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Detection of Ultraviolet Radiation Using Tissue Equivalent Radiochromic Gel materials

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Abstract. Ferrous Xylenol-orange Gelatin gel (FXG) is known to be sensitive to ionising radiation such as $\gamma$ and X-rays. The effect of ionising radiation is to produce an increase in the absorption over a wide region of the visible spectrum, which is proportional to the absorbed dose. This study demonstrates that FXG gel is sensitive to ultraviolet radiation and therefore it could functions as UV detector. Short exposure to UV radiation produces linear increase in absorption measured at 550nm, however high doses of UV cause the ion indicator colour to fade away in a manner proportional to the incident UV energy. Light absorbance increase at the rate of 1.1% per minute of irradiation was monitored. The exposure level at which the detector has linear response is comparable to the natural summer UV radiation. Evaluating the UV ability to pass through tissue equivalent gel materials shows that most of the UV gets absorbed in the first 5mm of the gel materials, which demonstrate the damaging effects of this radiation type on human skin and eyes. It was concluded that FXG gel dosimeter has the potential to offer a simple, passive ultraviolet radiation detector with sensitivity suitable to measure and visualises the natural sunlight UV exposure directly by watching the materials colour changes.

1. Introduction:
Ultraviolet light is the section of electromagnetic radiation that lies between visible light and X-rays. Human eyes are sensitive to wavelengths of between 790nm (red) and 400nm (violet), while soft X-rays have wavelengths that are less than a few nano-meters [3]. The ultraviolet spectrum is generally subdivided to the following spectral bands: UVC (100-280 nm), UVB (280-315 nm), and UVA (315-400 nm) [1]. UVA is the main component of the terrestrial ultraviolet spectrum, and is important in the generation of photochemical smog and also in the fading of plastics, paints and fabrics colors. Only 1% of solar radiation lies within the UVB band, and most of this is absorbed by ozone [2]. However, small changes in ozone cause large changes in UVB radiation reaching the Earth’s surface. UVC is totally absorbed by ozone and other gases and does not reach the Earth’s surface. Time of day, season, latitude and altitude affect the level of terrestrial UV as the light attenuation is greater the further it has to travel through the atmosphere. Between 20% and 30% of the total daily UV amount is received during two hours around within the local midday at mid latitudes in summer. One kilometer increase in altitude will increase the UV flux by 6%. Similarly, the increases of cloud cover and high levels of pollution in the atmosphere reduce the amount of UV incident at the surface.

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The sun is responsible for the development and continued existence of life on Earth, but the ultraviolet content of sunlight causes a deleterious effect on biological systems. In some regions on the earth, skin tumor is the most common human cancer. It is estimated that one out of three people might develop a skin cancer in their lifetime [2]. Non-melanoma skin cancers are attributed to cumulative UV exposure and malignant melanomas are thought to be linked to infrequent, intense exposures, especially sunburn in childhood [3]. Cancers typically take one of three forms corresponding to the three major types of skin cells: basal cells, squamous sells and melanocytes [4]. Cancer of the melanocytes, malignant melanoma, is the most lethal variety but also the least common. Despite the fact that UVC is the most energetic part of the UV spectrum, no UVC reaches the Earth’s surface and, hence, UVB is the most damaging light to biological systems [5]. The most effective wavelength of sunlight for the production of erythema is 300nm (UVB), rapidly falling to just 1% of the effectiveness at 320nm [3] and in general, UVB is approximately one thousand times more effective at producing sunburn than UVA. The production of vitamin D by sunlight incident on skin is the only thoroughly established beneficial effect of UV radiation [6]. From spring until autumn, 15 minutes of sun exposure for the hand, face and arms between 9am and 4pm is adequate to provide the vitamin D requirement. Also, many common devices and industrial processes involve the emission of UV radiation, including arc discharges and bactericidal lamps.

2. Detector materials and preparation:

The materials used to produce detection medium sensitive to UV radiation are the following. Pure water triply distilled and deionised makes about 95% of the detector, 5% by weight of gelatin powder (C17H32N5O6)x with high gel strength indicator; analytical grade ferrous ammonium sulfate hexahydrate Fe(NH4)2(SO4)2.6H2O with a 0.5 mM concentration, 0.1mM of the xylenol orange-sodium salt ion indicator, C31H28N2O13SNa4; and finally a small amount 50 \times 10^{-3}N of concentrated sulfuric acid H2SO4. The radiochromic gel is prepared according to a procedure described in [7]. Ultraviolet effects are determined through quantitative evaluation of induced changes in gel material. Gels samples are put in standard size 1cm light pass length UV grade quartz cuvettes. Samples which have different thicknesses were also made in order to study the percentage absorption of UV radiation energy.

2.1. Irradiation:

An ultraviolet (UV) source simulating the solar radiation is used to irradiate the FXG gel samples. It is also known as sun simulator, and reproduces UVA and UVB spectrum equivalent to natural sunlight. The ground level of solar radiation reaching the earth's surface varies significantly with atmospheric condition, location, time of the day, earth/sun distance, and solar activity. Standard spectra have been developed to provide a basis for standardization of theoretical evaluation of the effects of solar radiation.

![Figure 1: UV irradiation setup.](image-url)
Xenon arc lamp and power supply, Model XPS-200, (Solar Light Company, 721 Oak Lane, Philadelphia, PA 19126, USA.) is used as UV radiation source. The sun simulator UVA beam is reduced by applying suitable filters to the natural sunlight level of $55 \pm 5 \text{ W/m}^2$ [8], measured with Optometer P9710 (Gigahertz-Optik GmbH, Postfach 1445, 82170 Puchheim, Germany). Figure 1 gives a schematic representation of the irradiation experimental setup.

2.2. Spectrophotometry analysis of samples
Optical measurements were obtained from a SPECORD-210 double beam UV-visible spectrophotometer. A baseline was set with empty quartz cuvettes in both beams in order to establish a zero reading, and then cuvette filled with FXG gel was placed in the analyzing beam in order to get the changes in the gel absorption. The absorption was measured in the wavelengths range from 350nm to 650nm with 1nm intervals and a peak centered at about 550nm is found suitable for quantitative measurements. Quartz cuvettes are transparent to UV therefore it can be used for the irradiation and optical measurement of gel samples. The gel itself absorbs UV radiation much better than water; for example, UVB has the ability to penetrate about 17 cm of water with reduction of only 30% in its intensity [8].

3. Results and Discussion:

3.1. The Action of Radiation on FXG Gel
The Fricke solution depends on the radiolysis of water giving number of free radicals which are active species that will interact with the ferrous ions and cause them to oxidize. Similarly, the aerated FXG system relies on H$_2$, OH, and H$_2$O$_2$ to oxidize the ferrous ions [7]. The energy of UV light is such that it lies between ionizing and non-ionizing radiation for water. However, it is found that the ionizing events that can produce highly reactive radicals inside FXG materials are not the only processes taking place in the gel, but the excitation collisions also serve as an intermediary species within the interactions between radiation and the sensitive chemical system. Furthermore, it may also be the case that vibrationally excited (rather than electronically excited) molecules may instigate chemical reactions [7]. The production of ferric ions is not strictly dependent on the radiolysis of water. Instead, the ferric ions are likely to be produced indirectly by oxidizing events that are happening in the water by the absorbed energy of UV radiation. Figure 2 shows the optical absorbance measured for FXG sample irradiated with 105 W/m$^2$ artificial UVA radiations.

![Figure 2: The optical absorbance of 1cm thick FXG samples under 105 W/m$^2$ UVA irradiation.](image-url)
3.2. Ferrous Xylenol orange Gel (FXG) Dosimeter

By exploiting the visible colour change from orange to purple, FXG samples optical absorption measurements can be made to quantify the production of ferric ions. The ferric ions, produced by the radiation action, form complex with xylenol, but the ferrous ions do not, therefore the changes in ferric ion concentration results in proportional changes in the absorption of light. The conversion of ferrous to ferric ions is utilized to provide a practical dosimeter; the changes in the light absorption measured at different wavelengths for irradiated gel samples can be quantified and related to the delivered radiation doses. The optical response of the gel system (FXG) was studied at the wavelength 550nm. Before irradiation the FXG gel is orange, but once the gel is irradiated, the absorption at the 550 nm increases and the gel color becomes purple. By increasing the UVA irradiation \( (E_u) \) W/m² after filtering the beam to the measured natural sunlight level light absorption found increases linearly over the range 0 up to 15 minutes at exposure rate of 55 W/m² to UVA radiation, see figure 2.

\[
y = 0.0104x + 0.5026 \\
R^2 = 0.9909
\]

Figure 3: FXG response to UVA measured with standard size quartz cuvettes at 550 nm.

Figure 4: Absorption variation for three FXG layers of different thickness after illuminating the absorption of the unexposed samples.
Figure 3 illustrates the UVA effects on three FXG samples with different thicknesses. These samples were studied in order to evaluate its penetration ability and to demonstrate the hazards caused by this type of radiation and its damaging effects on human skin. It shows that major portion of UVA radiation get absorbed in 5 mm thickness of FXG gel.

4. Conclusions
The results show that exposing FXG gel to ultraviolet radiation gives a measurable and reproducible effect. The increase in absorption at 585nm has been shown to be linearly dependent on the energy incident on the gel and, consequently, the gel can potentially measure the ultraviolet exposure and visualize its harmful effects directly. Finally, the UV exposure of the population has a prominent profile, due to the grave implications of its link to skin cancer. The public awareness of UV is very high, and burn times are even routinely included in weather forecasts during the summer. Hence, there could be a demand for a passive UV detector made from very simple chemical ingredients and which has the attractive property of changing from orange to purple with increased exposure.

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