学位論文

Effects of ultraviolet rays on L-band in vivo EPR dosimetry using tooth enamel

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Effects of Ultraviolet Rays on L-Band In Vivo EPR Dosimetry Using Tooth Enamel

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Abstract

L-band electron paramagnetic resonance (EPR) in vivo dosimetry has the potential advantage of being able to accurately and sensitively measure the absorbed dose of ionizing radiation by measurements of teeth in situ. The equipment is transportable to the site where a radiation incident occurred and can be operated without specialized facilities. It, therefore, is very suitable for medical triage of victims in a large-scale radiation incident to quickly determine whether the dose was large enough to require urgent care. The measurements are made on the outer surfaces of the two upper incisor teeth. However, some in vitro studies of extracted teeth using higher frequency EPR have suggested that exposure to ultraviolet rays (UV) from sunlight might confound estimates of the dose of ionizing radiation made with EPR. Because the outer surfaces of incisors are likely to be exposed to UV/sunlight, it, therefore, is essential to determine the potential quantitative impact of UV on L-band EPR dosimetry measurements based on incisors. We, therefore, investigated the quantitative effect of UV on the EPR signal from ionizing irradiation of human teeth using the L-band spectrometer developed for field dosimetry. The UV-generated EPR signal was very small relative to the signals resulting from doses of ionizing radiation that are used for triage. For example, using our estimates of the effects of UV, for a lifetime of 50 years of exposure of these teeth (assuming an average exposure to sunlight of two hours/day), the expected average lifetime effect of UV-induced signal would be equivalent to 0.33 Gy; in contrast, triage criteria for accidental exposure to ionizing irradiation generally start at 2.0 Gy.

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1 Introduction

1.1 EPR Tooth Dosimetry

1.1.1 The Basic Mechanism That Allows EPR to Detect Ionizing Radiation in Enamel

Ionizing radiation generates unpaired electron species in irradiated materials, including biologic tissues. The fundamental basis for tooth dosimetry is that radiation generates stable carbonate anion radicals in the calcium hydroxyapatite of tooth enamel, and the intensity of these radicals can be measured using electron paramagnetic resonance (EPR). The radicals generated in tooth enamel are very stable, persisting indefinitely at levels that are directly proportional to the absorbed dose [1, 2]. Because the signal is both near instantaneously detectable and also stable over thousands of years, it can be used retrospectively to assess exposures, ranging from immediately following an event to decades or more later [3].

1.1.2 From Using In Vitro Samples to Making In Vivo Measurements in Subjects

Dosimetry based on the EPR signal was first proposed and performed more than 50 years ago in the laboratory of H. M. Swartz [1] on extracted teeth (and bone) in animals irradiated in vivo, human bone irradiated in vivo, and in human fingernails irradiated in vitro. Since then, many others have used standard microwave frequency EPR (e.g., 8–12 GHz, X-band) to assess dose retrospectively. X-band EPR tooth dosimetry has typically been performed using extracted teeth or tooth enamel samples long after victims' exposures in radiation incidents [3–13].

With more recent developments of lower frequency (1–3 GHz, L-band) EPR spectrometers, measurements can now be made in vivo with good sensitivity. Thus, it is now possible to assess radiation dose in vivo by EPR measurements of teeth in situ in the mouth [14, 15].

1.1.3 Dosimetry Used to Triage Victims for Medical Care

While the possibility of extending the approach to measurements in vivo was shown 20 years ago [16], its full potential had not been achieved until very recently. Initially, the apparatus was so large that it was not feasible to easily transport it to the field, thereby limiting its suitability in major accidents. Recently, technological changes to miniaturize the magnets and other parts of the apparatus have made the spectrometer more easily transportable (Fig. 1). Therefore, when disasters such as nuclear plant accidents occur, we can now transport the spectrometer close to the site of the exposure to estimate the absorbed dose in subjects.

Therefore, it is now feasible to use tooth dosimetry to carry out triage after a major event, i.e., to quickly and accurately distinguish people whose exposure warrants receiving immediate treatment or mitigators from those who do not need to use resources. This capability to use biodosimetry for triage is particularly crucial

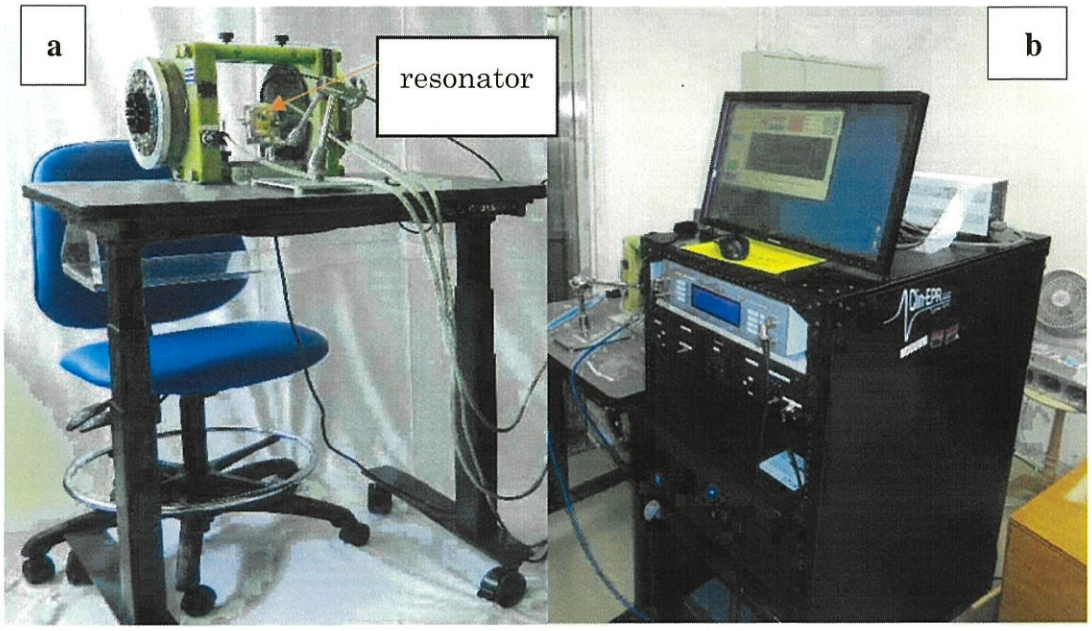

Fig. 1 Transportable L-band EPR measuring device for in vivo tooth dosimetry. **a** The magnet and resonator on an articulating arm. Subjects sit at the table and place their head in the opening between the poles of the magnet. While not visible, there is a bite block in the middle of the opening that gently holds the subject's mouth open and exposes the upper central incisors for measurement. The operator places the coupler (small loop that extends from the resonator) against the incisor; the articulating arm is tightened to hold the loop against the tooth during measurement. **b** The spectrometer (RF microwave bridge, computer, power supply, etc.), with the spectra displayed on the monitor in real time during measurements. The EPR device has been downsized and made lightweight and can be transported to the measurement site

in large events because healthcare resources would likely be overwhelmed if all potentially exposed people were treated, regardless of knowing their dose [17, 18]. Measurements of natural human upper central incisors mounted within a simple anatomic mouth model have demonstrated the ability to achieve 0.5 Gy standard error of inverse dose prediction [17–19]. In these works, a geometrical correction was applied to account for the impact of different tooth sizes on the signal amplitude and an age-based correction was considered.

1.2 Identifying Significant Confounders of Tooth Dosimetry

As an important next step, to further improve the accuracy of the dose used to triage in real-world situations, it is important to consider whether and, if so, how much other factors might impact assessments of exposure for biodosimetry purposes. In this paper, we focus on determining whether ultraviolet (UV) exposures would impact tooth dosimetry as measured by the L-band device we are using.

1.2.1 Why UV Is a Potential Significant Confounder: The Tooth Surface Used

The transportable in vivo EPR tooth dosimetry device uses the front surface of the upper central incisors for measurement at L-band frequency. These surfaces in

humans are generally the most likely teeth to be visible (e.g., when talking or smiling) and therefore they are the most likely teeth to be exposed to UV/sunlight.

1.2.2 Why UV Is a Potential Significant Confounder: Evidence from X-Band EPR

Investigations into the effects of solar radiation (which includes UV frequencies) on EPR signals in human tooth enamel have been reported to be similar to those induced by gamma irradiation [20]. Radical formation by UV has been shown using X-band EPR on isolated enamel, also providing evidence that sunlight could be an important confounder for using tooth enamel in dosimetry [21, 22]. For X-band EPR tooth dosimetry, it has been generally recommended to avoid the use of buccal incisors due to potentially confounding effects of UV irradiation [23]. These recommendations have tended to focus on the use of tooth dosimetry for epidemiological and long-term exposure investigations, as opposed to triage for acute radiation syndrome where the pertinent dose levels and uncertainties are significantly larger.

Many in vitro studies have been carried out to investigate the production of EPR signals by UV irradiation using grains of isolated tooth enamel and isolated plates of enamel [20, 24–27]. These studies report equivalent-dose rates for UV irradiation of 10–25 mGy/hr. In these reports, numerous methods are proposed to reduce the impact of UV irradiation, including etching to remove surface layers, thermal annealing and delays to remove transient signals, and identification of spectral differences between UV and gamma-generated signals. Some of these papers have concluded that UV would be a significant confounder for the use of incisors for triage. However, Ivannikov et al. [28] reported an analysis of EPR spectra collected for a large-scale study of Central Russian populations with a focus on the dosimetric impact of natural in vivo UV irradiation of in situ teeth, rather than laboratory-based in vitro irradiation of processed enamel sampled. Tooth position and surface were noted and the age of the tooth donor was related to the dosimetric EPR signal. Based on the donor age, and accounting for the impact of natural background radiation, Ivannikov and his colleagues found that the annual rate of UV dose-equivalent signal generation in buccal incisor tooth enamel was 10 ± 2 mGy/yr for both X-band and L-band. This result is consistent with other reports of larger dosimetric signals from incisor teeth. For example, Sholom and colleagues [29] measured tooth samples from Chernobyl liquidators and noted that incisor dose estimated (without UV corrections) was on average 140 mGy larger than those measured from molar teeth.

There have not been previous reports on the impact of UV using the L-band frequency of the in vivo EPR instrument and with intact unperturbed teeth. Thus, the aim of this report is to determine whether exposure to sunlight would be an important confounder for triage based on in vivo EPR dosimetry.

1.3 Variability in Exposures to UV over a Lifetime and Between People

The amount of UV exposure to the upper front teeth on a given day depends on the exposure time and the time of day spent in sunlight with one's mouth open enough to expose the teeth to sunlight. Similarly, tooth quality (e.g., whether the teeth were

capped or had fillings), location (i.e., latitude, longitude and altitude) and the season can impact how much UV exposure a person's front teeth will have. Factors that can vary among people include social factors such as the person's occupation, recreational habits (including exposure to reflective surfaces such as water or snow), use of protective apparatus like hats, and changing the location where a person lives and works. Environmental factors include ozone layer quality, pollution, and clouds [30].

There are some studies of the magnitude of UV exposure to human subjects, albeit they are typically attempting to estimate skin exposure rather than teeth. Some studies of UV exposure have asked subjects to wear dosimeters, but most rely on subjective questionnaires, usually self-administered and seldom asking about protective measures taken [30]. Thus, there is no reliable estimate of lifetime exposure of the teeth to sunlight.

2 Methods

2.1 L-Band EPR Dosimetry

2.1.1 The In Vivo L-Band EPR Tooth Spectrometer That Was Utilized

The measurements reported here used an EPR tooth dosimeter obtained from Clin-EPR, LLC. This instrument was based on instruments designed for in vivo dosimetry by the EPR Center for the Study of Viable Systems, Geisel School of Medicine at Dartmouth College in Hanover, NH USA (the laboratory of H.M. Swartz) [2, 19, 31]. The spectrometer operates in continuous-wave (CW) mode and uses homodyne detection at an excitation frequency near 1.15 GHz (L-band) using a 41 mT dipole magnet weight 30 kg with 17 cm pole separation. The integrated field sweep and modulation coil provide a 4 mT sweep range and 0.4 mT modulation at 20 kHz. Teeth were measured using a specially developed surface loop resonator for maxillary incisors which has a detection loop with an inner diameter of 6.0 mm [2, 14, 32]. The detection loop was brought into contact with the enamel on the outer (labial) side of an upper incisor, and the radicals on that surface were measured (Fig. 2).

2.1.2 Acquiring Simultaneous EPR Spectra for the Sample and a Standard Reference

The EPR spectra were acquired using standard parameters: scan range, 2.5 mT; scan time, 3 s; average scans, 30; modulation amplitude, 0.4 mT [16, 33–35]. A plastic tube containing a solution of 4-oxo-2,2,6,6,-tetramethylpiperidine d_{16}-1-^{15} N-1-oxyl (also known as ^{15} N perdeuterated tempone [PDT]) was placed in close proximity to the surface loop and was used as a simultaneously recorded reference standard, to monitor several aspects of the EPR signal [31, 34, 35]. The ^{15} N-PDT EPR spectrum includes two resonance peaks that are offset from the peak of the irradiated tooth. Five measurements are made of each sample during a given session. Typical EPR spectra for RIS and the associated PDT are illustrated for a tooth irradiated to 2 Gy in Fig. 3. Note that the RIS in the tooth has a g-factor of 2.009, while the PDT has

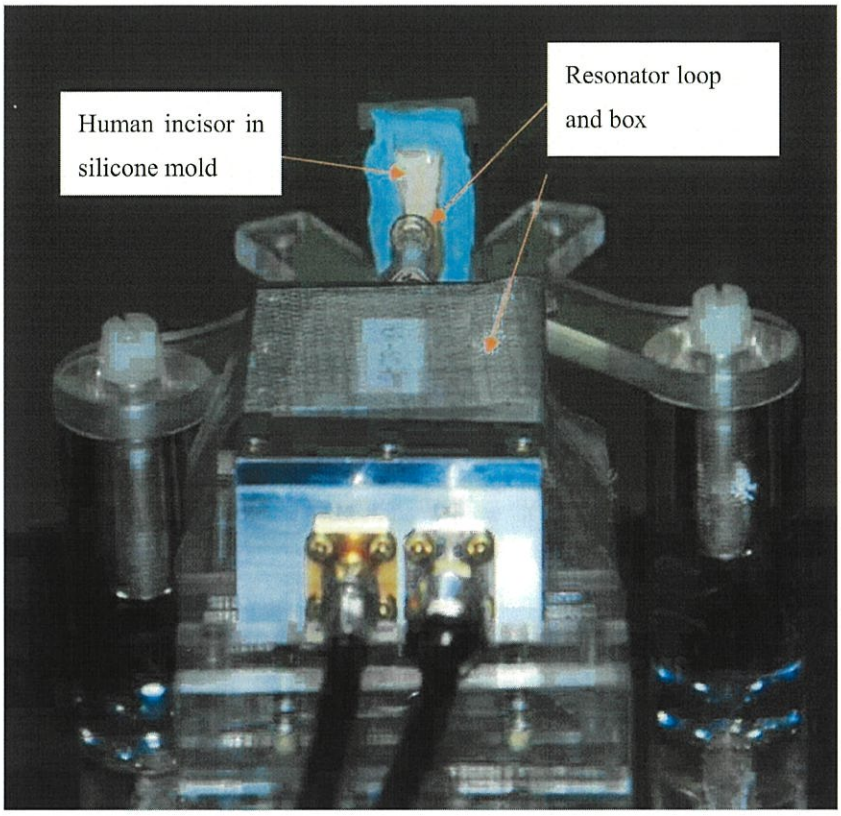

Fig. 2 Setup for measuring extracted incisors in the L-band in vivo EPR Dosimeter. The sample is embedded in a blue silicon mold and the position is fixed, using a special plate, in the same location within the opening between the poles as the human subject 'bites' using a bite block. The resonator box is shown with the loop ready to be placed on the incisor

a g-factor of 2.007; because of this difference in g factors, the signal of the PDT is fully separated from the RIS and, therefore, does not impact the quantitation of the RIS. We will return to this figure below.

The ^{15} N-PDT signal is used to provide many quality control functions, including continuous overall verification that the spectrometer is operating correctly, accurate measurement of the amplitude of the applied modulation field, calibration of the magnetic field scan width, and absolute physical magnetic field calibration for each of the recorded spectra for use in data analysis [31, 35].

2.1.3 Analyzing the EPR Data

The spectra from each of the collected datasets were analyzed using nonlinear least-squares fitting to estimate the peak-to-peak signal amplitudes of the radiation-induced signals (RIS), and of PDT. Measurements were then averaged to provide a mean amplitude (i.e., voltage [V]) for each tooth and at each dose of UV (referred to as VRIS and VPDT, respectively).

To account for variations in RIS amplitude due to instrument variability or external environmental factors, the ratio of VRIS to VPDT for each measurement was calculated and normalized to the same ratio as for a standard tooth exposed to 20 Gy by irradiation in a Gammacell 40 Exactor Best Theratronics (137Cs

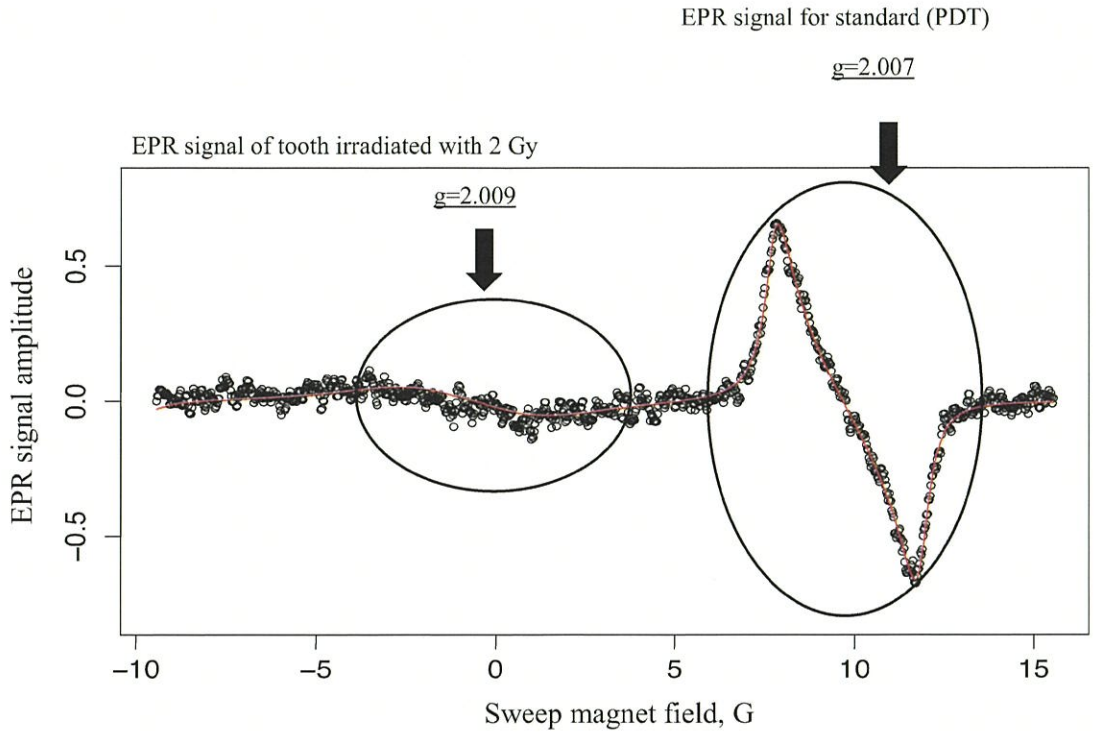

Fig. 3 Typical L-band EPR spectra (observed signal and fitting signal) of a human incisor irradiated with 2 Gy (using Cs^{137}) and a standard, the stable radical (PDT). The horizontal axis represents the sweep magnetic field (G), and the vertical axis represents the amplitude of the EPR signal. The amplitude of the signal is a relative value obtained by differentiating the magnitude of the radio wave absorbed by resonance. The radiation-induced signal (RIS) in the tooth is consistent with a g-factor of 2.009, and the PDT, with a g-factor of 2.007; this difference in g factors shows that the signal of the PDT is fully separated from the RIS and, therefore, does not impact quantitation of the RIS

148TBq). Therefore, the dosimetric-relative RIS amplitude (RelRIS) associated with each tooth was calculated as the ratio of these ratios of VRIS and VPDT to 20 Gy.

2.2 UV Irradiation

2.2.1 Using a Light Source Standardized to Replicate UV from Sunlight

There are three types of UV designated as UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm). Inasmuch as significant amounts of UV-C are not present in the sunlight that reaches the surface of the earth, we studied the effects of only UV-A and UV-B. A xenon light source of 100 W was used for the UV irradiation (Asahi Spectroscopy Co., Ltd. LAX-C100). The latitude near Japan was chosen for the solar standard because we have conducted EPR tooth dosimetry studies in Japan and wanted to estimate the impact of this confounder on our current studies. As shown in Fig. 4, indicating that the UV produced by the lamp we used is a reasonable approximation of the spectral distribution of sunlight.

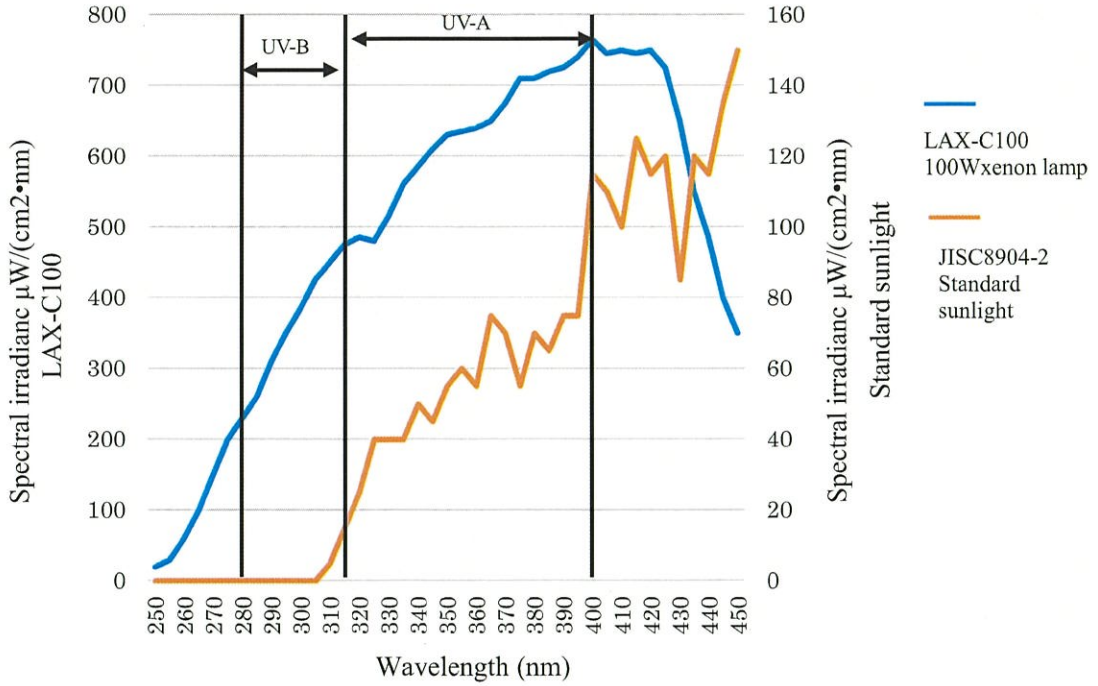

Fig. 4 Spectral distribution of the 100 W xenon lamp and sunlight, assuming a latitude approximately the same as Japan. LAX-C100 shows the spectral distribution for the xenon lamp used; JIS ETC shows the spectral distribution of standard sunlight at the latitude near Japan. UV-C = 100–280 nm; UV-B = 280-315 nm; UV-A = 315–400 nm. (data provided by Asahi Spectroscopy Co., Ltd.)

2.2.2 Using the Light Source to Produce UV-A and UV-B

To obtain UV-A from this device, a mirror module for UV-A and a band pass filter (LX0320) were used to selectively extract the wavelength of 315–400 nm. Since the size of the irradiation field using a rod lens was set to 20 mm, the radiant exposure of UV-A in this apparatus was about 8,200 mJ/cm^2 per hour.

For UV-B, a mirror module was used to selectively extract the wavelength of 280–315 nm, and a band pass filter (LX0280) was used which was made transparent to the wavelength of 280 nm. Since the size of the irradiation field was 20 mm using a rod lens as in the case of UV-A, the radiant exposure of UV-B was about 4200 mJ/cm^2 per hour. The calculation of the irradiation doses took into account that the irradiation efficiency was reduced due to the deterioration of the ultraviolet irradiation device over time, using data on deterioration of the UV spectra from the lamp (data were provided by Asahi Spectroscopy Co., Ltd.).

2.2.3 Exposing the Samples to the Light Source to Produce UV-A and UV-B

For each of the sample teeth (all were whole human maxillary central incisors), we first measured it with L-band EPR dosimetry five times before adding any UV exposure from our lamp. Since the extracted teeth can be presumed to have been exposed to some sunlight during the donor's lifetime, this initial measurement serves as a baseline, and our exposures to UV are additive to the baseline. This strategy is based on the apparent stability of the tooth radical from ionizing radiation (lasting

thousands to millions of years) and the apparent similarity of UV-induced radicals to radicals induced by ionizing radiation.

We irradiated three teeth in six stepwise exposures to the UV-B wavelength range of the xenon lamp and irradiated three different teeth in two stepwise exposures within the UV-A range. What is reported as exposure to UV in our figures is the additive effect of our exposures to UV over the baseline, expressed in the energy of the exposure.

To convert the UV exposure in energy to a likely lifetime exposure of a person's incisor to sunlight, we chose an arbitrary but conservative estimate[1] of UV exposure. We assumed an exposure of UV to the maxillary incisors for a lifetime daily average of 2 h for 50 years (arguably this corresponds to ~ 56-year-old adult because of the typical time for these adult teeth to erupt); these results can of course be converted to different scenarios of potential exposure to UV.

3 Results

An example of the EPR spectrum obtained by measuring a tooth exposed to about 80,000 J/cm^2. UV radiation is shown in Fig. 5. The smaller amplitude of the tooth irradiated by UV-A is consistent with a signal equivalent to ~ 1 Gy.

While not shown here, the shape and g-value of the EPR signals were similar for both ranges of UV (A and B) we studied.

Note that the g-factor in Fig. 5 is identical to the g-factor of the tooth (and the PDF) in Fig. 3. The fact that the g-factors for the tooth sample in both Figs. 3 and 5 are identical is consistent with the conclusion that the EPR spectra of a tooth irradiated by cesium cannot be distinguished from one irradiated by UV-A. This finding that the tooth radical produced by UV cannot be distinguished from the native tooth radical is consistent with the literature, including studies conducted at X band references. To try to estimate how much UV could confound our in vivo EPR tooth dosimetry measures of people incidentally exposed to ionizing radiation (particularly gamma rays), we turn to estimating the likely lifetime impact of exposure to UV by sunlight.

Figure 6 shows the relationship between the magnitudes of the EPR signals generated by UV-B (in units of energy (J) per unit area (cm^2)) and the ionizing radiation dose equivalent. The relationship is directly proportional, and it can be seen that about 5000 J/cm^2 is required to obtain a dose equivalent to 2 Gy. (As noted in Fig. 6, the R^2 for the estimated slope is 0.64.)

Also shown in Fig. 6 (in the upper scale on the X-axis) is the relationship between the irradiation dose (Gy) converted by Cs^{137} and the irradiation time

[1] The estimate of 2 h daily exposure of the upper incisors to UV on average over a lifetime is 'conservative' in that it is likely to be much higher than most people would have. Therefore, our estimates of years that correspond to achieving a given exposure level from sunlight in a 'typical lifetime' is likely to be too low; most people would receive much lower levels of exposure on their teeth and take many more years to achieve this level.

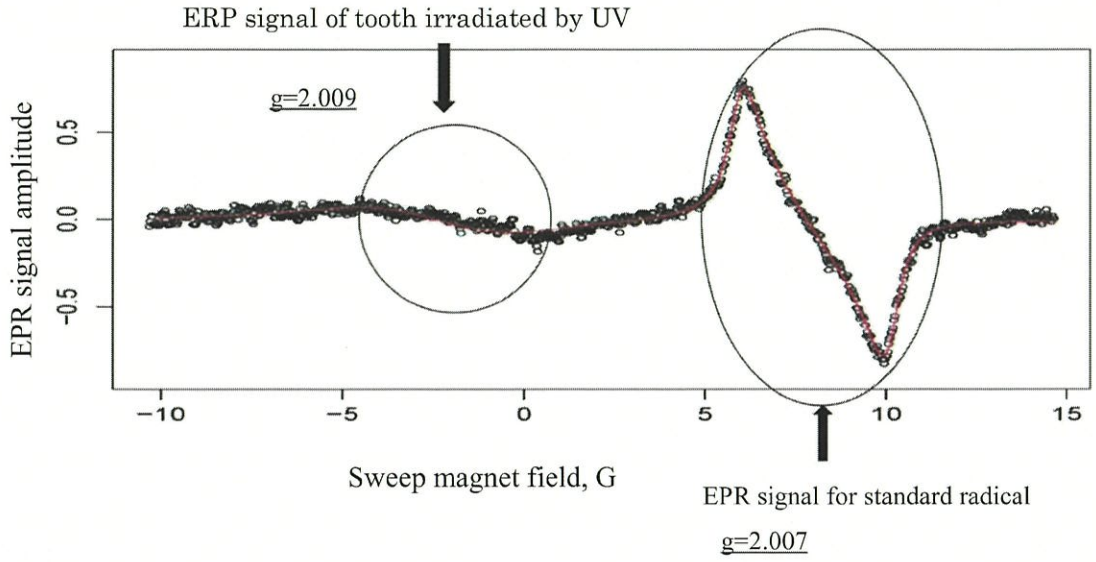

Fig. 5 An example of L-band EPR spectra of the tooth exposed to UV-A irradiation and a standard radical. Each dot shows the EPR response measured at each magnetic field and is represented as a fitted curve. The horizontal axis represents the magnetic field (G), and the vertical axis represents the amplitude of the EPR signal. Note that the g-factors in Fig. 5 are identical to the g-factors of the tooth (and the PDF) in Fig. 3. This is consistent with the finding that the spectra of a tooth irradiated by cesium cannot be distinguished from one irradiated by UV-A. The smaller amplitude of the tooth irradiated by UV-A is consistent with a signal equivalent to ~ 1 Gy. The irradiation amount of UV-A is about 80,000 J/cm^2 (though not shown here, the EPR spectra were similar for all types of UV-B)

(in years) that would be required for an in vivo incisor to be exposed to sunlight UV-B, (assuming an average daily exposure of 2 h) to achieve an equivalent intensity EPR signal.

These data indicate a dose-equivalent rate of ~ 6.1 mGy/yr for UV-B under the postulated conditions. At this rate, the postulated 2 h/day daily irradiation by UV-B would need to occur to the incisor for about 300 years to obtain a dose equivalent to 2 Gy (which is an important cutoff level for triage in radiation dosimetry). (300 years and 2 Gy are based on extrapolating the lines in this figure.) Expressed instead as a likely lifetime exposure for a 56-year-old Japanese subject (assuming eruption of the maxillary incisors at ~ 6 years old and 50 years of exposure), our data suggest that the accumulative lifetime exposure to UV-B would be equivalent to ~ 0.33 Gy of ionizing radiation.

The parallel results of UV-A irradiation are shown in Fig. 7. The figure shows the relationship between the irradiation time (in yr) of sunlight UV-A, assuming a daily average of 2 h, and the irradiation dose (Gy) when the EPR RIS signal is converted by Cs^{137}. Here the dose-equivalent rate is ~ 6.8 mGy/yr; the R^2 for the estimated slope is 0.94. About 300 years of 2 h daily exposure to UV-A irradiation would be required to obtain an irradiation dose equivalent to 2 Gy. Expressed as a lifetime accumulated dose for a 56-year-old Japanese subject, UV-A would contribute ~ 0.33 Gy total to the upper incisors.

There was no apparent difference when comparing the dose–response relationships between the amount of energy delivered by UV-A and UV-B and the magnitude of the EPR signal.

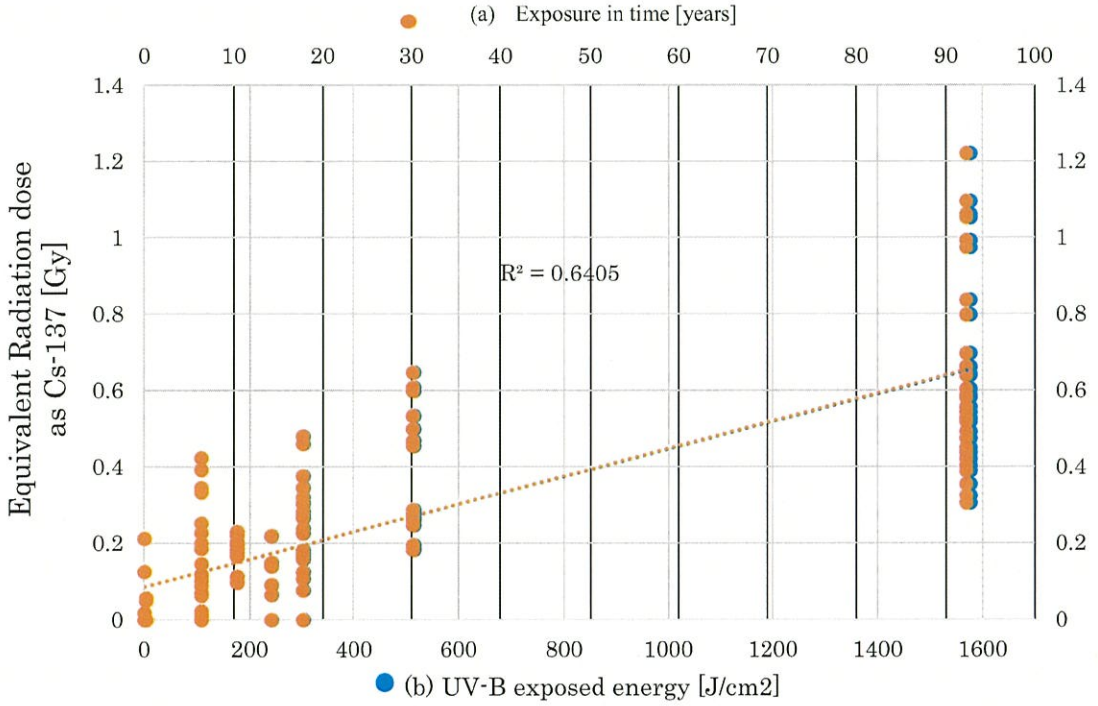

Fig. 6 The relationship between standardized EPR signal and UV-B exposure energy per unit area and exposure in time. The two legends for the X-axis portray UV-B: (**a**) based on assuming an average exposure of 2 h/day, in years to reach the corresponding exposed energy (orange dots) and (**b**) in exposed energy to the tooth (blue dots). $R^2 = 0.6405$ and the constant (0.0881) are identical for both relationships. For UV-B exposed energy, $y = 0.0004x + 0.0881$; for UV-B exposure time, $y = 0.0061x + 0.0881$. At each exposure, three incisors were each measured stepwise across doses, with 5 different measurements on each tooth at each dose. Dots portray 15 measurements at each exposure but may appear to be fewer when they overlap. Blue and orange dots largely overlap

4 Discussion

In this study, we demonstrated, using L-band EPR, that exposure of teeth to UV-A and UV-B resulted in the generation of EPR signals that were similar to those found with ionizing radiation. This result is similar to the findings using X-band EPR.

Assuming an average lifetime exposure to the UV found in sunlight of 2 h per day, it would take about 300 years of such exposure to generate a signal equivalent in magnitude to the usual triage dose level (2 Gy) of exposure to a major radiation event. While UV exposure is not likely to generate a signal equivalent to the triage dose level, the accuracy of individual dose estimates would certainly benefit from age-based corrections for the impact of UV exposure. For example, based on our estimate of 6–7 mGy/yr, UV exposure may contribute 0.3–0.4 Gy toward a dose estimate for an individual 50–60 years old. Incorporation of an age-based UV correction decreases the overall uncertainty for dose estimation across a general population of measured subjects, thereby increasing the accuracy of dose-based triage decisions with fewer false positives and false negatives [36].

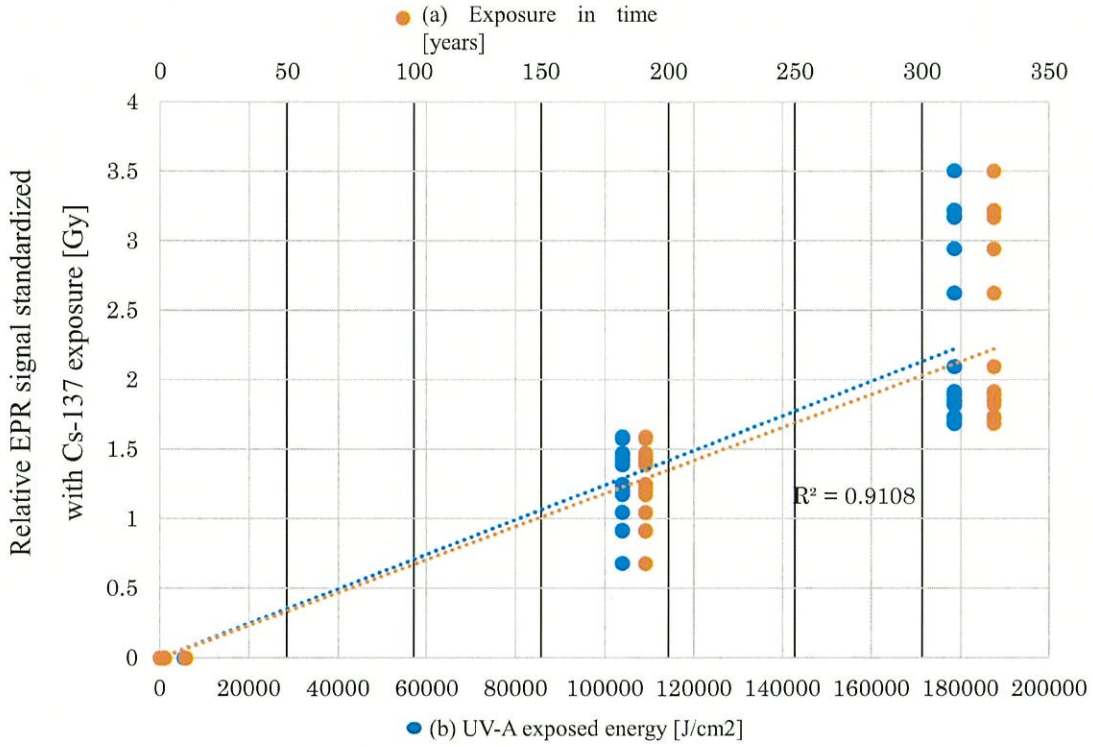

Fig. 7 The relationship between standardized EPR signal and UV-A exposure energy per unit area and exposure in time. The two legends for the X-axis portray UV-A, (**a**) based on assuming an average exposure of 2 h/day, in years to reach the corresponding exposed energy (orange dots) and (**b**) in exposed energy to the tooth (blue dots). $R^2=0.9108$ is identical for both relationships. For UV exposed energy, $y=0.0000125x$; for UV exposure time, $y=0.0068x$. The greater offset in dots in Fig. 7 compared to Fig. 6 is due to a bigger difference between the two slopes. At each exposure, the three incisors were each measured serially, with 5 different measurements each. There are, therefore, 15 measurements at each exposure; dots overlap in some cases

5 Summary and Conclusions

Quantitative in vitro studies of EPR signals generated in incisor teeth by well-defined UV- A and UV-B sources indicate that the impact on triage decisions based on a threshold of 2 Gy from UV exposure on the magnitude of the EPR signals is very low (approx. 6–7 mGy/yr) when measured in the L-band in vivo spectrometer that usually is used for measurements in teeth in vivo. These results indicate that the UV radiation in sunlight is very unlikely to be a significant confounder to EPR dosimetry for triage based on in vivo L-band tooth dosimetry measurements in upper incisor teeth.

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Author contributions YN: Wrote the first draft of the paper and carried out most of the experiments. HH: Contributed to the planning and analyses of the data and improved some parts of the equipment and

maintained the instrument. HMS: Contributed to the design of the research and the interpretation of the data. ABF: Contributed to the interpretation of the results of the experiments and to the discussion of the relation between the findings in this paper and prior work; corrected the language of the paper to make it more readily understood; checked English grammar. BBW: Contributed to the theoretical analysis of the measurements and the validation of the technical descriptions. WS: Provided technical support of the EPR spectrometer and the methods for interpreting spectra. MM:Provided overall supervision of the research and finalization of the paper.

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Availability of data and material Yes.

Declarations

Conflict of interest HMS and ABF are co-owners of Clin-EPR, LLC, which manufactures L-band EPR dosimeters for investigational use. Other authors declare that they have no conflict of interest.

Ethical approval Approved by (#H24-004) IRB of Kagawa University.

Consent to participate Written consent was obtained.

Consent for publication The publication is authorized by IRB of Kagawa University dosimeters.

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