# Dosimeter for the measurement of UV exposures related to melanoma induction

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Short title: Dosimeter for UV exposure and melanoma

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**Abstract**
This paper reports on the development of a dosimeter for the measurement of biologically effective UV exposures related to melanoma induction. The melanoma ($UV_{Mel}$) dosimeter is based on the combination of polysulfone and nalidixic acid. This research found that the combination of these photosensitive chromophores reacts to UV wavelengths from 290 to 390 nm. It was found that a large change in optical absorbance occurred at 345 nm when the dosimeter was employed to quantify the solar UV waveband. Preliminary results indicate that this $UV_{Mel}$ dosimeter can measure exposures of more than 189 $kJ/m^2$ of biologically effective weighted solar UV radiation with an inter-dosimeter variability of no more than ± 5%.

## 1. Introduction

Exposure to harmful solar UVA (315–400 nm) and UVB (280-315 nm) radiation is linked to skin cancer, DNA damage and immunosuppression in humans. Skin cancer is considered the most common malignant neoplasm in Australia and the USA (Kricker and Armstrong, 1996; Glanz and Mayer, 2005; NCI, 2010). Over 1,600 Australians die from skin cancer each year and a further 380,000 Australians are treated for skin cancer each year (Staples, 2003; AIHW, 2004; AIHW, 2005). The American Cancer Society estimated that in 2009, approximately 68,720 new cases of malignant melanoma would be diagnosed, and approximately 8,650 persons would die from skin cancer in the USA (CFF, 2010). Incidence rates for melanoma in Australia and New Zealand are around four times as high as those found in the United States, Canada and the United Kingdom (AIHW, 2004).

It is thought that intermittent severe exposures (severe enough to cause sunburn) are critical for UV-induced melanoma and that UV exposures during infancy are more dangerous than exposures later in life (Ambach and Blumthaler, 1993; Hill et al, 1992; Stanton et al, 2000). Although melanoma is generally a disease of adulthood, research has shown that children in Queensland, Australia, had the highest incidence rates of melanoma in the world (MacLennan et al, 1992). A study by Moan et al (1999) also linked melanoma development to UV exposure in childhood.

Research has shown that UVA can induce a variety of damage types to DNA, proteins and lipids and plays a significant role in causing mutagenic and carcinogenic effects on human skin (Ridley et al, 2009; Wang et al, 2001; McKenzie et al, 2009; Agar et al, 2004; Moan et al, 1999). UVA has longer wavelengths than UVB and therefore can penetrate deeper into the skin. Researchers have estimated that approximately 19-50% of UVA can reach the depth of melanocytes, whereas only about 9-14% of UVB reaches a similar depth (Schothorst et al, 1987; Kaidbey et al, 1979; Bruls et al, 1984). Transmission of UVA has been experimentally verified in human skin tumors by Agar et al (2004), where deeper cells were found to harbour proportionately more UVA fingerprint mutations than UVB. Pfeifer et al (2005) found that UVA induced major mutations in the DNA of melanocytes as a result of oxidative stress. Wang et al (2001) showed that UVA radiation could stimulate melanocyte proliferation, causing abnormalities in DNA, and modifying gene expression. He et al, (2006) found that chronic exposure to UVA was sufficient to induce a malignant phenotype in cultured human keratinocytes. Lee et al, (2005) also found that high dose and long lasting psoralen phototherapy with UVA irradiation (PUVA) increased the risk of melanoma development. An increasing risk with greater frequency and duration of use has also been found between sunlamp use and melanoma risk (Clough-Gorr et al, 2008). Gorham et al, (2007) suggests that use of common sunscreens that absorb almost all UVB but transmit large quantities of UVA may contribute to risk of melanoma in populations at latitudes greater than $40^{o}$. Increased UVA exposures along with inadequate vitamin $D_3$ levels in the skin are now being linked with the promotion of melanoma development (Godar et al, 2009).

Latitude plays an important role in relation to UV radiation and human exposure. UVB is reduced significantly due to its interaction with the earth's atmosphere and exposures at the equator are generally much higher than those closer to the poles. However, UVA varies much less significantly with latitude than UVB due to the longer wavelengths. Garland et al, (2003) proposed that the global distribution of UVA accounts for much of the global variation in mortality rates from melanoma, especially the high rates in latitudes far from the equator.

UV radiation can cause serious damage to the human eyes and skin. Therefore it is essential to decrease any exposure to damaging UV radiation that the population experiences. For example, the long-wavelength property of UVA allows it to penetrate most automobile, office and household windows, whereas UVB is blocked by window glass (Wang et al, 2001; Parisi et al, 2007; Kimlin et al, 2002). Monitoring of personal UV exposures is extremely important in order to establish the levels of UV radiation received by the population (WHO, 1994). This requires constructive methods to understand the UV radiation environment that humans live in. Quantification of the individual level of UV radiation exposure requires personal dosimetry due to changes in the position of people compared to the radiation source (Parisi et al, 2010).

Commonly used photoactive chemical dosimeters are polyphenylene oxide (Davis et al, 1976a) and polysulphone (Davis et al, 1976b). Other less commonly used photoactive chemicals are phenothiazine (Diffey et al, 1977), 8-methoxypsoralen (Diffey and Davis, 1978) and nalidixic acid (Tate et al, 1980). At present, a variety of chemical dosimeters exist that are used for the measurement of UV exposures. However, no dosimeter exists that can be used for the measurement of UV radiation exposures related to melanoma induction (a spectral response that is high in the UVB and extends well into the UVA). Turner et al (2009) conducted measurements utilizing a dual-layer dosimeter made from a sheet of polysulphone and a sheet of nalidixic acid (in a polyvinyl chloride matirx). Spectral tests showed that this dual-layer dosimeter responded to wavelengths well into the UVA region. Therefore, this past research was used as a starting point for the development of a single layer dosimeter that can be used for exposures related to melanoma induction.

Several models in which both UVA and UVB have been shown to cause melanoma are the Xiphophorus, Opossum, Mondelphis domestica, mouse models and human skin engrafts into other animals (Ley et al, 1987; Setlow et al, 1989; Setlow et al, 1993; Kusewitt and Ley, 1996; Setlow, 1999; Ley et al, 2000; Ley, 2002; Noonan et al, 2003; de Laat et al, 1997; Husain et al, 1991; van Schanke et al, 2005; Klein-Szanto et al, 1994). For this research, the action spectrum produced by Setlow et al (1993) will be utilized to produce a dosimeter that can approximate this specific biological response to the UVA and UVB wavebands.

## 2. Materials and Methods

### *2.1 Thin Film Casting*

The chromophores of polysulfone and nalidixic acid were chosen for this research to produce the dosimeter to measure the UV exposures related to melanoma induction ($UV_{Mel}$). Polysulfone has been shown to have a spectral sensitivity that is high only in the UVB region; whereas nalidixic acid has been shown to respond to both UVB and UVA wavelengths. Tate et al (1980) showed that nalidixic acid responded to wavelengths from 280 to 350 nm. The polysulfone and nalidixic solution was cast into thin film form of approximately 40 μm thickness. The solution was cast on a glass slab that is optically flat to 1 micron. A motor driven blade sweeps across the glass slab to spread the solution evenly and the solvent is allowed to evaporate and to leave a thin film. The thickness of 40 μm was employed as the starting point based on the results from previous dosimeter studies (e.g. Diffey et al, 1977; Parisi et al, 2005).

### *2.2 Spectral Response*

The film was cut into 2.0 x 1.5 cm pieces and mounted onto 3.0 x 3.0 cm rigid plastic holders, each with a 1.95 $cm^2$ central aperture to produce dosimeters. In order to determine

the wavelength at which the largest change in optical absorbance occurs due to radiation exposure, the optical absorbance spectrum at these wavelengths was measured in a spectrophotometer (model UV1601, Shimadzu Co., Kyoto, Japan). The spectral response was measured by irradiating the dosimeters with a known monochromatic exposure at given wavelengths in the UVB and UVA wavebands followed by measurement of the change in absorbance of the material. The 1600W xenon mercury system (model 66870) with digital exposure controller (model 68951) from Oriel Instruments (Stratford, CT, USA) was utilised. Each dosimeter was exposed to 20 $kJm^{-2}$ of monochromatic UV radiation that was applied in 10 nm steps from 290 to 400 nm. The input and output slit widths were adjusted to provide an output beam with a FWHM of approximately 5 nm. The irradiance output of the irradiation monochromator at each setting was measured with a spectrometer system (model USB4000, Ocean Optics, Dunedin, FL, USA) to determine the period of exposure necessary to produce the required irradiance. The spectrometer is based on a CCD array and has a slit width of 25 μm to give a resolution of less than 1 nm. The USB4000 was used to measure monochromatic radiation and the influence of stray light is minimised. Wavelength and irradiance calibration of the USB4000 was undertaken by employing the 365 nm mercury spectral line and a 150 W quartz halogen lamp with calibration traceable to the National Physical Laboratory, UK standard. A two meter fibre optic cable connects a CC-3 cosine receptor to the input of the housing for the array. The USB4000 measured the spectral irradiance from 280 nm to 400 nm in approximately 0.2 nm steps with an integration time of 20 ms and averaged over 20 scans.

*2.3 Cosine Response*

The cosine response of the dosimeter was tested by utilizing a solar simulator (model 15S solar UV simulator, Solar Light Co., Philadelphia, USA). Using a stand and a rotating dosimeter clamp, the dosimeter was positioned in front of the solar simulator aperture. One dosimeter was exposed on a plane normal to the incident radiation (0°) and then used as a comparison for the measurements at the other angles of incidence. The mount holding the dosimeter was then rotated 10° from the normal plane and another dosimeter was exposed for the same period of time as the initial dosimeter at 0°. This was carried out for the following angles from the plane normal to the incident irradiance: $10^{o}$, 20°, 30°, 40°, 50°, 60°, and 70°. All dosimeters were exposed to the same amount of UV radiation. The change in absorbance of the dosimeter at a given angle was normalized and then compared to the cosine curve.

*2.4 Dark Reaction*

A set of ten dosimeters were exposed during summer to solar UV for three hours around noon on a clear day and the optical absorbance for each dosimeter was measured before and immediately after exposure. The dosimeters were then stored in a UV radiation free environment for twenty-four hours and then measured again for absorbance. This was followed by storage in the same UV radiation free environment for a week after exposure and the absorbance measured again. The differences between absorbance measured immediately after exposure, twenty-four hours after exposure and a week after exposure indicated the dark reaction of the $UV_{Mel}$ dosimeter.

*2.5 Exposure Response*

The dosimeters were calibrated by exposing a series of dosimeters on a horizontal plane, to relatively clear sky solar radiation from approximately 1030 to 1530 h Australian Eastern Standard Time (EST) on January 25, 2010. This calibration was at a subtropical Southern Hemisphere site at the University of Southern Queensland, Toowoomba, Australia ($27.6^{o}$S, $151.9^{o}$E, altitude 693 m). The solar zenith angle (SZA) ranged from approximately $9^{o}$ to $48^{o}$.

The dosimeters were calibrated by comparing the change in optical absorbance of the dosimeter with the spectral measurements obtained with a scanning spectroradiometer (Bentham Instruments, Ltd, Reading, UK). The spectroradiometer is based on a double grating monochromator, a UV sensitive detector and amplifier with software variable gain provided by a programmable high voltage power supply. The interior of the spectroradiometer enclosure is temperature stabilised to 25.0 ± 0.5$^{o}$C, using a Peltier heater/cooler unit. The input optics of the spectroradiometer are provided by a PTFE (polytetrafluoro ethylene) diffuser and connected by an optical fibre to the input slit of the monochromator. The spectroradiometer is programmed to start scanning the global UV spectrum in 0.5 nm increments from dawn, and thereafter every 10 minutes till dusk. The instrument is wavelength calibrated to the UV spectral lines of a mercury lamp and irradiance calibrated to a 150 Watt quartz tungsten halogen lamp with calibration traceable to the National Physical Laboratory, UK standard.

*2.6 Reproducibility*

To test the reproducibility of the dosimeters for the measurement of $UV_{Mel}$ exposures, ten dosimeters were exposed simultaneously to solar UV over a three hour period on a horizontal plane. These exposures were conducted for clear sky conditions.

## 3. Results

The spectral response of the polysulfone and nalidixic acid film is shown in Figure 1 along with the fish melanoma action spectrum (Setlow et al, 1993). The polysulfone and nalidixic acid film has a response across the majority of the UV waveband (maximum at 310 nm) but drops off after approximately 390 nm. The response in the UVA waveband is due to the nalidixic acid, as polysulfone has been shown to have a negligible response above approximately 340 nm.

The spectral absorbance of the $UV_{Mel}$ dosimeter was measured pre-exposure and post-exposure to solar UV radiation. The change in spectral absorbance of the $UV_{Mel}$ dosimeter is provided in Figure 2. The change in optical absorbance ($\Delta A$) at 345 nm was chosen as this wavelength provided a reliable response in the chemical film for differing exposure levels. The change in $\Delta A$ after an exposure of nearly 189 kJ/m$^2$ was approximately 0.467. Although the agreement between the spectral response of the dosimeter and the fish melanoma action spectrum is not exact, it is possible to allow for this, if the relative spectral distribution of the incident irradiance is quantified (Davis et al, 1976b) or by calibrating the $UV_{Mel}$ dosimeter to the UV spectrum that will be encountered in the measurements.

The cosine response of the $UV_{Mel}$ dosimeter compared to the cosine curve for the range of 0$^{o}$ to 70$^{o}$ is provided in Figure 3. The error bars represent ± 8% variance for post-exposure absorbance measurements. The cosine response of the $UV_{Mel}$ dosimeter is within 14% of the cosine curve for the range up to 70$^{o}$.

The dark reaction of the $UV_{Mel}$ dosimeter measured at 345 nm for the periods of 24 hours and 1 week after exposure is provided in Table 1. From Table 1 it can be seen that the $UV_{Mel}$ dosimeter changed on average by 8.2% after 24 hours and 13.1% after 1 week. In comparison, polysulfone has been shown to have a dark reaction of approximately 4% and 5% after 24 hours and 1 week, respectively (Davis et al, 1976b). Tate et al (1980) found a 10% change due to the dark reaction for the nalidixic acid and polyvinyl chloride dosimeter.

The calibration of the $UV_{Mel}$ dosimeters for solar exposure is shown in Figure 4. The dosimeters were exposed to biologically effective UV levels of up to 189 kJ/m$^2$. The data points are the averages of the four ΔA's measured for each dosimeter. An exponential function was fitted to the data with the form of:

$$UV_{Mel} = 3.41e^{8.65x} \quad \text{kJ/m}^2 \qquad (1)$$

where $x$ is the change in absorbency. The resulting $R^2$ for the calibration was greater than 0.99.

For reproducibility tests, ten dosimeters were placed on a horizontal plane and exposed to solar UV. All dosimeters received the same exposure of solar UV producing a mean $\Delta A_{345}$ of 0.383 with a coefficient of variation equal to approximately 2%. This variation may be due to minor variations over the surface of the sheet of the film from which the dosimeters were fabricated and the influence of dust particles that accumulated on the surface of the dosimeters during the exposure period.

## 4. Discussion

Different UV wavelengths produce different responses in the skin (Wolber et al, 2008). UVA causes immediate tanning and persistent pigment darkening through oxidation of pre-existing melanin or melanogenic precursors, while UVB induces delayed tanning which takes several days or longer to develop and requires activation of melanocytes (Wolber et al, 2008). Although non-melanoma skin cancers are predominantly caused by UVB wavelengths, melanoma induction has been observed by the longer wavelength UVA in both animal experiments (Ley, 1997; Ley, 2001; Setlow et al, 1993) and human epidemiological research (Moan et al, 1999; Wang et al, 2001; Garland et al, 2003). A role for UVA is also indicated by research showing melanomas arising in those who receive UVA for treatment of dermatologic conditions (Hannuksela-Svahn et al, 1999; Lindelof et al, 1999; Stern, 2001).

Preliminary results indicate that this $UV_{Mel}$ dosimeter can measure exposures of more than 189 kJ/m$^2$ of biologically effective weighted solar UV radiation with an inter-dosimeter variability of no more than ± 5%. The response of the $UV_{Mel}$ dosimeter showed a spectral response up to approximately 390 nm. The dark reaction of the $UV_{Mel}$ dosimeter is slightly larger than that for polysulfone and is most likely due to the addition of the nalidixic acid. The dark reaction needs to be taken into account when using this dosimeter. Post-exposure measurements need to be taken at consistent time periods following exposure (CIE, 1992). The size and lightweight properties of this dosimeter means that it can be attached to any anatomical site on the human body. It can also easily be used in different environments such as office buildings or in vehicles in order to measure the solar UV exposures effective for possible melanoma induction in the human body. The usage of the dosimeter requires the calibration against a calibrated UV meter. The level of accuracy of the dosimeter and the profile of the calibration curve will vary with the season and environment. This can be overcome by calibrating the dosimeter in the season and for the environment that it will be employed to measure the solar UV exposures.

The dosimeter developed in this research was calibrated for the fish melanoma action spectrum (Setlow et al, 1993) due to the films response to both UVA and UVB wavelengths.

It remains to be determined whether the Xiphophorous melanoma action spectrum can be extrapolated to humans (Ridley et al, 2009). Research into melanoma induction in Xiphophorous fish has strongly implicated UVA in its aetiology (Setlow et al, 1993); however, the role of UVA in melanoma induction remains controversial (Robinson et al, 2000; De Fabo et al, 2004; Wood et al, 2006). The $UV_{Mel}$ dosimeter can easily be calibrated to any melanoma action spectrum that has a response in both the UVA and UVB wavebands.

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Table 1. Average dark reaction of the $UV_{Mel}$ dosimeter.

| Period of time | Change in absorbance | Change (%) |
|---|---|---|
| 24 hours | 0.032 | 8.2 |
| 1 week | 0.049 | 13.1 |

**Figure legends**

**Figure 1.** Fish melanoma action spectrum (Setlow et al, 1993) and the spectral response of the dosimeter.

**Figure 2.** Before and after exposure absorbance characteristics of the $UV_{Mel}$ dosimeter after a total $UV_{Mel}$ exposure of 190 $kJ/m^2$.

**Figure 3.** Comparison of the cosine response of the $UV_{Mel}$ dosimeter to the cosine curve.

**Figure 4.** Dose response curve of the $UV_{Mel}$ dosimeter for the measurement of the $UV_{Mel}$ exposures.

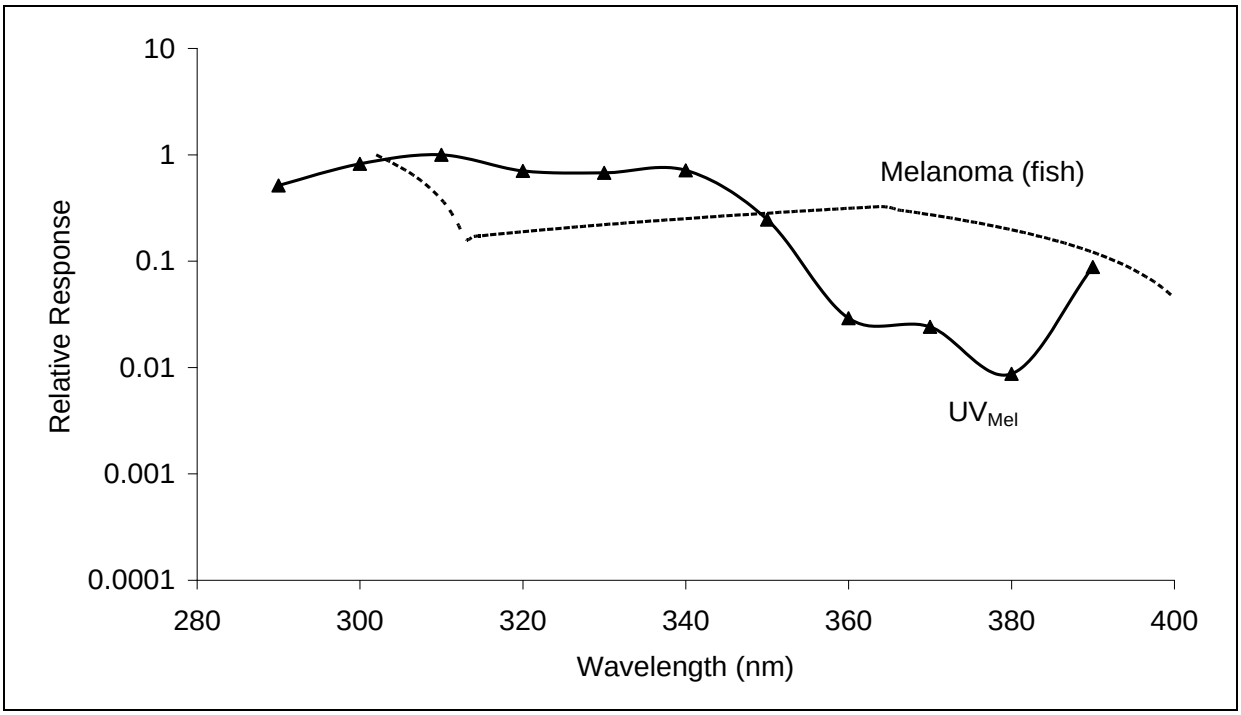


Figure 1. Fish melanoma action spectrum (Setlow et al, 1993) and the spectral response of the dosimeter.

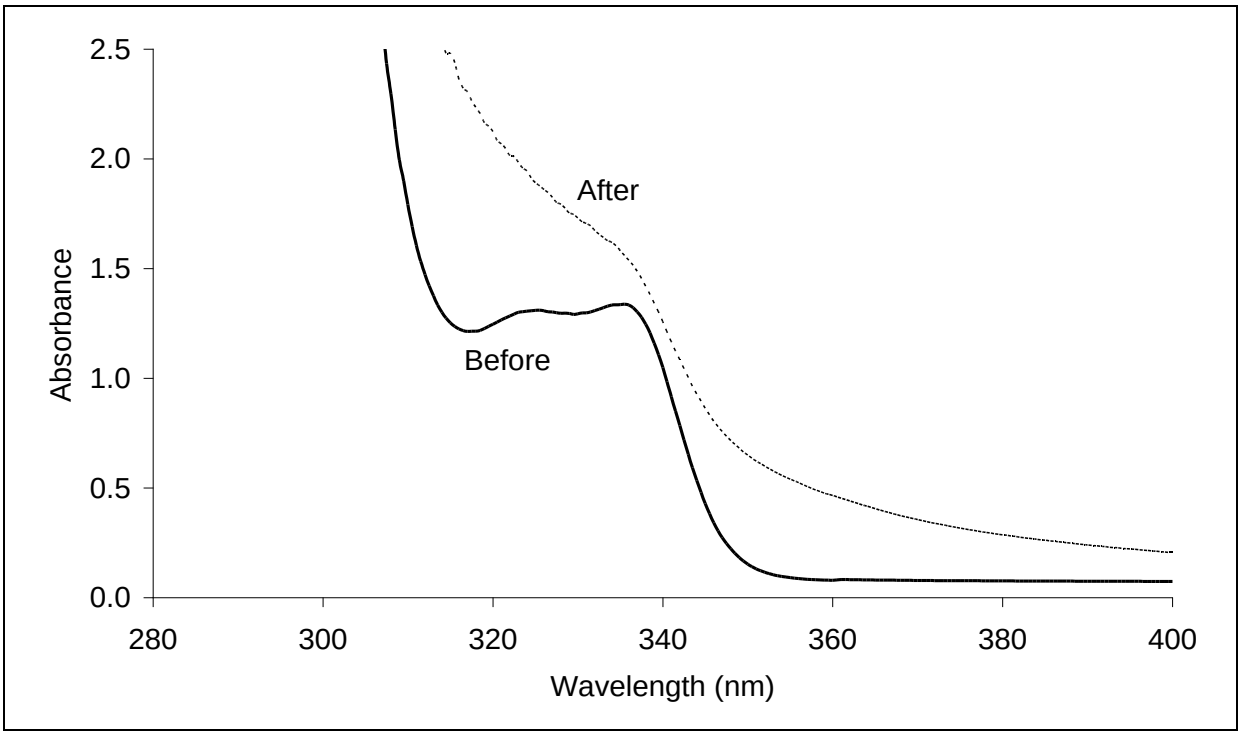


Figure 2. Before and after exposure absorbance characteristics of the $UV_{Mel}$ dosimeter after a total $UV_{Mel}$ exposure of 190 $kJ/m^2$.

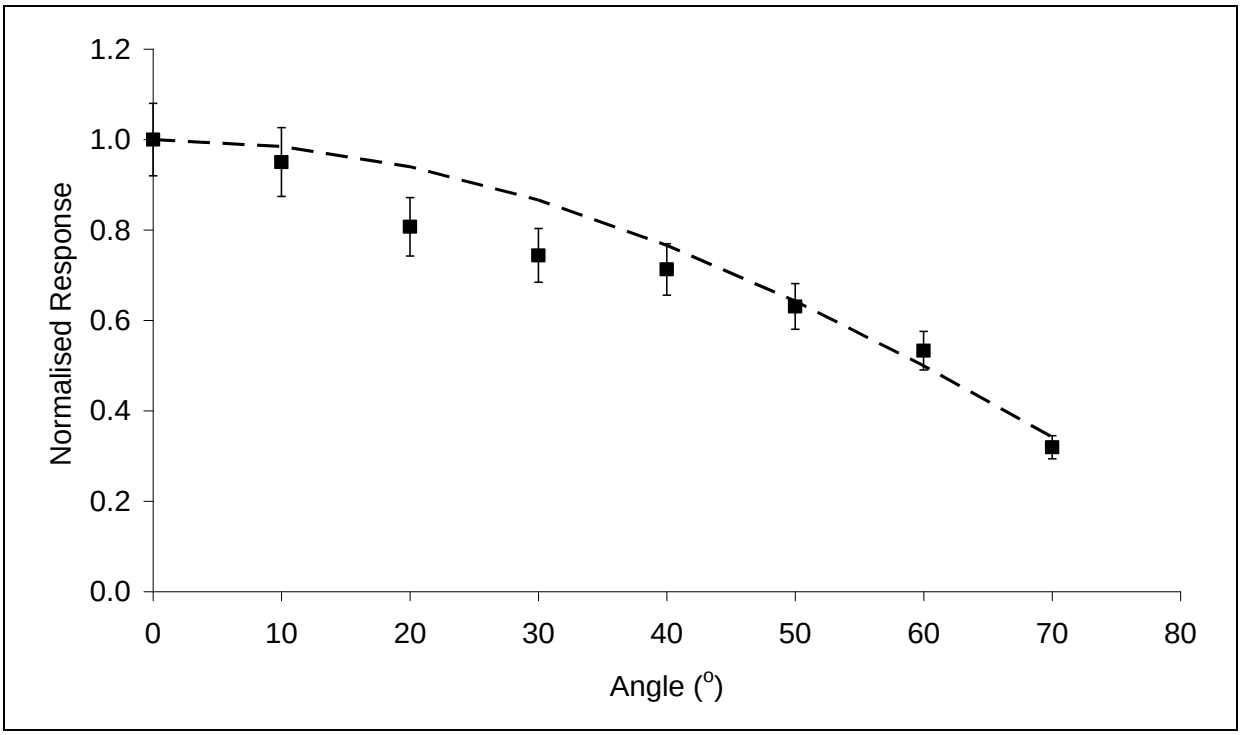

Figure 3. Comparison of the cosine response of the $UV_{Mel}$ dosimeter to the cosine curve.

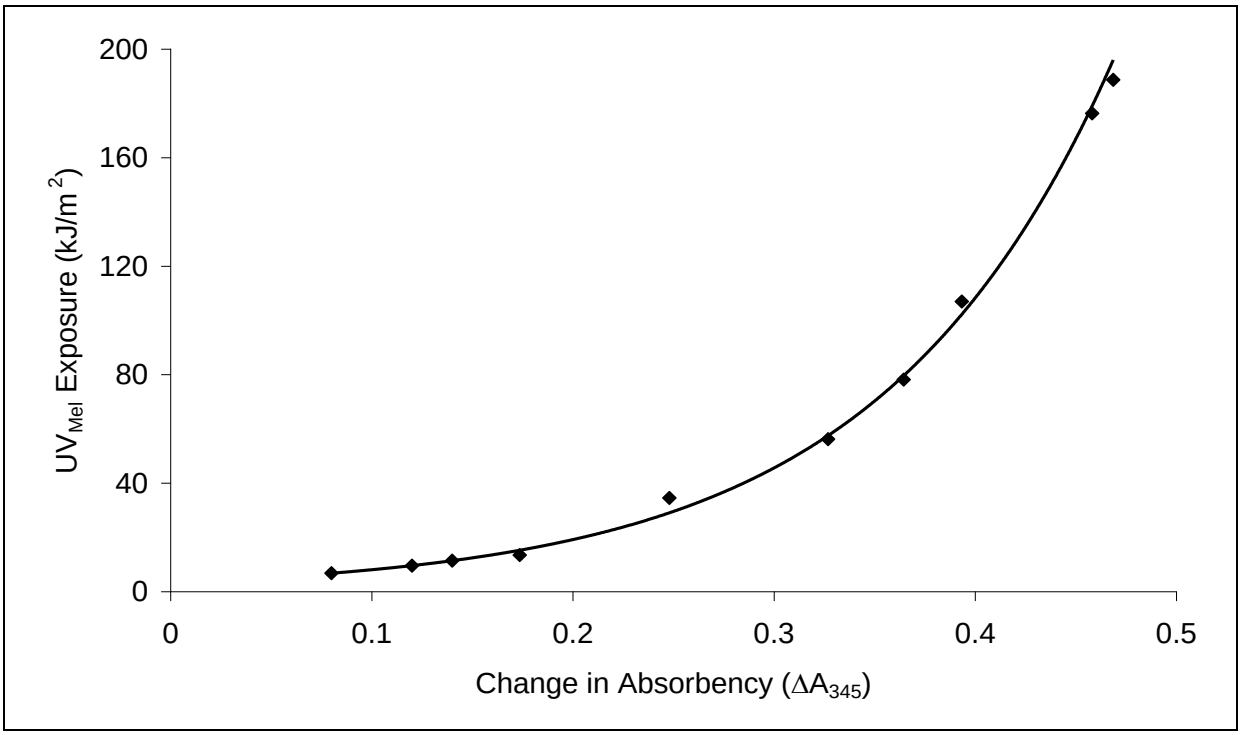


Figure 4. Dose response curve of the $UV_{Mel}$ dosimeter for the measurement of the $UV_{Mel}$ exposures.