Solar ultraviolet radiation incident upon reef snorkelers determined by consideration of the partial immersion of dosimeters in the natural ocean environment

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Abstract

Reef snorkeling is potentially a high risk activity for persons visiting tropical and sub-tropical waters due to possible overexposure to solar ultraviolet radiation (UVR). Measurements and modelled estimates of the UVR received by human subjects are presented for a 10^{o} latitudinal gradient of Australia's Great Barrier Reef and some Melanesian Islands (15^{o}S to 25^{o}S). A technique is described to measure the erythemally effective UVR received by the neck and the lower back. Measurements were made by application of a hybrid in-air and submerged calibration for polysulphone dosimeters. Measured exposures were used to model UVR exposure distributions at a number of popular snorkeling sites. A total of 11 snorkeling trials were held between 29 September 2009 and 26 January 2010. Exposures measured to the back and expressed relative to the horizontal plane ambient UVR have shown there to be some variation in the UVR distribution, with the neck receiving the greatest proportion of ambient UVR (0.56 ± 0.14 (1σ)), followed by the lower back (0.36 ± 0.14 (1σ)). Similarly high UVR exposures were determined at neck and lower back sites for different seasons, different times of day and over the latitudinal range of the study.

Introduction

Exposure to ultraviolet radiation (UVR) plays a critical role in the health of humans. Excessive exposure to UVR is known to be the cause of skin cancer while limited exposure to sunlight has been linked with vitamin D deficiencies which are responsible for imbalances in calcium metabolism, influencing human bone development, and a number of other diseases including some cancers (1). Excessive exposure to solar UVR is common in low latitudes, particularly in the southern hemisphere which experiences lower ozone concentrations compared to similar northern latitudes (2). Populations, such as the Australian population which experiences the highest incidence rate of skin cancer in the world are aware of the environmental risks to public health caused by exposure to the sun, yet the incidence of diseases like skin cancer continue to rise (3). Further public education may assist in reducing incidence rates. The need for more suitable health education strategies concerning environmental hazards that influence the health of holiday makers, including UVR has been highlighted previously (4). Quantification of the actual exposures received in different environments, for different activities and under different circumstances is needed to raise awareness for situations that present potentially high risks to the public.

Snorkeling may rank as one of the highest personal risk activities that can be undertaken by population groups residing in high ambient UVR climates, however no data has yet been presented for this population group. Snorkeling may also potentially have a greater impact upon visiting foreign population groups less aware of the extremes that exist in popular destinations frequented by holiday makers. The risks of over exposure to UVR for snorkelers are caused by: limited use of protective clothing; increased proportion of the body surface being exposed to UVR incident upon a horizontal plane; potential UVR enhancement caused by water surface albedo and focusing due to wave action; behavioural risk of increased exposure time caused by the cooling influence of water; exposure of unacclimatised skin often covered by clothing during other activities; popularity with unacclimatised holiday makers visiting extreme tropical and sub-tropical environments; and the removal of sunscreens from the body by both sea water and perspiration. Recently, Moehrle (5) completed work detailing the distribution and severity of UVR exposure to ironman athletes engaging in swimming activities. Measurements of UVR exposure have also been measured to beachgoers (6). This study (6) determined that Hawaiian beachgoers spend an average of 3 hours at the beach and experience an exposure of approximately 1040 Jm^{-2} of erythemally effective UVR in that time. Exposure distributions to seaside sunbathers (7) and those received in proximity to a pool (8) have also been studied. However, specific measurements of UVR exposure to snorkelers are not present in the literature.

One reason for there being limited information on exposure distributions of snorkelers may be attributed to the difficulty in calibrating UVR sensitive dosimeters for use on human subjects in a marine environment. The calibration of polymer film dosimeters is known to change with variations in physical parameters such as solar zenith angle (SZA) and column ozone concentrations (9) requiring such dosimeters to be calibrated near to the time of intended use. Polymer film dosimeters such as poly 2,6-dimethyl-1,4-phenylene oxide (PPO) have been calibrated for use in the marine environment (10,11,12), provided the dosimeter remains submerged. Calibrating polymer film dosimeters for snorkelers requires the partial in-air and immersion of the dosimeter to be taken into account in order to take measurements that are affected by variations in wave motion that keep the snorkeler's back in a dynamic state of wet and dry. This paper describes a new technique for the use of dosimeters on snorkelers and provides results on UV exposures to snorkelers over the latitude range of 15 ^{o}S to 25^{o}S.

Materials and Methods

As the backs of reef snorkelers experience a unique temporal variation between exposure in air and exposure below the surface of the water, a new calibration technique has been developed for the calibration of polysulphone (PS) film dosimeters for this research. This has involved the development of a waterline calibration technique that makes the assumption that the backs of reef snorkelers are horizontally orientated at the ocean surface and are not submerged at a range of depths for any extended period of time. For shallow coral reef snorkelers this is a reasonable assumption, given the limited diving space available and the tendency of reef snorkelers to "float" over regions of interest. In previous research, calibrated PS dosimeters have been used extensively to measure personal UVR exposures on land (13, 14) and recently, Schouten et al. (10) demonstrated that PPO film dosimeters could also be used in aquatic environments by calibration to solar UVB radiation (298 nm to 320 nm) for a range of depths. Here, PS film dosimeters were calibrated to the partial in-air and underwater erythemally effective solar UVR (UVE_{AW}), where the UVE_{AW} is the solar radiation in the 280 nm to 400 nm UVR waveband weighted to the human erythemal response (15) and measured on an air-water boundary. The UVE_{AW} represents a hybrid air-water calibration. For this research, UVE is used to denote the erythemally effective UVR not measured on the air-water boundary.

The dosimeters used for this research were manufactured from PS film cast to an approximate thickness of 40 μm and adhered to slide frames with a clear aperture of 16 mm x 20 mm. PS film dosimeters have been examined for underwater use previously and have a quoted UVB measurement error of less than 5% within tropical latitudes for most of the day (16). The absorbance of the PS dosimeters was measured pre and post exposure at 330 nm using a spectrophotometer (model 1601, Shimadzu Co., Kyoto, Japan). This is the wavelength at which the maximum change in absorbance of PS can be measured in the UVR waveband (14). The error threshold for optical absorbance measurements in the spectrophotometer has been quoted as ± 0.002 by the manufacturer. Measurements of the change in absorbance, ΔA_{330} following exposure were made at four separate locations over the dosimeter film surface area and averaged to minimise error caused by film defects that could have been present across the aperture surface. The measured change in absorbance was calibrated against the measured UVE_{AW}, which for this research is expressed in units of Standard Erythema Dose (SED), representing 100 Jm^{-2} of erythemally effective UVR (17).

Dosimeter calibration

Dosimeters used to measure exposure to the backs of snorkelers were calibrated on the air-water plane. These dosimeters were calibrated at a beachside location by initially calibrating to a portable UVR meter (IL1400, International Light, USA) which was itself calibrated for UVE to a scanning spectroradiometer (model DTM300, Bentham Instruments, Reading, UK). The spectroradiometer used to calibrate the portable instruments is mounted on a rooftop site at the University of Southern Queensland (USQ). Complete operational and response specifications for the IL1400 portable UVR meter can be found at http://www.solarlight.com/products/501.html. At this website the manufacturer states that the IL1400 portable UVR meter has an angular response of within ± 5% compared to the ideal cosine response. The total uncertainty of the IL1400 portable UVR meter has been calculated to be approximately ± 11% (18). PS dosimeters were also placed on land during snorkeling exposure periods. These dosimeters were calibrated in-air at the beachside site to a portable broadband UVR meter (model 501, Solar Light co. Philadelphia, USA) which was also calibrated for UVE to the USQ scanning spectroradiometer. The measurement stability of the portable broadband meter used for in-air calibrations was determined by comparison of repeated UV measurements of a model 15S solar UV simulator (Solar Light Co. Philadelphia, USA). This uncertainty was determined to be approximately ±12%. The broadband meter varies from the ideal cosine response by approximately ± 5% for SZA ranges less than 70^{o}, giving a total uncertainty for in-air measurements of ± 17%. The USQ scanning spectroradiometer is a double grating monochromator calibrated using standard quartz tungsten halogen lamps to the National Physical Laboratory, UK standard and the emission lines of a mercury vapour lamp. Parisi and Downs (19) measured the uncertainty of this instrument to be approximately ±10% based on temporal stability, wavelength variation, the cosine response of the input diffuser optic up to 70^{o} SZA, dark count variability and traceability of the calibration lamps. For this research, the total uncertainty in the calibrated UVE_{AW} is greater than ±5%, determined previously by Dunne (16) for PS dosimeters used in a marine environment. This is due to the uncertainty of both the portable field instruments and their calibration to the USQ scanning spectroradiometer, effectively doubling the error. An additional uncertainty due to the mean variation in the absorbance of PS film dosimeters measured at 330 nm over the field calibration absorbance range was estimated at ±14%. The variation in PS film uncertainty is derived from previous measurements of 46 individual sets of PS film dosimeters known to have received equivalent UVE exposures (20). This variation was considered for each calibrated snorkeling exposure. Therefore the total uncertainty in calibrated snorkeling measurements is ±35% and ±41% for respective UVE_{AW} and UVE measurements, traceable to the National Physical laboratory, UK standard. For snorkelers that received UVE_{AW} exposures in this study between 0.4 and 4.4 SED, this uncertainty contributes to an error of between 0.1 and 1.5 SED, with the mean error measured across all trials being 0.6 SED.

The IL1400 portable UVR meter measured the cumulative UVE_{AW} exposure received by the PS dosimeters at the calibration site by placing a series of PS dosimeters on the air-water boundary of a natural sea water body such that the dosimeters received submerged and in-air UVR due to the temporal variation of wave action over the calibration plane. For this research, the PS dosimeters were attached to brick weights which were placed into a shallow natural water body. A small waterproof diffuser input optic (SUD240, International Light, USA) was utilised by the IL1400 portable UVR meter to measure the UVE_{AW} on the calibration plane. The diffuser optic was attached to the brick weight so that the diffuser face was aligned to the same plane as the PS dosimeters (Figure 1).

FIGURE 1

In the PS dosimeter calibration process, the cumulative UVE_{AW} exposure was recorded for a series of 10 minute exposure intervals for each of twelve PS dosimeters placed on the air-water boundary at low tide on clear sky calibration days of 15 October 2009 (Spring) and 10 January 2010 (Summer). During the calibration process the brick weight was moved as necessary following the removal of each calibration dosimeter to ensure the dosimeters remained on the air-water boundary due to tidal variations. The PS dosimeter calibrations were performed at a beach site located in Hervey Bay, Australia (latitude 25^{o}S). This site is a protected bay, and experiences minimal surf conditions which were ideal for the calibration of the PS dosimeters. The spring and summer calibration curves for the PS dosimeters placed on the air-water boundary are shown in Figure 2. The Figure also shows the calibration curves of PS dosimeters calibrated in-air at the same time the air-sea calibrations were performed. This calibration was performed in proximity to the air-sea calibration location using the portable broadband UVR meter. The calibrations were undertaken at an unshaded location on a sand flat, 50 m from a tree-lined shoreline.

FIGURE 2

Measurements to snorkelers

Exposures were measured to the backs of snorkelers while they were engaged in snorkeling activities. To replicate the actions of a reef snorkeler, participants were instructed to snorkel on the water line and not to dive. Measurements of exposure were performed in Hervey Bay (25^{o}S, 151^o E) with the exception of one measurement carried out at Luecila beach, New Caledonia (21^{o}S, 167^{o}E). A total of 11 individual snorkeling trials were performed from September 2009 to January 2010. The exposure of each snorkeling trial was limited to a maximum period of one hour but was often shorter than this depending upon participant fatigue. In order to ensure a high degree of safety, all study participants were experienced snorkelers. Human ethical clearance was sought and obtained from the USQ human ethics committee in conducting this research. Participants engaged in snorkeling were required to wear wetsuits or rash vests to which dosimeters were taped to the neck or lower back. During one trial, measurements were also made on the left and right shoulder however movement of the shoulder blades resulted in early detachment of the dosimeters from these sites.

Exposure modelling

Calibrated UVE_{AW} exposures measured to the backs of snorkelers were also expressed relative to the horizontal plane UVE exposure measured simultaneously on land during each snorkeling trial. The exposures are represented by the ratio:

$$ER = \frac{E_{site}}{E_{hor}} \qquad (1)$$

where E_{site} is the UVE_{AW} exposure measured to any particular site on the back, E_{hor} is the horizontal plane ambient UVE measured on land and *ER* (exposure ratio) is the proportion of the horizontal plane ambient UVE measured at any particular back site. The mean ER determined for spring and summer seasons and for each of the neck, and lower back sites was used to model the UVE_{AW} exposure of a snorkeler frequenting popular snorkeling destinations of the Great Barrier Reef, New Caledonia, Vanuatu and Fiji covering a latitude range from 15^{o}S to 25^{o}S. Modelled UVE_{AW} exposure estimates were made for a period of one hour during mid summer and mid spring. The exposure period of one hour was chosen as this is likely to represent the upper time limit during which a snorkeling activity takes place, based upon the fatigue level of study participants. Modelled exposures are therefore likely to represent an upper exposure limit for most cases.

Results

Table 1 presents the UVE_{AW} exposures measured to the neck and lower back sites of a snorkeler for the period 29 September 2009 to 26 January 2010. Horizontal plane UVE exposures are also given in the table. The exposures are presented for the SZA ranges 0^o-25^o and 26^o-50^o. The total column ozone for each measurement day is listed in Dobson Units (DU) from interpolated measurements made by the Ozone Monitoring Instrument (21). Cloud cover was estimated by visual inspection during each trial and is given in oktas or eighths of the sky covered. Measurements were taken in Hervey Bay except where specified in the table.

Table 1: UVE_{AW} exposure and proportion of ambient exposure received by the neck and lower back of a snorkeler for low and high SZA ranges. Measurements were recorded in Hervey Bay, October 2009 through January 2010. Ozone concentration is given in Dobson Units (DU). Exposures are standard erythema dose (SED). Site exposure ratio is the proportion of site exposure to horizontal plane ambient exposure (ER).

SZA	Date (dd/mm)	Cloud (Oktas)	Ozone (DU)	Exposure Interval	Ambient Exposure (SED) / (SED/10 min)	Neck Exposure (SED) / (SED/10 min)	Lower Back Exposure (SED) / (SED/10 min)	Neck (ER)	Lower Back (ER)
0^o-25^o	29/09	1	271	11:25-11:55		1.7[a] ± 0.6 / **0.6 ± 0.2**			
	22/10	1	n/a	11:05-11:20	2.3 ± 0.9 / **1.5 ± 0.6**		0.4 ± 0.1 / **0.3 ± 0.1**		0.19
	23/10	1	303	11:45-12:30	5.8 ± 2.4 / **1.3 ± 0.5**		2.5 ± 0.9 / **0.6 ± 0.2**		0.43
	20/01	3	247	10:38-11:21	3.5 ± 1.4 / **0.8 ± 0.3**	1.3 ± 0.5 / **0.3 ± 0.1**	0.7 ± 0.2 / **0.2 ± 0.1**	0.38	0.21
	21/01	2	247	11:37-12:22	9.6 ± 3.9 / **2.1 ± 0.9**	4.4 ± 1.5 / **1.0 ± 0.4**	2.9 ± 1.0 / **0.6 ± 0.2**	0.46	0.30
	26/01	0	257	12:16-13:11	10.2 ± 4.2 / **1.9 ± 0.8**	4.1 ± 1.4 / **0.7 ± 0.2**	2.4 ± 0.8 / **0.4 ± 0.1**	0.41	0.23
26^o-50^o	30/10	7	305	8:45-9:20	2.5 ± 1.0 / **0.7 ± 0.3**	1.9 ± 0.7 / **0.5 ± 0.2**	1.5 ± 0.5 / **0.4 ± 0.1**	0.76	0.59
	25/11	2	n/a	14:11-14:55	3.6 ± 1.5 / **0.8 ± 0.3**	2.4 ± 0.8 / **0.5 ± 0.2**	1.5 ± 0.5 / **0.3 ± 0.1**	0.65	0.40
	26/11	2	274	14:27-14:40	1.3[b] ± 0.5 / **1.0 ± 0.4**	0.7 ± 0.2 / **0.5 ± 0.2**	0.3 ± 0.1 / **0.2 ± 0.1**	0.56	0.27
	02/12	4	n/a	8:13-8:47	2.2 ± 0.9 / **0.6 ± 0.2**	1.4 ± 0.5 / **0.4 ± 0.1**	1.2 ± 0.4 / **0.4 ± 0.1**	0.66	0.55
	22/12	2	278	13:50-14:00	1.4 ± 0.6 / **1.4 ± 0.6**	0.9 ± 0.3 / **0.9 ± 0.3**	0.6 ± 0.2 / **0.6 ± 0.2**	0.63	0.46

[a]Measurement made at Luecila Beach, Lifou, New Caledonia.

[b]Measurements of the left shoulder (0.5 ± 0.2 SED/10 min) and right shoulder (0.5 ± 0.2 SED/10 min) were also recorded on this day.

The measurements listed in Table 1 show a clear variation in the exposure distribution between the upper neck and lower back sites of a snorkeler. For each trial measurement that included both a neck and lower back measurement site, exposures measured to the neck were higher. This was likely caused by the upper body being further out of the water compared to the lower back while the snorkeler was horizontally orientated. Occasional rest periods during which the snorkeler stood up or was swimming in a vertical orientation are another possible explanation for the measured variation in exposure. Also evident in the table is a variation in exposure expressed relative to the horizontal plane with changing SZA. Measurements made to the neck and lower back sites received a lower proportion of the ambient exposure in the 0^{o}-25^{o} SZA range compared to the higher 26^{o}-50^{o} SZA range, although exposures received in the lower SZA range were often higher due to the decreased atmospheric path of the incident UVR.

The mean ER of the neck and lower back was determined to be 0.42 ± 0.04 (1σ) and 0.27 ± 0.10 (1σ) respectively for the SZA range 0^{o}-25^{o}. In the SZA range 26^{o}-50^{o} the respective neck and lower back ER changed to 0.65 ± 0.07 (1σ) and 0.45 ± 0.13 (1σ). The difference between the ER data for neck and lower back sites measured in each SZA range was tested by performing a 90% confidence interval *t*-test. The ER data measured to the neck in the 26^{o}-50^{o} SZA range were statistically significant, but not outside the limits of measurement uncertainty. ER data measured to the neck site in the 26^{o}-50^{o} SZA range were however among the highest ER data recorded in the study. This may have been due to an enhanced albedo contribution caused by sunlight being incident at angles of increasing magnitude to the surface normal. Here, steep angles, more closely approximating normal incidence result in greater sunlight penetration into the water column, while angles of increasing magnitude to the surface normal reflect a greater proportion of the radiation reaching the water surface resulting in more sunlight being reflected onto the back surface of a snorkeler when the snorkeler's body is located above the waterline. The degree to which direct solar radiation will be reflected at the air-water boundary can be calculated by application of Snell's law for a given refractive index of air and water respectively. Using a simple approximation, assuming the water surface to be a constant horizontal plane and given the refractive index of air (1.0003) and water (1.333), it can be determined that the direct solar beam will be refracted from between approximately 18^o at the maximum SZA limit measured in this study of 25^o in the low SZA range, to 35^o at the maximum limit measured in this study of 50^o in the high SZA range. Here for parts of the body located above the water line, namely the neck and back of the head, a greater proportion of sunlight is likely to be reflected onto the body when incident in the high SZA range, during which, UVR reflected at the water surface will have a maximum angle of reflection of 50^o (or 40^o to a non-oscillatory water surface) compared to a reflection angle of 25^o (65^o to a non-oscillatory water surface) in the low SZA range. This effect can therefore partially explain the increased mean exposures received by the back of the neck increasing from an ER of 0.42 to 0.65 (ΔER 0.23). As expected, shallow reflection angles in a high SZA range will have a small to negligible influence on parts of the body that remain submerged or underwater for longer periods than the neck. Thus, the increases in the mean ER of 0.27 to 0.45 (ΔER 0.18) being less than those measured for the neck may be explained by this simple physical mechanism of light refraction at the air-sea boundary. However, there are two other mechanisms at the air-sea boundary that can influence solar exposures, which include: the relative proportion of diffuse radiation incident at the time of exposure; and fluctuations in water movement and depth across the back of a snorkeler, particularly at the greater submersion depth of the lower back compared to the neck of a floating reef snorkeler.

Table 2 lists the modelled clear sky UVE_{AW} exposure for an individual engaged in snorkeling activities at various locations along the Great Barrier Reef and at some popular snorkeling destinations in Melanesia. Exposures listed in the table were calculated by application of a horizontal plane UVR irradiance model to determine the UVE_{AW} received on a horizontal plane over a 1 hour period between 12:00 pm and 1:00 pm on 1 September 2009 and 1 January 2010. This represents a likely maximum snorkeling exposure period. Hourly exposures were also expressed in units of SED/10 min to allow comparison with the measured results presented in Table 1. The UVR irradiance model has been discussed previously (22) and is implemented here by weighting to the measured neck and back site ER arithmetic mean in the SZA range 0°-25° or 26°-50° depending on the SZA experienced during each 12:00 pm to 1:00 pm exposure period. An ozone concentration of 280 DU was included in the model for each geographical site. The table provides a simple exposure evaluation of some of the most popular snorkeling destinations frequented by holiday makers visiting the Great Barrier Reef and Melanesia. Effective exposures are at times higher in spring compared to summer due to the greater ER measured in the 26°-50° SZA range.

Table 2: Some modelled clear sky UVE_{AW} (air-water calibrated) exposures in units of SED and SED/10 min for reef snorkelers in the latitude range 15°S to 24°S. Exposures were calculated for a period of 1 hour between 12:00 pm and 1:00 pm (standard time zones) under clear sky conditions and an ozone concentration of 280 DU. The mean neck and lower back ER are applied from measurements made in the 0°-25° SZA range for 1 January and the 26°-50° range for 1 September provided the SZA range was greater than 26° in the 12:00 pm to 1:00 pm exposure period. Results include an ocean surface albedo contribution of 5%. Modelled results are provided for comparative purposes. Uncertainty in calibrated dosimeters of ±35% (UVE_{AW}) and ±41% for calibrated ambient exposure measurements in addition to clear sky model uncertainties will influence the listed estimates.

Location	Latitude / Longitude	1 September 2009		1 January 2010	
		Neck site (SED) / (SED/10 min)	Lower back (SED) / (SED/10 min)	Neck site (SED) / (SED/10 min)	Lower back (SED) / (SED/10 min)
Lizard Island (Australia)	14°40'S, 145°27'	4.2[a] / **0.7**	2.7[a] / **0.5**	5.4 / **0.9**	3.5 / **0.6**
Green Island (Australia)	16°46'S, 145°58'S	6.2 / **1.0**	4.3 / **0.7**	5.5 / **0.9**	3.5 / **0.6**
Nananu-i-Ra (Fiji)	17°17'S, 178°13'	6.0 / **1.0**	4.2 / **0.7**	5.5 / **0.9**	3.5 / **0.6**
Port Villa (Vanuatu)	17°45'S, 168°18'E	5.8 / **1.0**	4.0 / **0.7**	5.3 / **0.9**	3.4 / **0.6**
Whitsunday Island (Australia)	20°15'S, 148°56' E	5.6 / **0.9**	3.9 / **0.7**	5.5 / **0.9**	3.5 / **0.6**
Luecila Beach, Lifou (New Caledonia)	20°46'S, 167°14'E	5.4 / **0.9**	3.7 / **0.6**	5.4 / **0.9**	3.5 / **0.6**
Heron Island (Australia)	23°26', 151°54'	5.0 / **0.8**	3.5 / **0.6**	5.4 / **0.9**	3.5 / **0.6**
Lady Elliot Island (Australia)	24°07'S, 152°45'S	4.9 / **0.8**	3.4 / **0.6**	5.4 / **0.9**	3.5 / **0.6**

[a]Both 1 September and 1 January are in the 0°-25° SZA range at this latitude.

FIGURE 3

The estimated results presented in Table 2 have implications for both local and international holiday makers planning to partake in snorkeling activities. Of the locations modelled (Figure 3), Table 2 shows clearly the influence of latitude and SZA on the UVE_{AW} exposure received by a snorkeler, where exposures are greater in low latitudes and at more oblique SZA ranges. From the results, it is conceivable that a snorkeler will experience a period of enhanced exposure before midday due to the increase in ER caused by sunlight incidence at increasing angle to the surface normal. Exposures in the latitude range from Green Island through to Luecila Beach are higher in September than in January between 12:00 pm and 1:00 pm due to this effect. At Heron Island and Lady Elliot Island, the September exposures become lower than the exposure experienced in January. Similarly, the September exposure for Lizard Island is lower than the January exposure, however for this case the lower exposure is due to the 0^o-25^o SZA ER also being applied to the lower spring time exposure. Snorkeling near midday in low latitude locations could potentially result in a lower UVE_{AW} exposure than that experienced if a snorkeler is exposed earlier in the morning or later in the afternoon when the higher 26^o-50^o SZA ER range applies.

Discussion

The focus of this work has been the development of a new method for calibrating dosimeters that experience both in air and submerged exposure periods, resulting in the first approximation of erythemally effective UV exposures measured on snorkelers. Future work utilising a multiplexer fibre optic system, capable of simultaneous in air and air water measurement will decrease the quoted uncertainties given for the calibrated dosimeters used in this project. Future research involving a larger number of participants than those involved in this preliminary study will further shed light on the possibility of UVE_{AW} exposure enhancements and help to determine diurnal exposure risk periods for individuals located in the partial in-air and underwater environment. The UVE_{AW} received by a snorkeler will however also depend on a number of other factors, particularly the level of personal protection used.

A new technique to measure the erythemally effective solar exposure to the backs of reef snorkelers has been presented in this research. These exposures have also been expressed relative to the ambient UVR exposure received on a horizontal plane, enabling modelled horizontal plane UVR exposures to be weighted with the UVE_{AW} exposure ratios for snorkelers. This has involved the development of a simultaneous in-air and partially submerged calibration. The partial immersion technique developed for this study has shown exposure to the lower back to be less than exposure to the neck.

The calibration of PS dosimeters placed on the air-water boundary has shown that these dosimeters undergo an optical change in absorbency more quickly than dosimeters placed in air. This will limit the effective exposure range of PS in the marine environment for long term exposure applications, in which case the use of polymer films with a more substantial dynamic range such as PPO could be employed (12). Measurements of exposure received by snorkelers made in this research using PS were taken over a maximum period of 55 minutes corresponding to a maximum ΔA_{330} of 0.31. The use of PS dosimeters for marine measurement applications has been demonstrated to be a viable lowcost option for short term UVR exposure measurements in a high UVR exposure climate such as that presented in the tropical regions of Australia and Melanesia.

In this research, the maximum exposure measured using the partial in-air and underwater calibration of PS dosimeters was 4.4 ± 1.5 SED, equating to 1.0 ± 0.4 SED/ 10 min. This exposure was received at a neck site. The greatest exposure received by the lower back was 2.9 ± 1.0 SED, equating to 0.6 ± 0.2 SED/10 min. Both of these exposures were measured in January over a period of 45 minutes. The greatest exposure measured in spring time within the SZA range 26^o-50^o to the back of the neck and lower back was found to be 2.4 ± 0.8 SED (0.5 ± 0.2 SED/10 min) and 1.5 ± 0.5 SED (0.3 ± 0.1 SED/10 min) respectively. These measurements were made over a period of 44 minutes. For beachgoers and holiday makers the high relative proportion of exposure received while snorkeling warrants the need to take specific sun protective measures aimed at reducing solar exposure to the back.

The calibrated exposures presented in this research are the first to determine the relative UVR exposures to reef snorkelers. Measurements made in this research were used to model possible UVE_{AW} exposures for a reef snorkeler at various popular sites of the Great Barrier Reef and tropical Melanesia. The modelled exposures are also the first to present UVR exposures for snorkeling activities over a 10^o latitudinal gradient. These results can be used as a guide to determine exposure risk during summer and spring at each of the chosen sites. The fact that modelled exposures were on occasion higher during periods of lower solar elevation indicates that there is a possibility of a reduced UVR period occurring near midday. This finding may be important in determining times that are best suited to snorkeling that result in lower personal exposure risk. From the modelled results presented, it was determined that there is a potential for greater exposures to occur in the latitude range 17^oS to 21^oS during September compared with January due to the possible influence of UVR incident at increased angles to the reflecting water surface normal. This effect resulted from greater ER measurements found to occur during the 26^o-50^o SZA ranges compared with the 0^o-25^o SZA range.

A possible explanation for this may be that radiation incident at an increased angle to the surface normal, due to the position of the solar disc in the sky will result in a greater proportion of that radiation being reflected as opposed to penetrating the water column at near normal angles of incidence. This will have the greatest effect to the neck, shoulder blades and head of a reef snorker, regions of the body that typically experience greater periods of exposure above the water surface. In a similar study conducted in proximity to a swimming pool, Schmalwieser et al. (8) found that the proportion of UVR received by a nearby sunbather increased at lower solar elevations. These findings emphasise the importance of applying UVR exposure countermeasures regardless of the time of year and also regardless of the time of day. It was also determined from the modelled UVE_{AW} exposures that little variation occurred over a 10^o latitudinal gradient. The influence of location can therefore not be seen as an indicator of exposure risk. From the results presented in this research, snorkeling in mid, sub-tropical latitudes presents the same risk as snorkeling in low latitude locations.

The tropical and sub-tropical snorkeling environment presents an extreme risk to unprotected snorkelers for the development of skin cancer. Additional factors which will influence the UVE_{AW} exposure received by a reef snorkeler and not modelled in this research may include: the shade provided by the local surrounding environment from pier and jetty structures, boats and the proximity of nearby mountains or trees for fringing coral reef locations; the local weather conditions which will influence the proportion of cloud; the turbidity of the water column; the amount of wave action occurring in and around the proximity of the snorkeler (specifically the average frequency and height of the waves); and the form of personal protection used, including for example the use of full body wet suits, rash vests or stinger suits and how frequently quality sunscreens are applied. Full body stinger suits such as those that are provided to holiday makers during marine stinger season on the Great Barrier Reef have the potential to greatly reduce UVE_{AW} exposure risks. By necessity full body stinger suits often cover the head and neck, however further research examining the ultraviolet protection of stinger suit materials is needed to determine the relative effectiveness of these suits at protecting vulnerable exposed skin surfaces. This is an avenue for further research.

Compared to measurements made to sunbathers, who also spend a significant period of time in a horizontal orientation, the measurements of ER made here show that snorkelers experience similar ratios of ambient exposure as those experienced by beachgoers (7) and poolside sunbathers (8), with this ratio increasing during periods when the sun is positioned at oblique SZA ranges. Siani et al. (7) measured the ER to the chests of beachgoers using PS dosimeters. This particular research showed that three groups of Italian sunbathers experienced an approximate ER of 0.2 and spent between 30 to 50% of their beach-side time lying down. The enhanced exposure risk to the back of a snorkeler compared to a beachgoer becomes immediately obvious when it is considered that a sunbather may spend between 30 to 50% of their beach-side time in a more or less horizontal position while lying down, and is likely to alternate between lying face-down and face-up in that time. A snorkeler's back does not experience much time out of direct sunlight due to the nature of the activity and as the results of this study have shown, experiences a high proportion of the ambient UVR. Recent research by Schmalwieser et al. (8) showed that the proportion of ambient UVE received by a poolside sunbather measured at a chest site could be greater than that received on a horizontal plane in a 10 min exposure interval (ER 1.20) at low, oblique solar elevations. However this proportion decreased with increasing exposure time (an effect of subject movement) to 0.39 over a 60 min exposure interval, which is lower than the mean ER measured in this study within the 26^o-50^o SZA range, being 0.65 ± 0.07 (1σ) and 0.45 ± 0.13 (1σ) for the neck and lower back respectively. Schmalwieser et al. (8) determined the ratio of ambient exposure to vary from 1.01 to 0.73 for solar elevations greater than 45^o over exposure intervals of 10 to 60 min. Here (8), measurements of exposure were made in Vienna, Austria up to a maximum solar elevation of 71^o (SZA of 19^o). Snorkeling trials made for this study were held over a minimum SZA range 7^o-5^o (21 January 2010). The mean ER for snorkelers in the 0^o-25^o SZA range was determined to be 0.42 ± 0.04 (1σ) and 0.27 ± 0.10 (1σ) for the neck and lower back respectively. These ER sets apply for a high ambient UV environment in which tropical and sub tropical minimal SZA ranges apply. While the 0^o-25^o SZA range ER data are lower than those measured to poolside sunbathers (8), the proportion of high ambient UV received in tropical and sub tropical snorkeling environments highlight the value of the results, the first determined for this particular activity.

Conclusion

The risks of developing skin cancer and other health issues such as the degradation of skin fibres, the reduction of skin elasticity and the inhibition of cell growth are increased by solar UVR exposures. Increased levels of solar ultraviolet incident upon holiday makers visiting the seaside environment warrants the necessity to quantitatively evaluate the exposure risk to such a population. Popular activities for holiday makers using the sea side environment include reef snorkeling. While solar UVR is reduced significantly at depths greater than two meters in the underwater environment, particularly in the biologically significant UVB, snorkeling presents a case in which UVR exposure can be enhanced above typical exposure levels received on land surfaces, due largely to the constant face-down body orientation of the snorkeler. However, there is a major gap in the scientific knowledge on the amount of solar UVR exposures received by reef snorkelers. This research has developed the first hybrid in-air to water calibration of UVR film dosimeters for use on snorkelers to accurately determine the exposure received by this population group. Furthermore, this research has assessed the UVE_{AW} exposures at a range of high ambient UVR tourist locations. It is anticipated that this information could be used to inform the population of the likely exposure levels in this environment and in turn will have an impact on reducing skin cancers and other diseases associated with unnecessary exposures to solar UVR caused by unprotected snorkeling activities.

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List of Figures

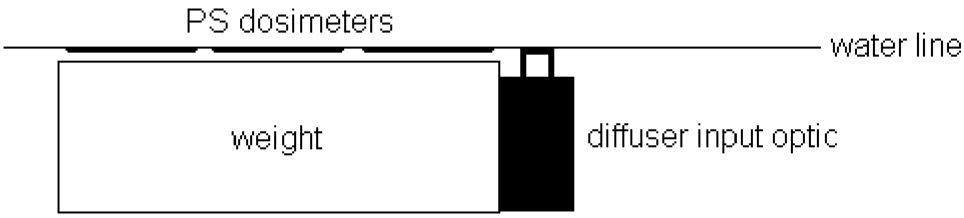

Figure 1: A total of twelve calibration dosimeters were attached to two brick weights that were placed into a natural sea water body so that the dosimeters received both air and submerged UVE exposures caused by dynamic wave action over the calibration plane to measure UVE_{AW}.

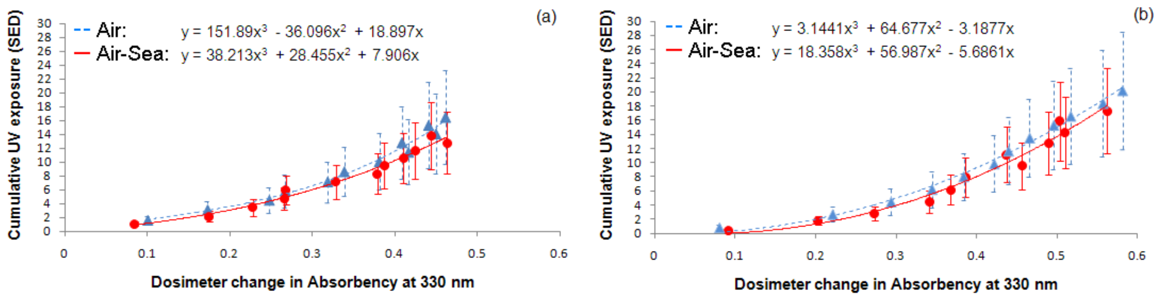

Figure 2: In-air and air-sea boundary calibration curves for PS dosimeters used to measure UVE exposure to the backs of snorkelers. Dashed curves represent in-air calibrations (triangle data points), solid curves are air-sea calibration curves (circle data points). (a) Spring calibration on 15 October 2009; (b) Summer calibration on 10 January 2010. Both the spring and summer calibrations were performed in Hervey Bay over 2 hours under clear sky conditions near midday. Error bars represent calibration uncertainties of ±41% and ±35% for in-air and air-sea dosimeters respectively.

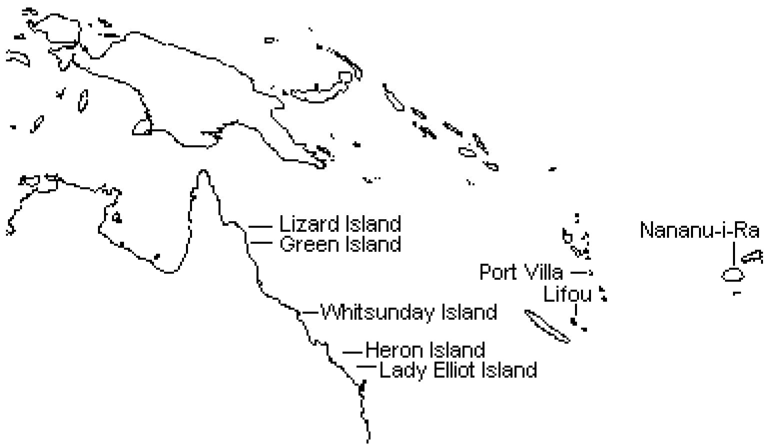

Figure 3: Geographic distribution of snorkeling sites presented in Table 2.