Assessing a portable, real-time display handheld meter with UV-A and UV-B sensors for potential application in personal sun exposure studies

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Background: Observing accurate real-time measurements of solar ultraviolet radiation (UVR) levels is important since personal excess sun exposure is associated with skin cancers. Hand-held measurement devices may be helpful but their accuracy is unknown. We compare a portable, science-grade solar UVR monitoring device against two fixed, science-grade solar UVR instruments.

Methods: Instruments were (1) a fixed Solar Light 501 UV-B biometer to measure UV-B; (2) a fixed Kipp and Zonen radiometer used to measure UV-A and UV-B; and (3) Goldilux ultraviolet probes which are commercially available portable devices. Two different probes were used, one measured UV-A and the other UV-B radiation. The Goldilux probes were levelled and secured next to the UV-B biometer. Between 10:00 and 14:40 UTC+2, the UV-B biometer was set to record at 10-minute intervals and measurements by the Goldilux probes were manually taken simultaneously. Results were compared for all data and by solar zenith angle (SZA) ranges.

Results: The Goldilux UV-B probe measured UV-B relatively well in its diurnal pattern, however, its readings were ~77% higher than those made by the UV-B biometer. While UV-A measurements from the Goldilux UV-A probe and those from the radiometer were in relatively good agreement in pattern, the radiometer read ~47% higher than the Goldilux UV-A probe. UV-B data from Goldilux UV-B probe had a moderately strong correlation with UV-B biometer data for small SZAs; conversely, for UV-A, the Goldilux UV-A probe had a strong correlation with the UV-A radiometer data for large SZAs.

Conclusion: Handheld devices may be useful to provide real-time readings of solar UVR patterns, however, to achieve synchronicity in the magnitude of readings to those made by science-grade fixed instruments, devices may need to be used during certain times of the day and in clear-sky conditions which may not be practical in personal exposure studies.

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Introduction

Although solar ultraviolet radiation (UVR) forms approximately only 5% of the total solar energy that reaches the Earth's surface, it plays a significant biological role (1,2,3). Given the absorption of UV-C (100-280 nm) by atmospheric ozone, the solar UVR of importance to humans consists of UV-A (280-320 nm) and UV-B (320-400 nm) (4). Even though UV-A penetrates human skin more deeply than UV-B, the action spectra for biological responses suggest that UV-B radiation is absorbed by DNA and when subsequent DNA damage occurs, this may play an important role in the initiation of skin cancer. Such detrimental effects are associated with excess exposure (4). Beneficial physiological and psychological effects are associated with sufficient UVR exposure and include production of vitamin D and regulation of the circadian rhythm, respectively.

To determine possible human health risks, in terms of both UV-A and UV-B exposure, it is important to assess the solar UVR environment and estimate personal solar UVR exposure. Several studies around the world have aimed to measure personal solar UVR exposure using equipment and devices that can be worn by study participants (5-10**)**. Often, a major shortfall of these studies is that ambient solar UVR exposure is either inferred from the nearest location with an ambient solar UVR sensor or satellite data may be used to estimate ground-based ambient solar UVR levels at the study location. In some studies, a personal electronic solar UVR monitoring device has been used to measure ambient solar UVR when placed on a flat surface (6, 10-11) however, this device does not permit instantaneous viewing of the current solar UVR level. It may be important to know the current, real-time solar UVR level, for example, in occupational health settings or in public health solar UVR exposure assessment studies. The challenge is to find a suitable device that accurately measures solar UVR and that gives an immediate read-out of measured solar UVR on a visual display in addition to logging data for download at a later stage. Here, we compare a portable, science-grade solar UVR monitoring device with two sensors, one for UV-A and one for UV-B, against two fixed, science-grade solar UVR instruments (one measuring UV-A and the other UV-B) in an attempt to find a cost-effective, simple device for accurate solar UVR measurement and with visual, immediate display of real-time solar UVR levels. We describe the measurements from the various instruments in relation to each other to determine the trustworthiness of the portable device and sensors.

Methods

Instruments

Three instruments were used in this study (Table 1): 1) a fixed Solar Light 501 UV-B biometer to measure UV-B (Fig. 1a); 2) A fixed Kipp and Zonen radiometer used to measure UV-A and UV-B (Fig. 1b); and 3) Two Goldilux ultraviolet probes (Fig. 1c) to measure UV-A and UV-B which are commercially available. The Kipp and Zonen device was used in the study to obtain UV-A data since the UV-B biometer does not measure UV-A.

Fig. 1a & b & c

The UV-B biometer is located at the South African Weather Service (SAWS) in Pretoria, on the roof of their headquarters, Bolepi House (25.49° S 28.15° E) (Fig. 2) at an elevation of 1 322 m. The analogue voltage output from the biometer is proportional to the solar radiation measured (14).

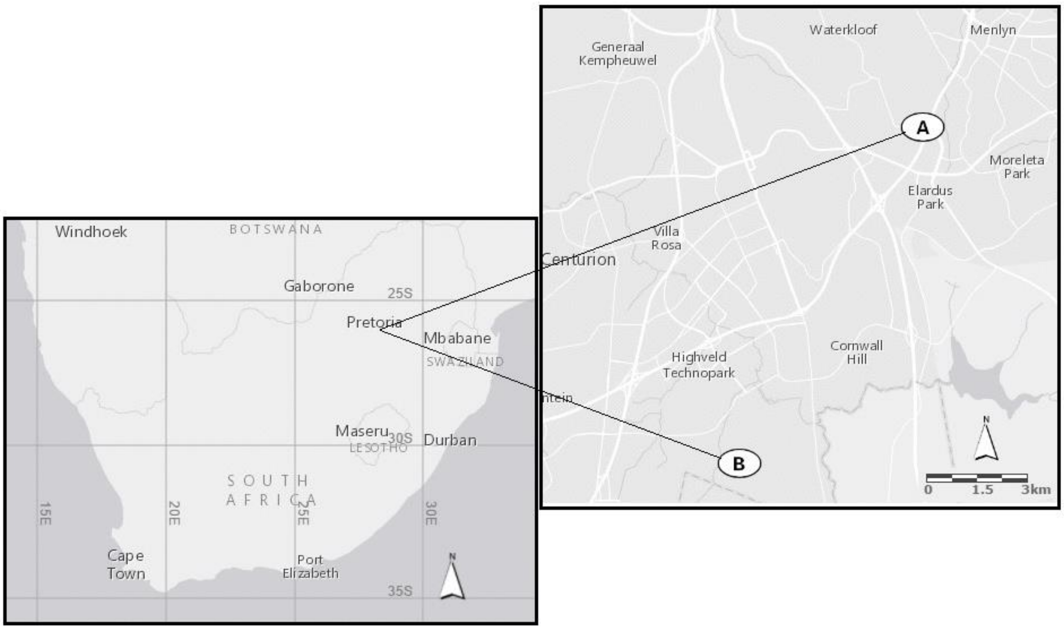

Fig. 2

The second instrument is a Kipp and Zonen radiometer which is mounted on a sun tracker at the SAWS Irene Weather Station (25.55°S 28.13° E) (Fig. 2) approximately 12 km south-south-west of Bolepi House with an elevation of 1 500 m. The radiometer measures UV-A and UV-B irradiance (15) where an analogue voltage output is used for each band of the dual band radiometer. The Goldilux instrument consists of two hand-held ultraviolet probes which connect to a readout unit. The one probe measures UV-A and the other measures UV-B. Each probe measures the power per unit area of UVR on the sensor.

as.

Experiment

On the 19th January 2017, which was clear-sky, cloud-free for the majority of the day, the UV-A and UV-B probes of the Goldilux instrument were levelled and secured next to the UV-B biometer. We followed the user specifications from the manufacturer for the application of Goldilux instrument. We mounted the probes horizontally, removed the protective cap over the senor on the probe, connected the probe to the display unit and pressed the hold button on the display unit to take a reading. The UV-B biometer was set to record at 10-minute intervals. The UV-A and UV-B measurements from the Goldilux instrument were taken manually and recorded at 10-minute intervals from 10:00 until 14:40 UTC+2, corresponding to the measurement time of the UV-B biometer. The radiometer measured UV-A and UV-B every minute.

Data analysis

UV-B data from the Goldilux UV-B probe were compared with the UV-B biometer measurements at Bolepi House as well as with the UV-B data from the radiometer at Irene. The UV-A data from the Goldilux UV-A probe were compared with the UV-A data from the radiometer. The instruments' data were compared using time series analysis and linear regression with second order polynomial curves fitted. If clouds were found to be obscuring the sun then these data points were removed to eliminate the effect of clouds on the data. All of the data was converted to J m^{-2}.

The solar zenith angle (SZA) was calculated for every 10-minutes that the measurements were made. The differences between the SZAs of Bolepi House and Irene were negligible. To assist with interpretation of the data, the measured solar UV-A and UV-B data were divided into three categories depending on the SZA. The three SZA categories were 5-15° (sun high in the sky), 16-26° and 27-37° (sun closest to the horizon). The second order polynomial correlation coefficient was obtained for each of the SZA categories for the comparison of the different instruments as stated above. The Bland-Altman method (16) was used with UV-B data from the UV-B Biometer and UV-B data from the Goldilux probe to consider the difference between measurements against the means of the measurements as an alternate approach to correlation coefficients.

Results

Diurnal solar UV-A and UV-B patterns and inter-instrument data comparison

The typical bell-shaped curves associated with the pattern for diurnal solar UVR on a clear-sky day are visible in Fig. 3a for the UV-B biometer data with solar UVR increasing until solar noon and then decreasing towards sunset. On average, the data from Goldilux UV-B probe was 346.57% higher than the data from the UV-B biometer (min: 27.31%; max: 523.12%).

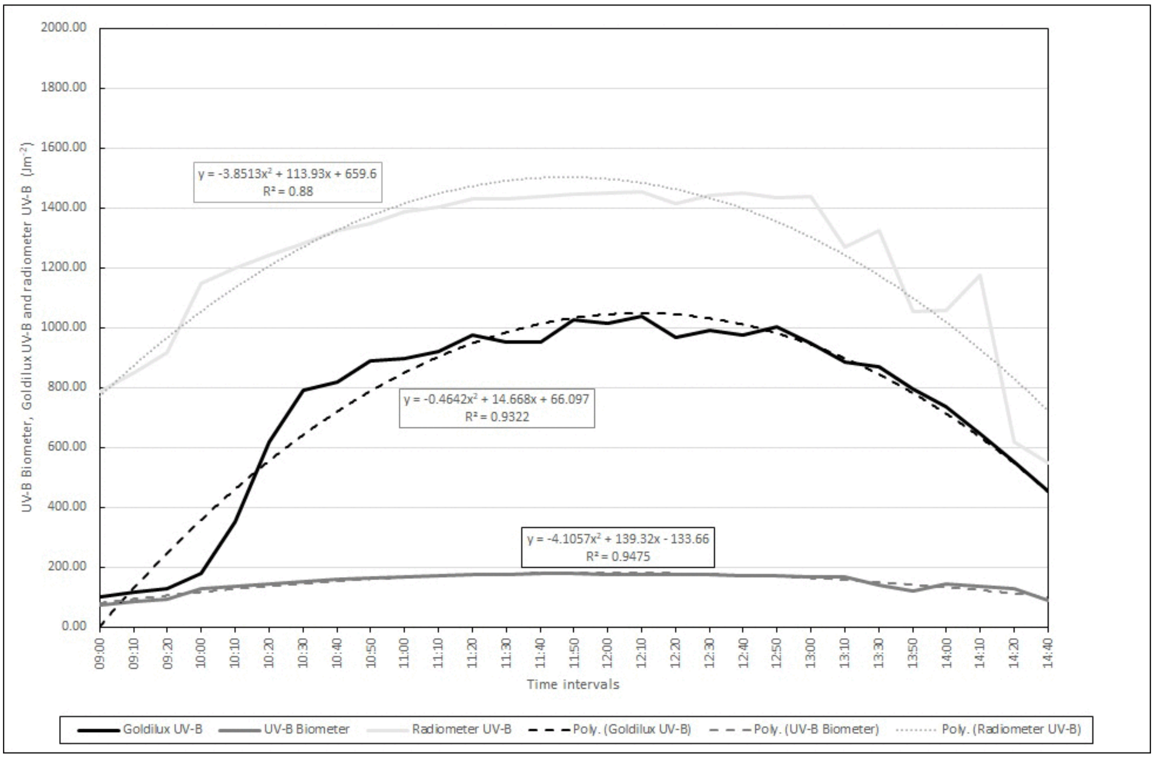

Fig. 3a

The typical daily UVR curve, although slightly less clear, can also be seen in the UV-A readings from the radiometer and Goldilux UV-A probe (Fig. 3b). UV-A measurements from Goldilux probe and those from the radiometer are of the same order of magnitude. The data from the UV-A radiometer is on average 47.25% higher than the data from UV-A Goldilux probe (min: -0.14%; max: 55.75%). The UV-B data from the radiometer is constantly one order of a magnitude larger than the UV-B biometer data. There was little variation between the UV-B biometer and the UV-B data from the radiometer.

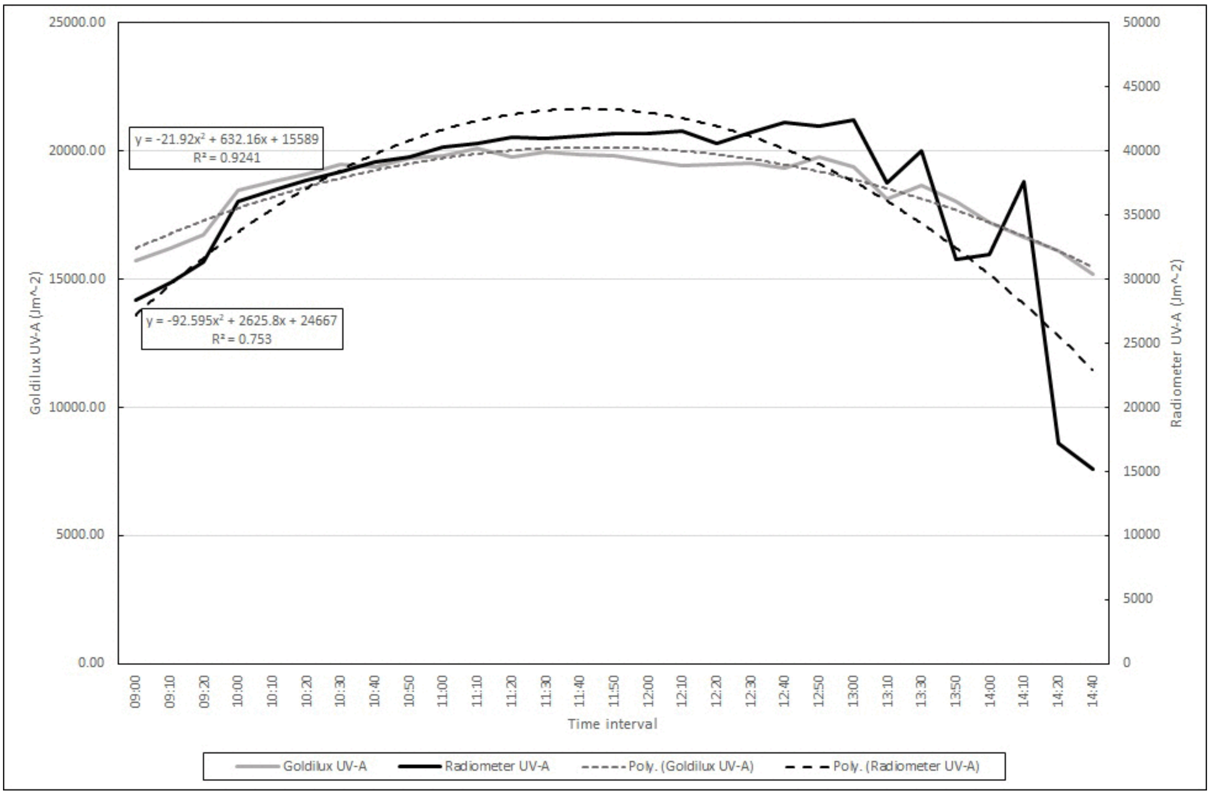

Fig. 3b

Results by SZA ranges

At SZAs larger than 15°, the UV-B data from Goldilux instrument and the biometer are of the same order of magnitude. At SZAs less than 15°, the UV-B data from the Goldilux instrument is one order of a magnitude larger than the UV-B biometer data. By all and specific SZA categories (Table 2), UV-B data from Goldilux instrument had a moderately strong correlation with the UV-B biometer data for SZAs between 5° and 26° (Fig. 4). The UV-B measurements by the biometer and radiometer were well correlated for all SZAs. The correlation between Goldilux UV-B data and the radiometer UV-B data was the strongest for SZAs between 5° and 26°. Comparing UV-A data from Goldilux instrument and the radiometer showed a very strong correlation for SZAs between 27° and 37°.

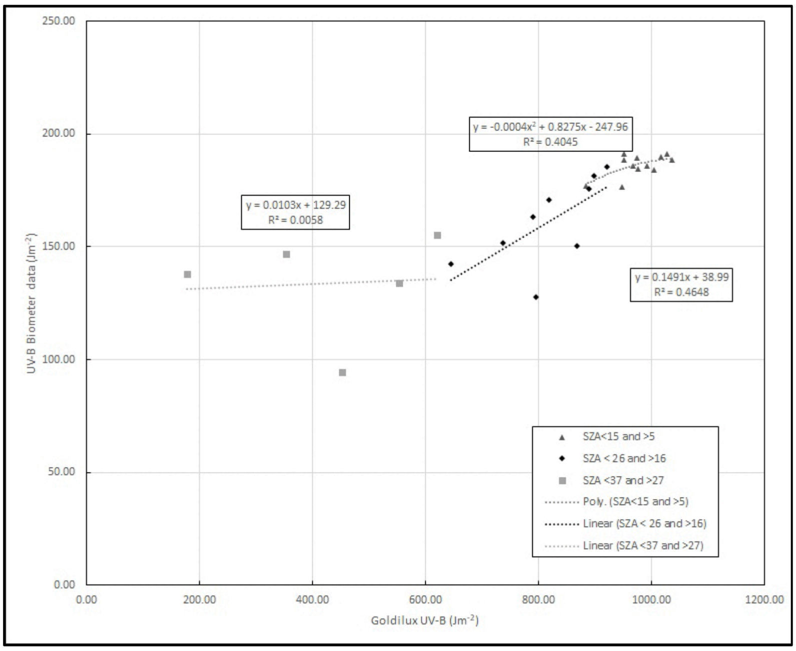

Fig. 4

Correlation between datasets

The correlations between the UV-B biometer measurements and UV-B measurements from Goldilux instrument and the radiometer are shown in Fig. 5a and Fig 5b, respectively.

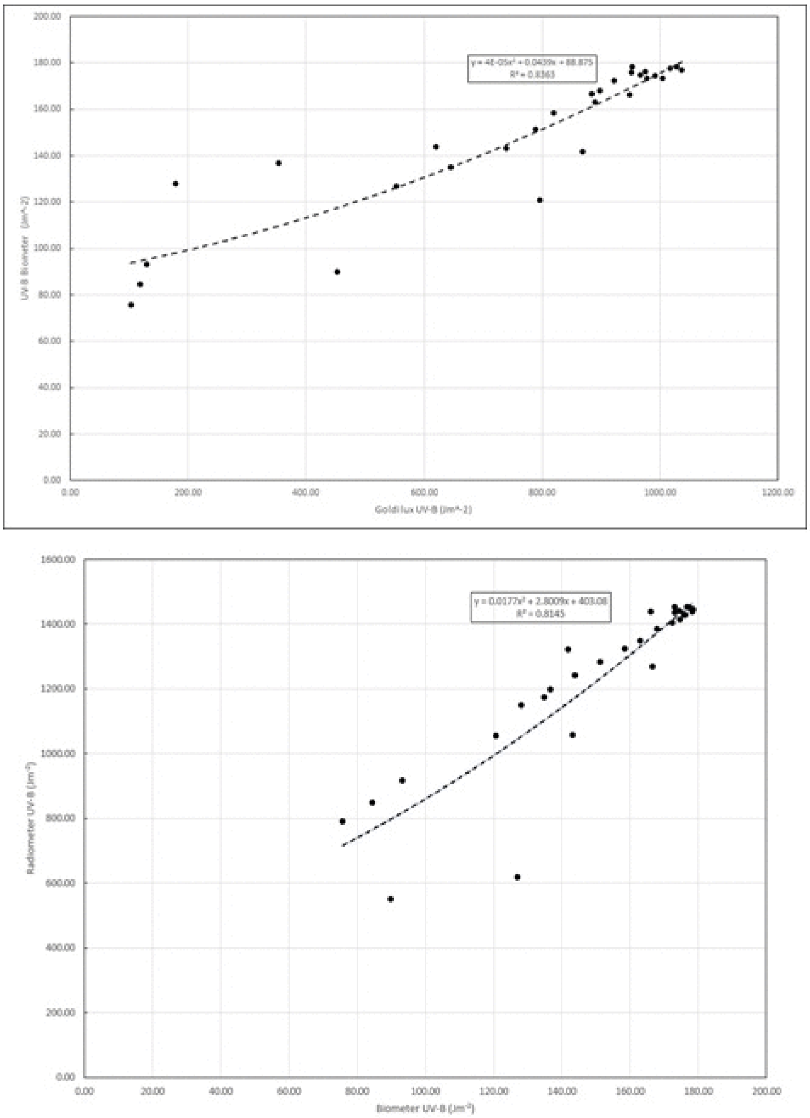

Fig. 5a &b

Figure 6a shows the results of the Bland-Altman plot for UV-B from the UV-B biometer and Goldilux UV-B probe comparing the difference between measurements are graphically plotted against the means. The positive bias indicates that the Goldilux UV-B probe constantly measures approximately 649.97 Jm^{-2} higher than the UV-B biometer. Similarly, Figure 6b shows the Bland-Altman plot for UV-B from Goldilux instrument and Radiometer. The positive bias indicates that the radiometer consistently measures 459.11 Jm^{-2} higher when compared to Goldilux UV-B probe.

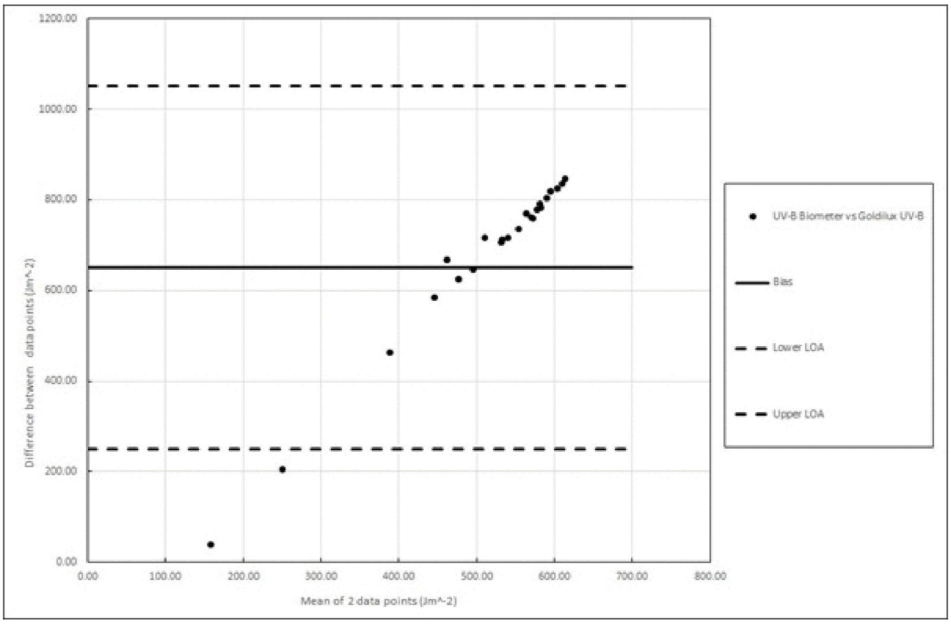

Fig. 6a

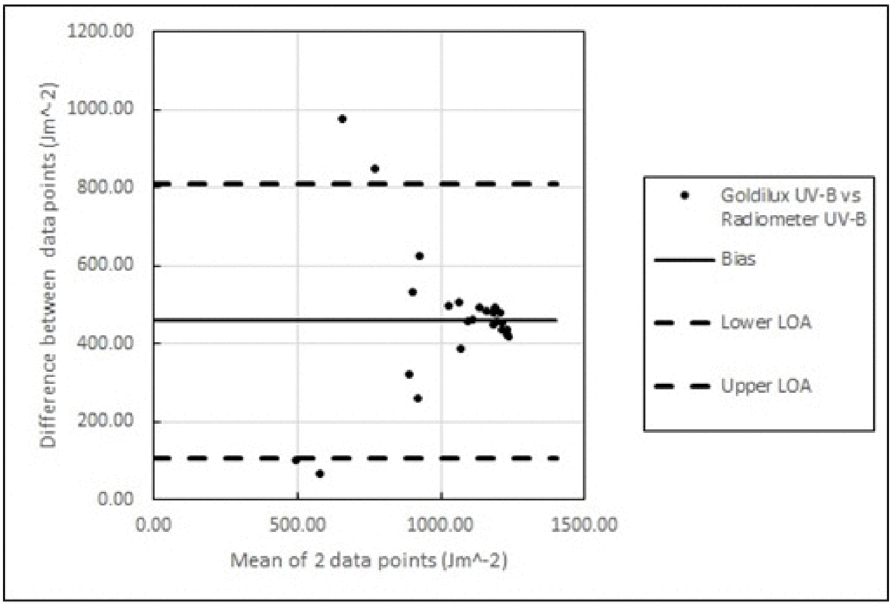

Fig. 6b

Discussion

Although previous studies have shown that the trustworthiness of commercially-available, consumer products that measure solar UVR has been mostly poor; here, based on our findings, we have provided evidence that data from the portable solar UVR meter device with UV-A / UV-B handheld probes showed relatively good agreement with the patterns of solar UVR data measured by meteorological science-grade fixed instruments. This finding is promising in light of the need for accurate research on and measurement of sun exposure among different population groups given the significant global burden of diseases from solar

UVR (4). However, despite the overall proven trustworthiness of the handheld device in mimicking the pattern of UV-A and UV-B levels, the unit values for J m^{-2} were very different when comparing the measurements made by the handheld device versus the two fixed devices. The Goldilux UV-B probe on average measured 346.57% higher compared to the UV-B biometer and 132.44% lower when compared to the Radiometer UV-B. It is possible that the handheld meter requires (regular) calibration against a fixed instrument for correction of their measurements to be in the same order of magnitude as a fixed science-grade instrument. We did find, in addition, that there was some variation between the UV-B data measured by the two fixed instruments and this variation may have due to the distance between Bolepi House and Irene, as well as difference in elevation, the effect of clouds and the relative surroundings of the station.

SZA is an important factor influencing levels of solar UVR and we considered the impact of SZA on the difference noted in levels of UV-A and UV-B measured by the biometer and radiometer compared to the handheld device. At SZAs larger than 15° the UV-B data from the handheld meter and the UV-B biometer were of the same order of magnitude. At SZAs less than 15°, the UV-B data from the handheld meter was one order of a magnitude larger than the UV-B biometer data. Conversely, when the sun was low in the sky, the handheld device measured lower levels compared to the biometer. We surmise that the positioning of the sensor on the device in relation to the sun is restricting solar radiation from entering the sensor and therefore reducing the solar UVR measured when the sun is low in the sky (at high SZAs). At larger SZAs, when the sun is rising or setting the correlation between measurements from the handheld device and the two other instruments was not good. When the sun is directly overhead the sensor and the SZAs are smaller the correlation between the Goldilux instrument and two other instruments is much stronger. The sensor on the handheld device sits within the casing of the device. This is very different to the sensor on the UV-B biometer and the sensor on radiometer which both sit within a dome. We mounted the handheld device on a horizontal surface as suggested by the manufacturer. Had we mounted the device in a perpendicular manner to the sun when readings were made, the solar UVR levels may have been higher. A similar finding was made for the Davis Vantage Pro UV Sensor (11) although this instrument was not portable. While the manufacturer did state that vertical orientation mounting was possible, it would not be possible to change the direction of the vertical mounting once fixed to ensure that the sensor was always ‘facing’ the sun, hence horizontal mounting was selected here.

The effect of SZA on the solar UVR readings of the handheld device could possibly be improved if the sensor was directed towards the sun for large SZAs and mounted on a level surface for small SZAs. This would require an individual being present to re-orientate the sensor prior to taking the measurements which would be laborious. We cannot explain the reason for the finding that UV-A data from the Goldilux UV-A probe. A had a strong correlation with the radiometer UV-A data for SZAs between 27° and 37° when the sun is low in the sky. This may be a spurious finding, or it may be due to the passage of UV-A through the atmosphere. The relationship between the solar UVR readings of Goldilux instrument and SZA requires thorough testing and is likely to be too complex to write into the manufacturer instructions for operation of the handheld device. Therefore, it may be preferable to only use the handheld device on clear-sky days and during the WHO peak UVR periods of the day, from 10h00 to 14h00 (or 15h00 during daylight saving) (18) in a horizontal orientation to provide as accurate readings, both in terms of pattern and magnitude, as possible. Realistically, this does not make practical sense for use in exposure studies when people may be outdoors at any time of the time; therefore we did not pursue additional experiments to test this. Notwithstanding, the instrument is still relevant for its manufacturer’s intended purpose, but its use for population exposure studies requires further consideration.

Conclusion

There is some evidence to suggest that a handheld device that measures solar UV-A and UV-B may be useful to provide a real-time reading of solar UVR levels, however, the device may work best during certain times of the day when the sun is highest in the sky which is not always practice since people may be exposed at other times of the day. These findings need to be confirmed in places with lower solar UVR levels as commonly observed in high latitude countries or at lower elevations. Further research is needed to better understand the discrepancies for this device, and similar handheld devices, before being used in scientific research or for awareness-raising in public and / or occupational settings. However, once confirmed as a trustworthy tool, these types of handheld devices may prove useful in sun exposure and skin protection research and public health.

Acknowledgements

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Disclosure

The authors confirm that they have no conflict of interests. They purchased the commercially-available probes described in the paper for research purposes and data from the radiometer and biometer were provided by the SAWS.

Author contribution

Dr Wright and Mr du Preez had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Dr Wright and Mr du Preez. Acquisition, analysis and interpretation of the data: Mr du Preez and Dr Wright. Drafting of the manuscript: Mr du Preez and Dr Wright. Critical revision of the manuscript for important intellectual content: Dr Wright and Prof du Plessis. Obtained funding: Dr Wright and Prof du Plessis. Administrative, technical, or material support: Prof du Plessis took the photograph in Plate 1. Study supervision: Dr Wright.

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TABLE 1. Specifications of the three instruments used in the study to measure solar UV-A and UV-B.

	UV-B biometer	**Radiometer**	**Goldilux Ultraviolet Probes**
Measured UVR spectrum	UV-B (280-320 nm)	UV-B (280-315 nm) UV-A (315-400 nm)	UV-B (280-315 nm) UV-A (315-400 nm)
Measuring unit	Minimal Erythemal Dose (MED)*	W m^{-2}	µW cm^{-2}
Measuring interval	10-minutes	1-minute and hourly	Manual

Voltage output	Analogue	Dual-analogue	Not given
Approximate cost (USD$^{\#}$)	6 397.00	Radiometer: 8 626.00 Sun tracker: 25 240.00	1 341.00
Calibration	Calibrated in 2012 against a travelling standard (SL-501 12010 broadband radiometer) that underwent absolute calibration at the National Metrology Institute of Germany.	Calibrated by the manufacturer in 2015.	Calibrated by exposing the sensor to a known power unit area of wavelength to which the sensor is sensitive. Newly purchased for this study and hence had just undergone calibration by the manufacturer.

Note. * 1 MED = 201 Jm^{-2}. # Costs in ZAR as at 18 April 2017 (1 USD = ZAR13.28) as provided by the supplier.

TABLE 2. Correlation coefficients for results of the linear regression to compare the instruments' measurements of solar UV-A and solar UV-B for three different SZA bands. A correlation coefficient below 0.500 is considered low, 0.600 to 0.800 is considered moderate and above 0.800 is considered strong (17).

	Biometer UV-B versus Goldilux UV-B	**Radiometer UV-B versus Goldilux UV-B**	**radiometer UV-A versus Goldilux UV-A**	**Biometer UV-B versus radiometer UV-B**
All SZA	0.905	0.783	0.878	0.905
SZA 5° - 15°	0.637	0.775	0.739	0.574
SZA 16° - 26°	0.679	0.735	0.672	0.857
SZA 27° - 37°	0.086	-0.273	0.990	0.818

List of Figure Headings

Fig. 1. (a) *The UV-B biometer located at the SAWS Bolpei House (Photograph taken by CY Wright); (**b**); The Kipp and Zonen radiometer (Photograph from the manufacturer). and (**c**) The UV-B probe of Goldilux instrument illustrating the position of the casing in which the sensor is located on top of the unit (Photograph taken by JL du Plessis).*

Fig. 2. Map of South Africa showing the two locations of the instruments at (A) SAWS Bolepi House and (B) Irene weather station (Map created on the ESRI website at http://support.esri.com/technical-article/000012040 on 16 May 2017).

*Fig. 3. . Diurnal pattern in UV-B (**a**) and UV-A (**b**) measurements from the biometer, radiometer and Goldilux on the 19th January 2017. Missing data and cloud-affected values have been removed at 09:30, 09:40, 09:50, 13:20, 13:40 and 14:30. The maximum UV-B biometer reading was ~ 180.00 J* m^{-2} *and the maximum Goldilux UV-B reading was 1 000.00 J* m^{-2}*. The maximum radiometer UV-A reading was ~42 000.00 J* m^{-2} *and the maximum Goldilux UV-A reading was ~20 000.00 J* m^{-2}*.*

Fig. 4.. Correlation between UV-B biometer UV-B data and Goldilux UV-B data by SZA category: 5-15° (sun high in the sky), 16-26° and 27-37° (sun closest to the horizon).

*Fig. 5. Correlation between UV-B measurements from (**a**) Goldilux and from the UV-B biometer, and (**b**) biometer and the radiometer at all of the time intervals with data available*

Fig. 6. Bland-Altman plot for UVB from the (a) UV-B biometer and Goldilux and (b) radiometer and Goldilux comparing the difference between measurements graphically plotted against the means.