Investigation of the applicability of the ESR nail dosimetry for assessment of accidental exposure in medical facilities

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Introduction

A major concern that our history has demonstrated is that despite all precautions, radiation accidents still occur and considering the fast development of advanced technologies in radiation medicine, a significant increase in the number of radiation accidents has been reported over the last decades. According to the radiation emergency assistance center/training site (REAC/TS) radiation accidents registries, in the period of 1944-2019, a total of 466 major radiation accidents worldwide has been recorded with the next most frequent coming from unsealed radioactive materials such as free isotopes used for diagnosis and therapy. Moreover, the greatest number of accidental deaths and significant exposures were reported to be associated with diagnostic or therapeutic procedures in medical facilities. In other words, the extant reported accidental exposures then make clear the fundamental importance to employ a practical method for retrospective dosimetry that could provide a precise dose assessment following the exposure.

Accordingly, the present study focused on retrospective dosimetry technique, which is based on the electron spin resonance (ESR) analysis of radiation-induced radicals in biological samples (e.g. bone tissue, tooth enamel, finger/toenails) resulting from reactions generated by ionizing radiation. While it is true that ESR analysis of bone tissue and tooth enamel has been effectively utilized for dose estimations and reconstructions, this still remains less pertinent for medical management of local radiation injuries because both requires invasive procedure to remove a suitable biomaterial. Therefore, fingernails have been considered a favorably attractive tissue material for dosimetric purposes because they are easier and painless to sample. Here, we report the applicability of fingernails as a retrospective dosimeter in radiological accidents, and some modified techniques are introduced to improve the ESR signal stability of the fingernail samples.

Materials and Methods

The collected fingernail samples in this study were irradiated under controlled exposure conditions with doses of 0, 35, and 70 Gy of high-energy X-rays using a clinical linear accelerator and ^{137}Cs gamma-rays using a gammacell40 irradiator. High-dose levels were used to simulate possible accidental overexposures. It should be emphasized that for high-energy X-rays, water treatment and drying of the samples were utilized. However, in the case of ^{137}Cs irradiations, no pre-treatment was employed. It is also important to note that all the samples for both irradiations were kept inside the vacuum desiccator at all times to control the humidity during samples' storage, excluding the measurement process. Quantitative analysis of the spectra which included baseline corrections and measurement of the peak-to-peak amplitude of ESR signal intensities were carried out using the A-System Data Processing software. The plotting and curve fitting were performed using the MATLAB R2018a software.

Results and Discussions

Fig. 1 compares two different drying conditions for vacuum-stored water-treated unirradiated samples. Signals in Fig. 1(a) were recorded from samples dried inside a vacuum desiccator while those in Fig. 1(b) were dried using a heat dryer sterilizer at 100°C temperature. Looking at the plot closely, one can notice that the samples dried in the vacuum desiccator exhibited signal increase within 10 days and became stable after 20 days. This is presumably resulted from the insufficient time for drying the samples inside the vacuum desiccator. On the other hand, the ESR response for samples dried at 100°C temperature showed good signal stability up to 30 days of postmeasurement. Although the ESR spectra from Fig. 1(b) were larger in signal size than in Fig. 1(b), which might be the influence of the drying temperature, the signal stability is still critically important for BKG corrections.

The stability of the BKG was further checked in two sample preparations (water-treated and untreated), shown in Fig. 2. A remarkably similar behavior of BKG signals can be observed for both sample preparations. The BKG signals were seen to slightly increase within 24 hours and proximately reached a stabilization state with very minimal fluctuations. Thus, the unirradiated samples kept under vacuum storage condition resulted in good stability of the BKG signal. It is worthy to mention that the use of water in the present study was to provide a more realistic representation in daily situations, especially that water contact is unavoidable in circumstances such as hand washing, taking showers, among others. Further, water humidification is reported to eliminate unwanted signals, for example, dirt or any physical factors induced by mechanical stress. It is worth noting, however, that the storage conditions (i.e. humidity and temperature) for both sample preparations were normally constant, which means that not only water humidification was responsible for the growth of the signal.

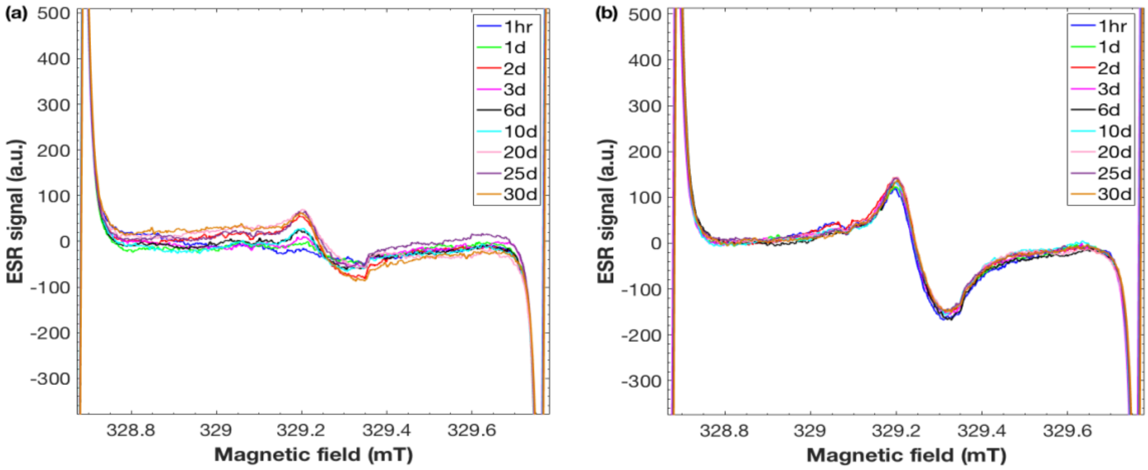

Fig. 1. Time evolution of the spectrum shape of unirradiated samples dried inside the (a) vacuum desiccator (30–40% humidity, 20°C) and (b) heat dryer sterilizer (100°C).

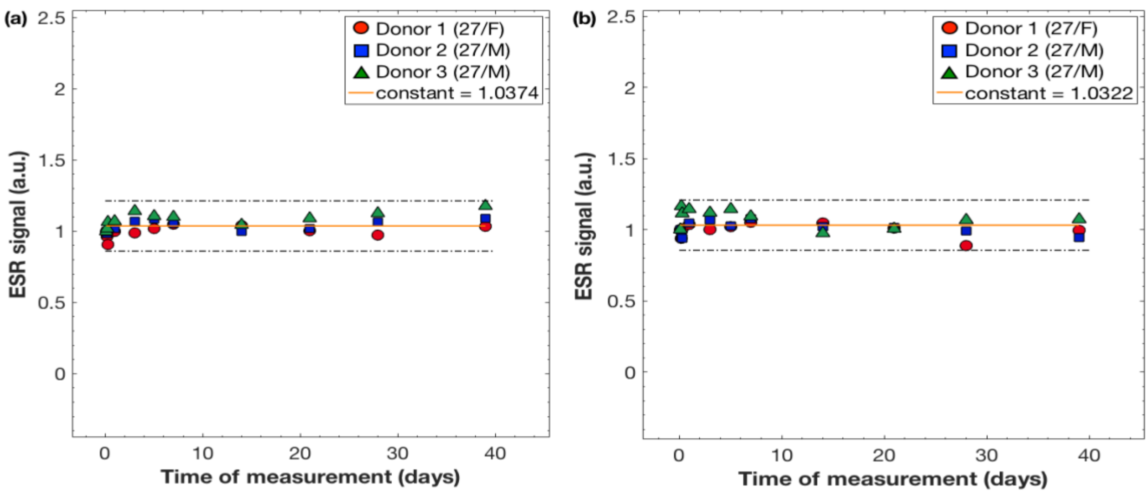

Fig. 2. Variation of BKG intensity for the (a) water-treated and (b) untreated samples measured at various times. All experimental data points were normalized with respect to the first measurement data. The solid lines represent the average measured data calculated from the three donors. The dashed lines represent 27% relative percent range.

In an attempt to further understand if the BKG signal is sensitive to other influential factors, perhaps to ambient light, another experiment with some setup modifications was performed. Similar corresponding water-treatment and drying conditions were utilized but the ambient light exposure was prevented starting from the sample drying, storage, and spectral measurements. As shown in Fig. 3(b), with the modified setup, the graph perfectly shows that the BKG intensity did not exhibit any prompt signal growth in the first few hours of measurements and remained relatively stable up to 39 day of postmeasurement. Moreover, the experimental data points with the modified setup in Fig. 3(b) were more comparable to one another than those recorded without the setup modification in Fig. 3(a). Based on the experimental data points, there has been a 5% reduction in the signal fluctuations. Thus, one can further say that if we prevent the fingernail samples from ambient light exposure, we can achieve a more stable BKG signal, which is important in fingernail analysis.

Fig. 4 the ESR spectra of the vacuum-stored samples irradiated to 70 Gy which is mainly consisted of RIS-singlet. One important observation from this graph is that the RIS-singlet intensity increased in the first few hours after irradiation and continued to increase until several days. It is important to emphasize that the increase of RIS-singlet was due to the increase of the BKG signal with storage time.

Fig. 5 compares the time dependence of RIS intensity in vacuum stored water-treated and untreated samples after 70 Gy exposure to high-energy X-rays. This figure clearly demonstrates how different the RIS-singlet behavior for both untreated and water-treated samples. No such large signal increases were apparent for untreated samples contrary to the observed signals from water-treated samples which tend to increase until the maximum peak was reached before the signal started fading. More importantly, the observed fading rate of the untreated samples is much faster than those for water-treated samples. Finally, one can further say that the fading patterns for each donor, even they are of the same-age, were significantly different.

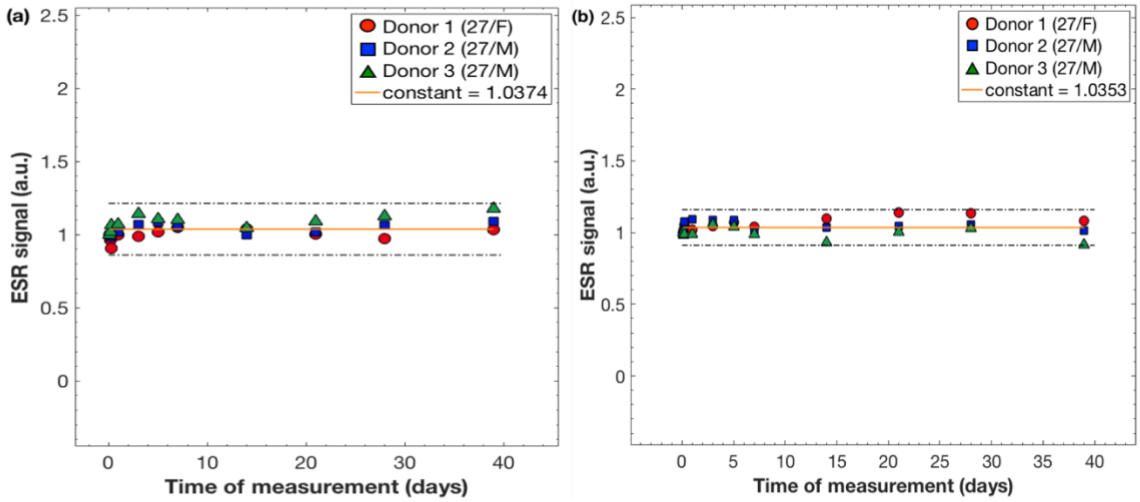

Fig. 3. Variation of BKG intensity for the vacuum stored water-treated samples (a) without (b) with setup modification measured at various times. The dashed lines represent 27% and 22% relative percent range for (a) and (b), respectively.

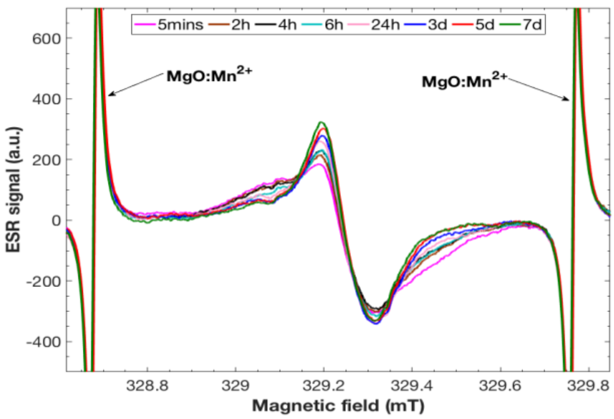

Fig. 4. Time evolution of vacuum stored samples irradiated to 70 Gy high-energy X-rays.

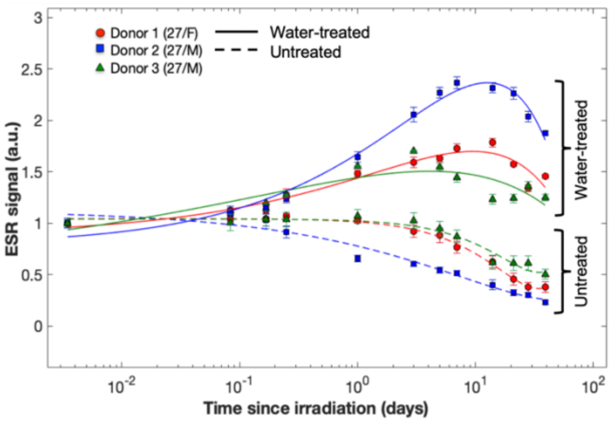

Fig. 5. Variation of RIS intensity for vacuum stored water-treated samples irradiated to 70 Gy high-energy X-rays in function of measurement time.

The dose-response curves obtained from the samples of different donors irradiated to two different radiation sources are presented in Fig. 6. From this figure, it can be observed that the slopes of the dose-response curves were distinct among different-age donors. Most notably, a variation in the radiation sensitivities among the same-age donors can also be seen. Another interesting observation from this figure is that the dose-response curves at high-energy X-rays were found to be linear in the dose range of 0–70 Gy, which covers the vast majority of accidental overexposure doses in radiotherapy. Based on the comparison of the dose-response curves among different donors, it is suggested that the calibration curves are not solely related to age but dependent on individual physiological properties.

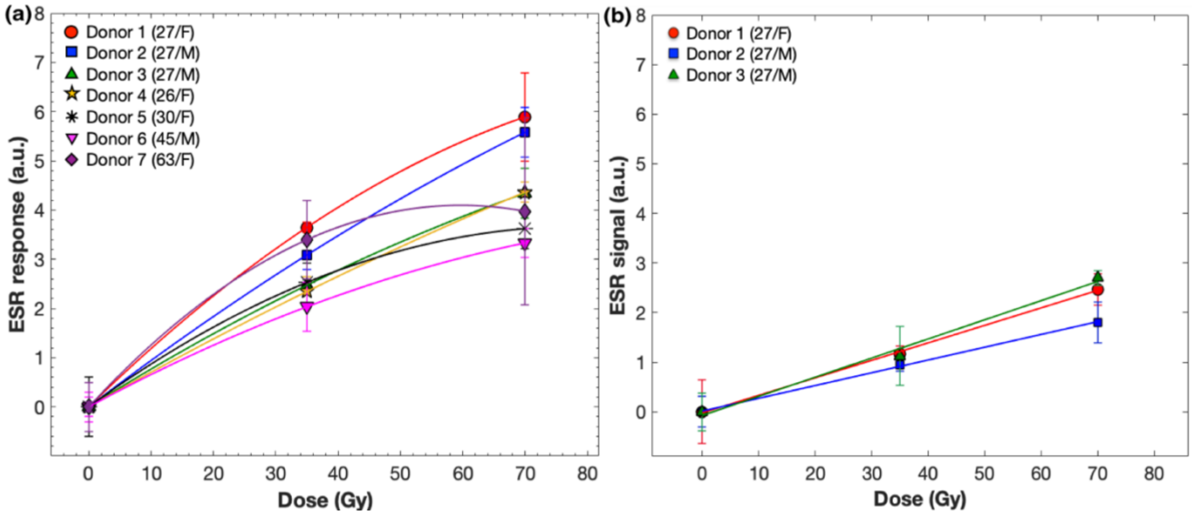

Fig. 6. Dose-response curves of samples irradiated to (a) ^{137}Cs gamma-rays and (b) high-energy X-rays.

Conclusions

The individual responses and stabilities of the ESR signals (particularly RIS and BKG) have been studied in irradiated human fingernails. Good linearities in the dose-response curves were observed for fingernail samples irradiated to high-energy X-rays (LINAC) and ɣ-rays (^{137}Cs source) up to 70 Gy dose range. While, unique behavior in the slopes of dose-response curves among the donors (different-age and same-age) was also observed. Furthermore, this study showed improvement in the signal stability for unirradiated samples dried at 100°C temperature up to 30 days. The ESR signal stability was also improved effectively under vacuum storage condition with limited ambient light exposure. Finally, despite the significant clinical advantages of radiation in medicine, accidental exposures to patient and staff are still possible when equipment malfunctions or procedural errors occurred. It is important to note, however, that the present study is limited to the following: first, only two radiation qualities were demonstrated and so further studies in the effects of other radiation qualities are necessary. Second, only high dose levels were employed thus it is also very important to investigate the responses in the low dose range. And lastly, there were only limited number of donors and understanding the variation in the dose-response of fingernails taken from a greater number of donors of different ages, gender, and lifestyles will result to more reliable practical applications of fingernail dosimetry.

This study is published on *Radiation Measurements*, 124: 91-97, 2019 and *Journal of Physics Conference Series* (JPCS), 1248 012072, 2019.