doses used in these treatments are relevant to doses that would be critical when screening a population in an actual incident. Preliminary results with TBI samples also fail to show significant differences from those obtained with typical laboratory samples. Thus, fresh and fresh frozen fingernail parings soaked in water for 10 min and dried for 15 min appear to be a good model for fingernail samples that would be obtained in an actual incident.

The development, deployment and use of fingernail EPR dosimetry will involve many aspects in addition to those described here (Trompier et al 2007). These include EPR instrumentation that can be transported to the site of an incident and operated under field conditions with minimal infrastructure (e.g., 110 V power supplied by a generator). Standard procedures for harvesting and handling fingernail samples and for obtaining and analyzing spectral data will be developed from results such as those described here. Finally, analysis of the EPR data and reporting of statistically significant results, either for population screening or for individual dose determination, will require automated and authenticated algorithms that are based on a significant number and diverse set of control measurements. The potential benefits of fingernail EPR dosimetry justify continued efforts to develop this method for determining radiation exposure.

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References

- Alexander GA, Swartz HM, Amundson SA, Blakely WF, Buddemeier B, Gallez B, Dainiak N, Goans RE, Hayes RB, Lowry PC, Noska MA, Okunieff P, Salner AL, Schauer DA, Trompier F, Turteltaub KW, Voisin P, Wiley AL Jr, Wilkins R. BiodosEPR 2006 meeting: acute dosimetry consensus committee recommendations on biodosimetry applications in events involving uses of radiation by terrorists and radiation accidents. *Radiat Measur* 2007;42:972–996.
- Chandra H, Symons MCR. Sulphur radicals formed by cutting alpha-keratin. *Nature* 1987;328:833–834. [PubMed: 2442616]
- Dalgarno BG, McClymont JD. Evaluation of ESR as a radiation accident dosimetry technique. *Appl Radiat Isot* 1989;40:1013–1020.
- Gonzalez AJ. An international perspective on radiological threats and the need for retrospective biological dosimetry of acute radiation overexposures. *Radiat Measur* 2007;42:1053–1062.
- Reyes RA, Romanyukha A, Trompier F, Mitchell CA, Clairand I, De T, Benevides LA, Swartz HM. Electron paramagnetic resonance in human fingernails: the sponge model implication. *Radiat Environ Biophys* 2008;47:515–526. [PubMed: 18584193]
- Romanyukha A, Trompier F, LeBlanc B, Calas C, Clairand I, Mitchell CA, Smirniotopoulos JG, Swartz HM. EPR dosimetry in chemically treated fingernails. *Radiat Measur* 2007;42:1110–1113.
- Swartz HM, Iwasaki A, Walczak T, Demidenko E, Salikhov I, Khan N, Lesniewski P, Thomas JA, Romanyukha A, Schauer DA, Starewicz P. In vivo EPR dosimetry to quantify exposures to clinically significant doses of ionizing radiation. *Radiat Prot Dosimet* 2007;120:163–170.
- Symons MCR, Chandra H, Wyatt JL. Electron paramagnetic resonance spectra of irradiated fingernails: a possible measure of accidental exposure. *Radiat Prot Dosimet* 1995;58:11–15.
- Trompier F, Kornak L, Calas C, Romanyukha A, LeBlanc B, Mitchell CA, Swartz HM, Clairand I. Protocol for emergency EPR dosimetry in fingernails. *Radiat Measur* 2007;42:1085–1088.

Figure 1.
Cut-away representation of the configuration of a whole fingernail sample in an EPR tube positioned in the EPR resonator cavity adjacent to an EPR standard.

Figure 2.

EPR spectra (1 mW) of a fingernail sample that had not been irradiated (top) and a fingernail sample that had received 10 Gy radiation (bottom); in each case the spectra were taken at the indicated time after the sample was cut into five pieces; features at 3455 and 3545 G are two of the six hyperfine lines of the Mn²⁺ in CaO EPR standard.

Figure 3.

EPR spectra (1 mW) of the initial transient MIS of a fingernail sample at the indicated time after it was cut into five pieces; EPR spectra of the final (persistent) MIS and the EPR standard have been subtracted from each spectrum.

Figure 4.

EPR spectra at the indicated microwave power of the final (persistent) MIS of a fingernail sample ≥ 2 hr after it was cut into five pieces; features at 3455 and 3545 G are two of the six hyperfine lines of the Mn^{+2} in CaO EPR standard.

Figure 5.

EPR spectra at the indicated microwave power of the $g = 2.003$ feature (top) and the broad features (bottom) of the final (persistent) MIS of a fingernail sample ≥ 2 hr after it was cut into five pieces; the $g = 2.003$ spectra were obtained by subtracting a normalized spectrum of the sample at high power, and the broad features were obtained by subtracting a normalized spectrum of the sample at low power; inserts indicate the signal intensity as a function of microwave power.

Figure 6.

EPR spectrum (3 mW) of a fingernail sample 2 min after it was cut into five pieces (black), and EPR spectra of its three MIS components; MIS2 (red) was obtained by subtraction of a 3 mW spectrum from a 12 mW spectrum, and MIS1 (green) and MIS3 (lavender) were obtained by subtracting MIS2 from the fingernail EPR spectrum obtained 2 hr and 2 min after the cutting, respectively.

Figure 7.

EPR spectra (1 mW) of a fingernail sample that had not been irradiated (top) and a fingernail sample that had received 10 Gy radiation (bottom) taken 2, 15 and 120 min after the sample was cut into five pieces; constant derivative features on both ends of each spectra are two of the six hyperfine lines of the Mn^{+2} in CaO EPR standard.

Figure 8.

Top: normalized EPR spectra (3 mW) of the initial transient MIS in fingernail samples from 11 volunteers obtained 2 min after the fingernails were cut into five pieces; Bottom: EPR spectrum of a 10 Gy irradiated fingernail sample obtained 2 min after it was cut into five pieces (black, MIS/RIS), a normalized average EPR spectrum obtained from non-irradiated fingernail samples 2 min after they were cut into five pieces (red, MIS), and the EPR spectrum (blue, RIS) resulting from subtraction of the MIS spectrum (red) from the MIS/RIS spectrum (black); EPR spectra of the broad MIS2 signal and the Mn^{+2} standard have been subtracted from each spectrum.