Zoo Biology 23:355–363 (2004)

A Comparison of Responses by Three Broadband Radiometers to Different Ultraviolet-B Sources

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Three types of broadband ultraviolet-B (UVB) radiometers were shown to display different irradiances from the same light source. Also, natural light and different lamp types were shown to have different vitamin D–synthesizing potential. Equations relating the irradiance readings from UVB radiometers from Gigahertz-Optik Inc., UVP Inc., and Spectronics Corp. to in vitro vitamin D–synthesizing potential are reported for four UVB sources. Zoo Biol 23:355–363, 2004.

Key words: radiometers; UVB sources; vitamin D

INTRODUCTION

An article by Joseph Laszlo [1969] dealing with light and ultraviolet radiation (UVR) signaled the beginning of an increasing interest in this subject by zoo biologists, especially herpetologists and herpetoculturists. With the role of zoos expanding into the realm of long-term captive care and reproduction, often associated with the growing interest in conservation, various pathologies and their patterns of emergence have been increasingly recognized. Prominent among these problems has been nutritional metabolic bone disease or nutritional secondary hyperparathyroidism associated with an insufficiency of dietary calcium and/or inadequate vitamin D. It had been well established that rickets in humans was often

Grant sponsor: TCU Research and Creative Activities Fund.

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Received for publication October 3, 2003; Accepted December 15, 2003.

DOI 10.1002/zoo.20014
Published online in Wiley InterScience (www.interscience.wiley.com).

related to inadequate exposure to ultraviolet-B (UVB, 290–315 nm) radiation (reviewed in Holick [1999]). A review of the literature revealed comparatively few studies of light and UVR effects on exotic species, especially reptiles [Gehrmann, 1994]. Studies with other species were warranted and these required the quantification of UVB radiation from natural light or lamps.

While light quality from various lamps as described by spectral power distributions (SPD), color temperatures, and color-rendering indices were readily available from manufacturers, the quantity of radiation as irradiance at various wavelengths was difficult to obtain, especially for UVR. Accordingly, Gehrmann [1987] described UVR irradiances and visible light illuminances for a variety of lamps used by zoos at that time.

The measurement of UVR, especially UVB, presents a number of problems. The type of meter that most accurately records the irradiance from a source is the spectroradiometer, which records values at 1 or 2 nm intervals. However, these radiometers are expensive and relatively cumbersome to work with. Broadband radiometers, which measure the total irradiance within a band, for example the UVB spectrum (290–315 nm), are less expensive and are conveniently portable. However, they have several potential drawbacks. To measure the relatively low irradiances encountered for some lamps commonly used in husbandry, a resolution down to one $\mu W/cm^2$ is essential. The currently available Model DMX from Spectronics Corp. (Westbury, NY), has a resolution of 10 $\mu W/cm^2$ and may not be able to adequately differentiate among irradiance levels from low wattage lamps. The older model (DM-300N), which did measure at the desired resolution, is no longer available, but literature reporting baseline data using this meter exist [Gehrmann, 1987; Ferguson et al., 2002, 2003]. Most broadband radiometers tend to underestimate the actual irradiance within a band because they progressively undervalue the irradiances toward the two boundaries of the band. This is related to the nature of the bypass filter, which has a Gaussian-type spectral sensitivity. For example, the irradiance at 312 nm near the upper boundary of UVB may be measured at only one-half of the actual value. Another problem encountered when measuring irradiances from lamps that emit visible light and some amount of infrared radiation is the fact that some of this radiation will be transmitted through the sensor filter and will be erroneously added to the actual UVB irradiance value. This is a significant consideration when working with sunlight or high-intensity output lamps such as the Westron self-ballasted mercury lamp (Westron Corporation, Oceanside, NY).

Gigahertz-Optik, Inc. (Newburyport, MA) has designed a broadband radiometer that largely reduces these and other deficiencies. The sensor is customizable for a particular type of lamp or natural light by a program that evaluates the spectral power distribution and makes the appropriate correction. The result is a reading that is a close approximation to that which would be measured with a spectroradiometer [Angelo, 2002; Gugg-Helminger, 2002]. In addition, separate sensors for measuring UVA (315–400 nm) and visible light (400–700 nm) are also available, and can be used with the same Gigahertz-Optik, Inc. P9710 Optometer processing unit.

When an irradiance reading has been obtained, the question arises: What does it mean? In working with UVB, a primary focus is the relationship between irradiance and vitamin D–synthesizing potential. The action spectrum relating vitamin D synthesis to wavelength shows that some wavelengths within the UVB band are better able to drive vitamin D production from the precursor, 7-dehydrocholesterol (7-DHC) or provitamin D_3, with the peak around 295 nm [MacLaughlin et al., 1982]. So it is possible for two types of lamps positioned so that their UVB irradiances are the same to exhibit different vitamin D–synthesizing capability if one has a greater concentration of energy close to 295 nm. If meter irradiances can be related to an independent measure of vitamin D–synthesizing ability, they become more meaningful. An elegant system for doing this, the in vitro model, was developed in the Vitamin D, Skin and Bone Laboratory at Boston University Medical Center. Boron-silicate ampules containing 7-DHC, the precursor of vitamin D, were subjected to a UVB source. Vitamin D photoproducts were analyzed by high performance liquid chromatography (HPLC) and the percentage synthesized was calculated [Webb et al., 1988]. This system can be used to compare the vitamin D–synthesizing ability of different artificial and natural light sources.

The purpose of this work is to relate irradiance readings from a Gigahertz-Optik UVB meter (Newburyport, MA), a UVX UVB meter (UVP, Inc., Upland, CA), and a Spectroline DM-300N UVB meter (Spectronics Corp., Westbury, NY) to vitamin D–synthesizing ability, as measured by in vitro ampules, for the four UVB sources (natural light and three different lamps).

MATERIALS AND METHODS

UVB irradiances of natural light at different hours of the day and from three types of lamps at different distances were recorded. Irradiances were measured sequentially at the same position by three broadband radiometers: model UVX with a UVB sensor, model Spectroline DM-300N, and a Gigahertz-Optik meter with a UVB detector. The lamps represented three types commonly used in animal husbandry, namely a full-spectrum fluorescent lamp (Reptisun 5.0, Zoomed Lab., Inc., San Luis Obispo, CA), a blacklight fluorescent lamp (Sylvania 350 BL, Osram Sylvania, Inc., Danvers, MA), and a Westron self-ballasted mercury spotlight (Westron Corporation, Oceanside, NY) designed for use in reptile husbandry. Meter sensors were placed at different distances directly beneath the midpoint of the fluorescent tubes and at the center of the light cone produced by the Westron reflector lamp. All measurements of natural light were made with the sensor facing upward at a solar elevation of 90°. Immediately after the irradiances were recorded, an ampule was placed at that position to measure the vitamin D–synthesizing potential of the source.

Boron-silicate ampules containing 50 μg 7-DHC dissolved in 1 ml ethanol were exposed at various distances from the lamps for 2 hr. Ampules were exposed to natural light at different times during the day for 30 min. All ampules were positioned to receive the maximum radiation available. The ampule contents were analyzed by HPLC for 7-DHC and for UVB-induced photoproducts (previtamin D_3, tachysterol, lumisterol); vitamin D_3 and the percent of photoproducts and vitamin D_3 synthesized were calculated. At the time of analysis, 100 μl aliquots were removed from the ampules, transferred into culture tubes, and dried under nitrogen. A total of 200 μl of 8% ethyl acetate in hexane was used to redissolve each sample. Samples were analyzed with a Waters 501 HPLC pump and a 490E multiwave detector set at 260 nm, operated by a Millennium 2010 Chromatography Manager Program (Waters Chromatography Div., Milford, MA). The column was Econosphere silica, 5 μm, 250 $\times$ 4.6 mm (Alltech Associates, Inc., Deerfield, IL). The mobile phase was 8% ethyl acetate in hexane with a flow rate of 1.8 ml/min. Three replicates per ampule were analyzed and the mean value of the percentage of photoproducts synthesized was calculated. The values from the same set of ampules for a given UV source were related to the irradiance readings from the three meter types.

Regression equations were calculated using a Statdisk program (Password, Inc., Reading, MA).

RESULTS

Table 1 relates irradiances for natural light recorded at different times of the day with a UVB radiometer (Gigahertz-Optik Inc., Newburyport, MA) to the ampule dose and the percent of photoproducts synthesized (Note: Dose [mJ/cm^2] = (irra-(irradiance [μW/cm^2] × time [seconds]) ÷ 1,000). Table 2 shows irradiances recorded at different distances with a Gigahertz-Optik, Inc. radiometer, as well as the ampule dose over a 2-hr period and the percent of photoproduct formed as measured for each of the three lamps. Table 3 indicates the irradiances for natural light recorded at different times of the day with a UVX UVB radiometer (UVP, Inc., Upland, CA), and the ampule dose and the percent of photoproducts formed. Table 4 shows the irradiances recorded at different distances with a UVX UVB radiometer, as well as the dose received by the ampules over a 2-hr period and the percent of photoproduct formed as measured for each of the three lamps. Table 5 relates irradiances for natural light at different times during the day recorded with a Spectroline DM-300N UVB radiometer (Spectronics Corp., Westbury, NY) to the ampule dose and the percent of photoproducts synthesized. Table 6 shows irradiances recorded at different distances with a Spectroline DM-300N meter, as well as the ampule dose over a 2-hr period and the percent of photoproduct formed as measured for each of the three lamps. Regression equations relating dose to percent of photoproduct formed are presented in Tables 1–6. Table 7 shows that a given dose of UVB can result in different amounts of photoproduct synthesized, clearly demonstrating that different UVB sources may have different vitamin D–synthesizing potential.

DISCUSSION

Broadband UVB radiometers may be used in animal husbandry in various ways. For example, they may determine the relative output of an unknown brand of

TABLE 1. Various characteristics of sunlight*

Time (CST)	Mean irradiance (μW/cm^2)	Irradiance ranges	Dose (mJ/cm^2)	% Product synthesized[a]
Natural light (21 September 2002; Boyd, TX)				
1250–1320	130	131–130	234	4.90
1450–1520	104	113–95	187	4.19
1050–1120	81	74–88	146	2.21
1645–1715	36	46–26	65	0.85

*Irradiances were measured with a Gigahertz-Optik, Inc. radiometer (Newburyport, MA). The regression equation relating the % of photoproducts formed to the radiation dose is presented. Ampules used to assess vitamin D–synthesizing potential of natural light were exposed for 30 min.

[a]% Prod = 0.025 (Dose)–0.944(r^2 = 0.953).

TABLE 2. Various characteristics of three UVB emitters*

Lamp Distance (cm)	Irradiance ($\mu W/cm^2$)	Dose (mJ/cm^2)	% Product synthesized
Reptisun 5.0[a]			
7	31.2	225	2.82
15	17.0	122	0.99
24	11.4	82	0.64
30	8.3	60	0.49
38	6.3	45	0.39
Blacklight 350 BL[b]			
10	15.6	112	4.38
15	10.5	76	2.40
25	5.7	42	1.18
38	3.4	24	0.96
51	2.0	14	0.63
Westron 160 W spot[c]			
33 (45°C)	110.0	792	4.34
41 (35°C)	56.2	403	2.98
92 (29°C)	21.0	151	1.11
131 (26°C)	9.6	69	0.67
180 (23°C)	5.0	36	0.28

*Irradiances were measured with a Gigahertz-Optik, Inc. radiometer (Newburyport, MA). The regression equation relating the % of photoproducts formed to the radiation dose is presented for each source. Ampules used to assess vitamin D–synthesizing potential of the UVB source were exposed for 2 h. The temperatures adjacent to the distances listed for the Westron 160 W spot were those measured after 2 h.
[a]%Prod = 0.014 (Dose)–0.398($r^2 = 0.966$).
[b]%Prod = 0.037 (Dose)–0.092($r^2 = 0.962$).
[c]%Prod = 0.005 (Dose) + 0.490($r^2 = 0.970$).

TABLE 3. Various characteristics of sunlight*

Time (CST)	Mean irradiance ($\mu W/cm^2$)	Irradiance ranges	Dose (mJ/cm^2)	% Product synthesized[a]
Natural light (21 September 2002; Boyd, TX)				
1250–1320	1078	1123–1032	1940	4.90
1450–1520	928	984–872	1670	4.19
1050–1120	750	706–794	1350	2.21
1645–1715	414	475–352	745	0.85

*Irradiances were measured with a UVX radiometer (UVP Inc, Upland, CA 91786). The regression equation relating the % of photoproducts formed to the radiation dose is presented. Ampules used to assess vitamin D-synthesizing potential of natural light were exposed for 30 min.
[a]%Prod = 0.0035 (Dose)–1.981($r^2 = 0.957$).

lamp compared to a known type within the same general category. However, it is essential that the conditions under which measurements are made are the same for all of the lamps measured. Furthermore, comparing a full-spectrum fluorescent to a Westron mercury lamp is subject to a large error because of differences in response

TABLE 4. Various characteristics of three UVB emitters*

Lamp Distance (cm)	Irradiance (μW/cm²)	Dose (mJ/cm²)	% Product synthesized
Reptisun 5.0[a]			
7	251	1807	2.82
15	133	958	0.99
24	86	619	0.64
30	60	432	0.49
38	43	310	0.39
Blacklight 350 BL[b]			
10	253	1822	4.38
15	168	1210	2.40
25	88	634	1.18
38	50	360	0.96
51	27	194	0.63
Westron 160 W spot[c]			
33 (45°C)	764	5501	4.34
41 (35°C)	380	2736	2.98
92 (29°C)	129	929	1.11
131 (26°C)	47	338	0.67
180 (23°C)	14	101	0.28

*Irradiances were measured with a UVX radiometer (UVP Inc., Upland, CA). The regression equation relating the % of photoproducts formed to the radiation dose is presented for each source. Ampules used to assess vitamin D–synthesizing potential of the UVB source were exposed for 2 h. The temperatures adjacent to the distances listed for the Westron 160 W spot were those measured after 2 h.

[a] $\%Prod = 0.0016\ (Dose) – 0.291 (r^2 = 0.963)$.

[b] $\%Prod = 0.0023\ (Dose) + 0.006 (r^2 = 0.968)$.

[c] $\%Prod = 0.0008\ (Dose) + 0.427 (r^2 = 0.971)$.

TABLE 5. Various characteristics of sunlight*

Time (CST)	Mean irradiance (μW/cm²)	Irradiance ranges	Dose (mJ/cm²)	% Product synthesized[a]
Natural light (21 September 2002; Boyd, TX)				
1250–1320	230	231–229	414	4.90
1450–1520	183	199–166	329	4.19
1050–1120	142	129–154	256	2.21
1645–1715	61	79–43	110	0.85

*Irradiances were measured with a Spectroline DM-300N radiometer (Spectronics Corp., Westbury, NY). The regression equation relating the % of photoproducts formed to the radiation dose is presented. Ampules used to assess vitamin D-synthesizing potential of natural light were exposed for 30 min.

[a] $\%Prod = 0.0140\ (Dose) – 0.847 (r^2 = 0.952)$.

to extraneous wavelengths and other factors, as described in the Introduction. Radiometers may be used to measure the transmission of UVB through various materials such as acrylics or wire mesh, as well as to monitor power depreciation over time. Radiometer measurements are essential in studies attempting to determine the effects of UVB on vitamin D synthesis or other processes.

TABLE 6. Various characteristics of three UVB emitters*

Lamp distance (cm)	Irradiance (μW/cm^2)	Dose (mJ/cm^2)	% Product synthesized
Reptisun 5.0[a]			
7	59	425	2.82
15	31	223	0.99
24	20	144	0.64
30	14	101	0.49
38	10	72	0.39
Blacklight 350 BL[b]			
10	53	382	4.38
15	35	252	2.40
25	19	137	1.18
38	11	79	0.96
51	6	43	0.63
Westron 160 W spot[c]			
33 (45°C)	426	3067	4.34
41 (35°C)	211	1519	2.98
92 (29°C)	70	504	1.11
131 (26°C)	25	180	0.67
180 (23°C)	6	43	0.28

*Irradiances were measured with a Spectroline DM-300N radiometer (Spectronics Corp., Westbury, NY). The regression equation relating the % of photoproducts formed to the radiation dose is presented for each source. Ampules used to assess vitamin D–synthesizing potential of the UVB source were exposed for 2 h. The temperatures adjacent to the distances listed for the Westron 160 W spot were those measured after 2 h.
[a]%Prod = 0.0070 (Dose)–0.282($r^2 = 0.966$).
[b]%Prod = 0.0109 (Dose) + 0.036($r^2 = 0.969$).
[c]%Prod = 0.0013 (Dose) + 0.445($r^2 = 0.971$).

TABLE 7. The % of photoproducts predicted to be synthesized at a dose of 50 mJ/cm^2 for four UVB emitters*

Source	Exposure time (hr)	% Product synthesized
Natural Light at 149,476,000 km	0.5	0.31
Reptisun 5.0 at 33 cm	2.0	0.30
Blacklight 350 BL at 29 cm	2.0	1.76
Westron 160 W spot at 136 cm	2.0	0.56

*Values were calculated from the equations in Tables 1 and 2.

Further studies of the relationship of the in vitro vitamin D–synthesizing potential of a UVB source to organismic processes, such as growth and reproduction in exotic species, are called for and may have practical applications. For example, Ferguson et al. [2002] reported that UVB irradiation resulting in 0.52 to 1.32% ampule conversion to photoproducts after a 2-hr exposure resulted in viable eggs in the panther chameleon. This occurred when the exposure to the source continued for 12 hr per day and the daily intake of dietary vitamin D was negligible; conversion percentages below or greater than these values significantly reduced hatchability.

With this known relationship between ampule conversion and hatching success, we can use data from Tables 2, 4, or 6 of this study to make recommendations for UVB source placement to the keeper who wishes to have successful reproduction in panther chameleons. For example, if all other husbandry requirements are met, a Reptisun 5.0 illuminated 15–30 cm from a female 12 hr/day should result in successful hatching of her eggs. Likewise, a Sylvania Blacklight 350 BL illuminated 25–51 cm from a female 12 hr/day should result in success. Finally, a Westron 160-W spot illuminated 92–131 cm from a female 12 hr/day will provide sufficient heat to maintain a female near optimum temperature (31°C) and sufficient UVB to result in successful hatching of her eggs. If the lamp were positioned a little closer, she could reach her preferred temperature and would probably be able to regulate her exposure to UVB by continually adjusting her position along the UVB/visible light gradient to avoid overexposure to UVB [Ferguson et al., 2003].

CONCLUSIONS

1. Different broadband UVB radiometers respond differently to the same light source, resulting in different readings.

2. The same UVB irradiance readings from different light sources do not necessarily indicate the same vitamin D–synthesizing potential.

3. The vitamin D–synthesizing potential of natural light and several lamps can be calculated from measured irradiances for each of the types of meters by using the appropriate equations.

4. The lower irradiance reading for a given light source measured with a Gigahertz-Optik radiometer compared to the other two meters reflects its superior ability to remove extraneous wavelengths, such as infrared, from the actual UVB value.

5. Using known relationships between ampule conversion and organic processes such as hatching success, one can predict optimal positioning of a UVB source to achieve that process.

ACKNOWLEDGMENTS

We thank Holly Garner for assistance in collecting data, and Helena R. Gehrmann for her help in manuscript preparation. David A. Roberts, proprietor of True Chameleons, and Eugene Roberts provided access to a rural outdoors site for the sunlight measurements. Funding for the project was from the TCU Research and Creative Activities Fund to GWF.

REFERENCES

Angelo R. 2002. UVR measurement errors sources: spectral response of filtered broadband detectors. In: Holick MF, editor. Biologic effects of light 2001. Boston: Kluwer. p 57–63.

Ferguson GW, Gehrmann WH, Chen TC, Dierenfeld ES, Holick MF. 2002. Effects of artificial ultraviolet light exposure on reproductive success of the female panther chameleon (*Furcifer pardalis*) in captivity. Zoo Biol 21:525–37.

Ferguson GW, Gehrmann WH, Karsten KB, Hammack SH, McRae M, Chen TC, Lung NP, Holick MF. 2003. Do panther chameleons bask to regulate endogenous vitamin D_3 production? Physiol Biochem Zool 76:52–9.

Gehrmann WH. 1987. Ultraviolet irradiances of various lamps used in animal husbandry. Zoo Biol 6:117–27.

Gehrmann WH. 1994. Light requirements of captive amphibians and reptiles. In: Murphy J, Adler K, Collins JT, editors. Captive management and conservation of reptiles and amphibians. Ithaca, NY: Society for the Study of Amphibians and Reptiles Contributions to Herpetology. Vol XI. p 53–9.

Gugg-Helminger A. 2002. Detectors for UV measurement- state of the art and new developments. In: Holick MF, editor. Biologic effects of light 2001. Boston: Kluwer. p 19–32.

Holick MF. 1999. Evolution, biologic functions, and recommended dietary allowances for vitamin D. In: Holick MF, editor. Vitamin D: molecular biology, physiology, and clinical applications. Totowa, NJ: Humana Press. p 1–16.

Laszlo J. 1969. Observations on two new artificial lights for reptile displays. Int Zoo Yearb 9:12–3.

MacLaughlin JA, Anderson RR, Holick MF. 1982. Spectral character of sunlight modulates photosynthesis of previtamin D_3 and its photoisomers in human skin. Science 216:1001–3.

Webb AR, Kline L, Holick MF. 1988. Influence of season and latitude on the cutaneous synthesis of vitamin D_3: exposure to winter sunlight in Boston and Edmonton will not promote vitamin D_3 synthesis in human skin. J Clin Endocrinol Metab 67:373–8.