A Comparative Study of Wearable Ultraviolet Radiometers

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***Abstract*— In this paper we describe the motivation, challenges, and design methods of miniaturizing UV Index radiometry into a wearable form factor. The UV Index is the standard metric to measure instantaneous UV exposure in a way that is relevant to the human skin. However, unlike FDA regulated sensors like the glucose sensor, there is a currently an absence of specifications for the performance of wearable UV Index radiometers. In this paper, we develop performance metrics based on accuracy and sensitivity, and further evaluate the performance of several commercially available UV Index wearable radiometers on the basis of these metrics. Comparisons to laboratory-grade equipment show that the Shade radiometer is the most accurate and the most sensitive commercially available wearable UV radiometer.**

Ethics statement: This paper does not describe research involving human or animal subjects and is therefore not subject to review by IRB or IACUC.

I. INTRODUCTION

Even though it does not induce ionization, photons from solar ultraviolet radiation (wavelength 280-400 nm) penetrate human skin and catalyze the formation of reactive oxygen species which damage cellular components including DNA, proteins, and lipids.[1] The sequelae of this chemistry have both adverse and beneficial effects on human health. The skin, on exposure to UV, synthesizes Vitamin D, which plays a critical role in regulating bodily functions.[2] Overexposure to UV increases the rate of apoptosis and inflammation that can result in sun poisoning or systemic reactions in diseases like lupus.[3] Accumulated damage has been associated with skin cancer in the longer term.[2]

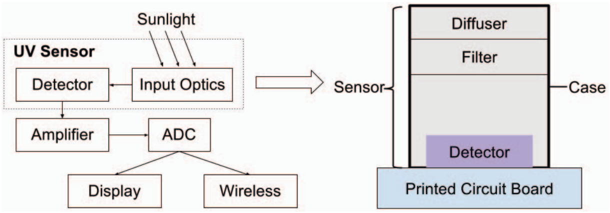

Fig. 1: Block diagram of a wearable UV radiometer, and schematic of the ultraviolet (UV) sensor

Despite public health initiatives to educate populations on the dangers of UV [4] and regulatory efforts to make sunscreen safer and more efficient [5,6], the incidence of melanoma, the most deadly form of skin cancer, has tripled over the past 30 years in the US.[7] Several attempts to quantify UV exposure have been made over the last 3 decades. Recent advances in wearable electronics and the prevalence of smartphones has enabled personal UV measurement in electronic form, leading to a number of consumer-friendly solutions. These devices can be *radiometers*, capable of measuring instantaneous UV intensity, or *dosimeters*, capable of measuring accumulated UV dose over time. To provide a radiometric readout of the UV Index, these instruments need to weight photons according to the *erythema action spectrum*.[8] This weighting function is based on Diffey's work on skin erythema (sunburn) as a function of UV exposure [9] which showed that higher energy photons are exponentially more damaging. However, there is a lack of standardization in the industry in terms of agreed methods to communicate the real-world accuracy of these devices. In this paper, we review common UV radiometer designs. We further develop metrics for standardizing comparisons between different wearable UV radiometers based on real world observation of accuracy. Finally, we present comparisons of several such commercially available devices.

TABLE I
PRIMARY COMPONENTS OF A UV SENSOR

Component	Definition and Function
Detector	Usually made of silicon, the detector converts light to electrical current. Its chemical composition dictates spectral response
Filter	Determines the relative proportions of each wavelength transmitted to the detector
Diffuser	Collects light from all directions and transmits it uniformly to the filter. Ideally has a cosine response
Case	Mechanical support and packaging for the combination
Printed Circuit Board	Allows connection to the auxiliary electronic components to measure/display detector output

II. DESIGN OF WEARABLE SOLAR UV INDEX RADIOMETERS

UV from sunlight is distinct from UV from lamps. It exhibits both large temporal and spatial variations. Factors that affect the spectrum are latitude, altitude, time of the day, day of the year and weather conditions including pollution, atmospheric ozone concentrations, reflection from vegetation, and cloud cover [4]. In this paper, we focus on electronic wearable UV radiometers and dosimeters. Chemical dye-based solutions [10, 25, 26] for measuring UV dose are outside our scope. A wearable UV radiometer is typically composed of one or more *UV sensors*, coupled with auxiliary electronics such as amplifiers, analog-to-digital converters (ADC) and microcontrollers (Figure 1). Additionally, there is a readout process either through a display, or through wireless technology, such as Bluetooth Low Energy. Below we describe the typical physical construction of a UV sensor, and the importance of its spectral response in measuring UV accurately.

A. Ultraviolet sensor

A UV sensor outputs an electrical signal when it is exposed to UV. It typically involves the components shown in Figure 1, and described in Table I. The output of the detector can be a voltage or a current, which is then converted to digital form by the auxiliary electronics on the PCB. Most wearables use photodiodes for UV sensing.

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B. Spectral Response

Each detector, with its filter has a *spectral response*, i.e. how sensitive the sensor is to each wavelength. The target spectral responsivity for a health relevant measure of UV is the *erythema action spectrum* [9], which has been standardized as ISO17166:1999/CIE and adopted by the World Health Organization.[4] It weights UVB (280-315 nm) more than 1000 times higher than UVA (315-400 nm). This action spectrum can be replicated with a combination of one or more sensors and proper calibration. Figure 2(a) shows the ideal erythema action spectrum. A radiometer's accuracy is determined by how closely it mimics the action spectrum and how well it is calibrated.

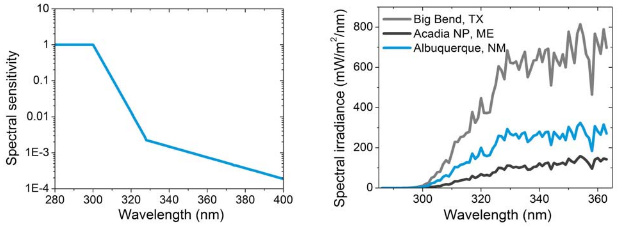

Fig. 2: (a) Ideal spectral responsivity of a UV Index detector (ISO 17166) (b) Measured UV spectral irradiance at the same time from 3 different locations

C. Calibration

Even though photodiodes produce an electrical response proportional to the input UV, absolute electrical output varies greatly from sensor to sensor. Hence, sensors must be individually calibrated. The most common way to calibrate UV sensors is to use a single source with known spectrum and develop a linear calibration function based on the measured output.

III. CHALLENGES AND METRICS FOR WEARABLE UV RADIOMETRY

Solar UV radiometry in a wearable form factor is challenging for a number of reasons:

1. *Source Spectra Variability*: Solar UV has high spatial and temporal variability. Figure 2(b) shows 3 sample spectral irradiance scans of solar UV from the Environmental Protection Agency's UV-Net database.[5] These are taken at local noon on the same day of the same year (Sept. 3, 2000) at three different locations. The UV index range can vary from fractional digits during winter and early/late hours to very high readings at noon in summer.
2. *Leakage and Stray Light*: UV is a small fraction of the total solar radiation. It is difficult to design perfect filters that can completely block visible light, while allowing UV.
3. *Calibration*: Single-source calibration would work well if the spectral response exactly matched the ideal response, or if the UV sensor was used to measure the same, stable, spectrum it was calibrated to. Neither is true for solar UV radiometry. Spectral response mismatch to the ideal response is common, and the spectrum is highly variable. This leads to large inaccuracies in measurement. The additional manufacturing challenge is that there are very few options for stable UV sources, and none that mimic the solar spectrum.
4. *UVA/UVB Intensities*: The erythemal action spectrum drops 4 orders of magnitude from UVB to UVA, while the solar spectrum does almost the reverse. The net result of weighting and emission is that both have comparable importance. Hence, a wearable UV radiometer must have the correct ratio of sensitivities to both UVA and UVB.

As an illustration of the above challenges, consider the use of visible light and infra-red to infer the UV Index. The Microsoft Band is one commercial product which adopts this method.[12] The fundamental flaw in this approach is that it is common to encounter real world spectra with completely different ratios of UV to visible light. For instance, direct sunlight at noon has the highest UVB levels. However, direct sunlight at noon through a car window does not have UVB at all, even if it has the same visible brightness. Our experiments with the Band, as well as previous work [13] further demonstrate the perils of measuring UV based on correlation to visible light .

TABLE II
SUMMARY OF UV RADIOMETERS TESTED

Product / Company	Form Factor	Category	Price	Resolution (UVI)
X1-4 UVE radiometer (Gigahertz)[14]	Handheld (reference)	Dual	\$5,500	0.001
Shade [11]	Magnetic clip	Dual	\$249	0.01
Band (Microsoft)[15]	Wristband	Radiometer	\$235	1
June (Netatmo)[16]	Wristband	Dual	\$49	0.1
Sunfriend (Sunfriend Corporation)[17]	Wristband	Radiometer	\$33.59	1
UV Watch (Dakota)[18]	Wristband	Radiometer	\$59.95	0.1
Sunsprite (Goodlux Technologies)[19]	Clip-on	Dual	\$99	0.1
EPAUVIndex mobile application[20]	N/A	N/A	Free	1

Based on the above, we propose the following metrics for a quantitative evaluation of any wearable UV radiometer:

A. *Category*: radiometer, dosimeter, or both (dual)
B. *UVA Sensitivity*: Response > 0 for a long-wave UV (UVA) lamp e.g. *UVG-L 25 Compact UV Lamp*
C. *UVB Sensitivity*: Response > 0 for a short-wave UV (UVB) lamp e.g. *UVG-L 25 Compact UV Lamp*
D. *Visible Light Rejection*: Response = 0 for a lamp with a pure visible spectrum e.g. *NatureBright SunTouch Plus Lamp* [40]
E. *Real World Accuracy* - Percentage of samples within 20% of true value from solar measurements. Sampling to be performed uniformly across the UVI range of 0-10.
F. *Resolution* - The minimum difference in UVI that can be displayed e.g. 0.1.
G. *Limit of detection* - The minimum UVI that is reliably detectable.

The following section describes experiments performed to quantify several commercially available wearable UV radiometers on the basis of the above metrics.

IV. EXPERIMENTS

A. Materials

To quantify the accuracy of all wearable UV sensors, we selected a research-grade instrument to provide a reference UV index measurement. Research-grade UV radiometers include products by Davis Instruments,[21] SolarLight,[22] Skye Instruments,[23] Gigahertz-Optik and Kipp&Zonen.[24] This study uses the X1-4 radiometer by Gigahertz-Optik which is based on two photodiodes, whose spectra combine to provide a very close match to the erythema spectrum. It additionally has a library of calibration functions, which make it accurate for a wide variety of solar UV measurements. All available and wearable devices were included (Table II) in the study, alongside UVI predictions given by the United States Environmental Protection Agency through their mobile application "EPA UVIndex." This is the data source for most, non-detector based, mobile applications displaying UV Index forecasts.

TABLE III

UV Radiometer Performance Under Lamps

Product	**Measure UVB**	**Measure UVA**	**Rejects Visible**
X1-4 UVE radiometer	Yes	Yes	Yes
Shade	Yes	Yes	Yes
Band (Microsoft)	No	No	Yes
June (Netatmo)	Yes	No	Yes
Sunfriend	*	*	No
UV Watch (Dakota)	No	No	Yes
Sunsprite	No	No	Yes
EPA UVIndex App	N/A	N/A	N/A

* The SunFriend has an LED based display that cannot be read safely while placed under a UV lamp.

The scope of this paper excludes wearable UV-sensing products that use light-sensitive chemical dye, such as the UV patch by L'Oreal[25] and the Sun meter UV card.[26] This study excludes certain products that were in development phase [27-31] at the time of writing, but not available for order. The survey also excludes portable, but not wearable devices [32-39]. These cannot currently be used for personal UV dosimetry, and the effort to miniaturize these into wearable form factor is significant. We did not study potential photodiode suppliers either, because they do not claim to provide a calibrated UV Index measurement. This is a study of devices, not detectors. However, several of the products we tested are based on these photodiodes.

B. *Methods*

A summary of the category and resolution of the selected radiometers is shown in Table II. We first illuminated these radiometers with the *UVG-L 25 Compact UV Lamp* that provides UVB and UVA separately. The UV lamp was placed on top of a box with an opening and each product was placed in the box on a horizontal plane. We ensured the UV index measured by the the reference radiometer was above 1.5 UVI because many radiometers have a resolution of 1 UVI. The experiments were performed at a room temperature of 75°F and humidity of 30%. We repeated the same experiments after changing the source to a *NatureBright SunTouch Plus Lamp*,[40] which emits a sun-like visible spectrum at 10,000 lux. Results are shown in Table III.

We next measured the real world accuracy of these radiometers by taking measurements outdoors in sunlight. The data was acquired in New York, NY and North Miami, FL under open skies on January 25 and February 12-14, 2017 respectively. A variety of cloud cover conditions were captured, ranging from clear skies to overcast. Measurements were also performed at different times of the day to cover a wide variety of solar zenith angles. Wearable UV radiometers are not constrained to be worn horizontal, unlike weather measurement equipment. Hence, measurements were taken in both horizontal and vertical orientations. The fixture for performing measurements in sunlight is shown in Figure 3. To ensure that all wearables could be oriented both horizontally and vertically and to stabilize against weather, we assembled a fixture made of 3-D printed ABS plastic parts and acrylic sheets. Each individual sensor was affixed to this in such a way that its UV detector was horizontal on the surface. Every 15 minutes, measurements were taken in both orientations. Vertical measurements were taken alternately facing north, south, east or west. In total, 162 measurements were made for each sensor, covering a UV Index range of 0 to 8.

Figure 3: Measurement fixture under open skies in New York, NY

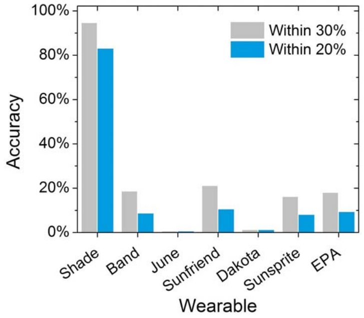

Figure 4: Real-world accuracy of wearable sensors. The X1-4 UVE radiometer was used as the reference

C. *Results*

Results show that there is wide divergence between various solutions in terms of sensitivity, accuracy and resolution. Figure 4 shows the results of the real-word accuracy study. We display two accuracy metrics for comparing between the devices - the percentage of samples within 30% of the reference, and the percentage of samples within 20%. These metrics are similar to those used to document blood glucose monitor accuracy.[41] Results show that the Shade radiometer outperformed others in accuracy by a significant margin. Over 80% of of its measurements were accurate to within 20% (of the reference radiometer). The MS Band, which is perhaps the most well-known UV radiometer, had only 8% of its measurements within 20%. This was comparable to the accuracy of the EPA UV Index app. The Shade radiometer was also the most sensitive, with a resolution of 0.01 (Table II), and measured both UVA and UVB, (Table III) the only one of the commercially available radiometers to do so.

V. CONCLUSION

In the era of wearables, the popularity of personal UV measurement is rising. The design of wearable UV radiometers and dosimeters creates unique challenges for measurements, based on spectral response mismatch and a constantly changing solar spectrum. In this paper, we proposed several metrics for comparisons between wearable UV radiometers. Evaluations of commercially available UV radiometers on the basis of these metrics demonstrated that Shade is the most accurate and sensitive solution. Interestingly the performance of other commercially available wearable UV index radiometers is similar to the performance of zipcode-level hourly forecasts of the UVI.

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