RESEARCH ARTICLE

Quantifying the Vitamin D_3 Synthesizing Potential of UVB Lamps at Specific Distances Over Time

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The purpose of this study was to quantify the ultraviolet B (UVB) output and in vitro previtamin D_3 synthesis over time from various artificial light sources. Three incandescent lamps, T-Rex Active UVHeat 160 watt spot, T-Rex Active UVHeat 160 watt flood, and ZooMed PowerSun 160 watt flood, and two 1.2 m fluorescent lamps, Sylvania Blacklight 350 BL and ZooMed Reptisun 5.0, were studied. Total UVB irradiance and concentration of previtamin D synthesized using an in vitro ampoule model were quantified initially and at monthly intervals for 1 year. Incandescent lamps were measured at distances of 0.9 and 1.5 m while fluorescent lamps were measured at distances of 30.5 and 45.7 cm at the lamp's center, using both the radiometer and ampoules. Fluorescent lamp irradiance was also measured at the lamp's ends. Data were analyzed as a repeated measures split-plot in time using SAS with all mean differences determined using Least Squares Means. Incandescent lamp irradiance differences were seen at various distances. The UVHeat lamps had consistently higher previtamin D_3 production and irradiance readings compared with the PowerSun lamp. Reptisun 5.0 was consistently higher in UVB irradiance over Sylvania BL 350 at both 30.5 and 45.7 cm. However, there were no differences when comparing conversion of 7-dehydrocholesterol to previtamin D_3. Irradiance differences were detected between the centers and ends of the fluorescent lamps. Until UVB requirements

Grant sponsor: Daniel F. and Ada L. Rice Foundation.

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Received 16 July 2009; Revised 20 May 2010; Accepted 4 August 2010

DOI 10.1002/zoo.20345
Published online in Wiley Online Library (wileyonlinelibrary.com).

for vitamin D_3 synthesis in animals are determined, it is impossible to state that one light is superior to another. Zoo Biol 29:1–12, 2010.

Keywords: UVB; metabolic bone disease; fluorescent lamps; mercury vapor lamps

INTRODUCTION

The term ‘‘metabolic bone disease’’ encompasses a variety of bone-related diseases, including rickets, osteomalacia, osteopenia, and osteoporosis, all of which are associated with a weakening of bone structure. Metabolic bone disease is considered a serious health problem among certain species of captive reptiles [Allen and Oftedal, 1996; Allen et al., 1994, 1996, 1999; Adkins et al., 2003; Ferguson et al., 1996; Fowler, 1986; Kenny, 1998; Laing et al., 2001; Ullrey and Bernard, 1999]. The occurrence of metabolic bone diseases can be a result of vitamin D deficiency and poor intestinal calcium absorption. If vitamin D deficiency is a chronic problem, the body begins mobilizing calcium stores from bone to satisfy the requirement for circulating plasma calcium concentrations.

Vitamin D can be obtained through the diet or synthesized in the skin when exposed to wavelengths of ultraviolet B (UVB) radiation from 290 to 315 nm [Holick, 1999; Webb and Holick, 1988]. The 7-dehydrocholesterol in the skin is converted to previtamin D_3, which then isomerizes by a membrane-dependant process to vitamin D_3 [Tanaka et al., 1971]. Some reptiles and New World primates exhibit signs of vitamin D deficiency even when nutritionally complete feeds are supplemented with vitamin D_3 at levels sufficient for other species [Bernard, 1995; Richman et al., 1995; Ferguson et al., 1996; Ullrey and Bernard, 1999]. Giving animals access to direct, unfiltered, and unobstructed sunlight with accessible shade and water is the best way to ensure the animal is receiving the UVB exposure necessary to produce vitamin D_3. Unfortunately, sunlight received through glass will contain little, if any, UVB radiation because UVB rays are absorbed by glass and most acrylics [Ullrey and Bernard, 1999].

Exposing animals to direct sunlight is not always possible, especially in a zoological setting where animals are often housed only indoors. For this reason, it is important to find a way to provide the animal with exposure to UVB radiation in the band width (290–315 nm) documented to synthesize vitamin D_3 [Holick, 1999; Webb and Holick, 1988]. Some lamps, which are specifically marketed for herpetologists, are manufactured to produce UVB irradiance for captive animals. Two scientific studies were conducted testing UVB lamps available in the United States several years ago, but most of those lamps were test lamps or are no longer manufactured [Bernard, 1995; Gehrmann, 1987]. Anecdotal information is also available on the Internet or in nonpeer reviewed literature. The purpose of this study was to quantify the vitamin D_3 synthesizing potential and UVB irradiance from the selected lamps over time.

METHODS

This study evaluated five different lamps, typically used by zoos, claiming to emit UVB. The three mercury vapor lamps included T-Rex Active UV-Heat 160 watt spot (Westron Corporation, Oceanside, NY), T-Rex Active UV-Heat 160 watt flood

(Westron Corporation), and PowerSun 160 watt flood (ZooMed Laboratories, Inc., San Luis Obispo, CA). The two linear fluorescent lamps were Reptisun 5.0 (ZooMed Laboratories, Inc.) and Sylvania Blacklight 350 BL (Osram Sylvania, Inc., Danvers, MA). All lamps were tested in replicates of three and checked daily for visual illumination. Lamps remained in the study as long as they emitted light.

The single lamp, F40 ballast, fluorescent fixtures had white reflectors and held 1.2 m lamps. Mercury vapor fixtures had 120 V and 250 W capacities and were equipped with a porcelain socket and a 27 cm bell shade.

Using timers, lamps were illuminated for 12 hr each day to mimic their use by herpetologists. The timers were checked monthly for accuracy. The light fixtures were separated by long, black sheets of plastic to avoid cross-over irradiance at points of measurement. High and low temperatures and humidity readings in the room were recorded daily. Room temperatures ranged from 22.7 to 30.6°C with an average high of 27.4°C and average low of 25.9°C. Humidity ranged from 30 to 74% and averaged 49.5%.

Irradiance of UVB was quantified on the first day (month 0) and then every 30–31 days using a UVB radiometer (Solarmeter® 6.2, Solartech Inc., Harrison Township, MI) for a period of 12 months. The lamps were illuminated for at least 2 hr before measuring UVB irradiance, recorded in $\mu W/cm^2$, at distances of 0.9 and 1.5 m for the mercury vapor lamps and 30.5 and 45.7 cm from the fluorescent lamps. For fluorescent lamps, radiometer readings at 30.5 and 45.7 cm were taken at lamp midpoint and 15.2 cm in from each lamp end. These ends were identified as "cord" (i.e., being the end near the light fixture electrical cord) or "other." These distances were selected based on manufacturers' recommendations for use, data obtained from a study evaluating a radiometer's reading of several artificial light sources [Gehrmann et al., 2004], and how the lamps are typically used in a zoological setting.

The irradiance fluctuated at various points beneath the mercury vapor lamps, though distance remained consistent. The highest reading for the mercury vapor lamps, which was not always directly under the lamp's center, was recorded.

UVB irradiance was also quantified using an in vitro ampoule model immediately after radiometer readings were recorded. The boron-silicate ampoules contained 35 μg of 7-dehydrocholesterol (50 μg/ml; Salsbury Laboratories Inc., Charles City, IA) in 0.7 ml of ethanol sealed under argon gas as previously described [Webb et al., 1988]. The 7-dehydrocholesterol is converted to previtamin D_3 upon exposure to the vitamin D synthesizing bands of UVB. The ampoule, placed at a 10–15° angle in a black Petri dish placed on ice, was positioned under the point of highest UVB irradiance (measured with the radiometer) for each lamp at each of the two distances. Each ampoule placed at the closer distance was paired with a foil-wrapped control ampoule. After 1 hr of exposure to the lamps, the ampoules were removed, labeled, wrapped in foil, and placed in −80°C freezer for temporary storage until shipped to the Vitamin D Research Laboratory at Boston University.

Aliquots of 200 μl were removed from each ampoule, transferred into glass test tubes, and dried under a stream of nitrogen gas. Two hundred microliters of 0.6% isopropyl alcohol in *n*-hexane were added to each test tube to redissolve the samples. The redissolved samples were then analyzed by high performance liquid chromatography (Waters 501, Milford, MA) equipped with a UV detector for previtamin D_3 and vitamin D_3. The Econosphere silica column dimensions were 5 μm, 250 × 4.6 mm (Alltech Associate Inc., Deerfield, IL). The mobile phase consisted of 0.6% isopropyl alcohol in *n*-hexane with a flow rate of 1.8 ml/min.

Separate statistical analyses were performed on the different lamp types. The data were analyzed as a repeated measures split-plot in time [Littell et al., 1998]. All differences were determined using Least Squares Means data ($P<0.05$) and all data analyses were performed using the 9.1 SAS package [SAS Inst. Inc., 2004].

RESULTS

Incandescent Lamps

Some mercury vapor lamps turned off by themselves, presumably owing to lamp temperature, but resumed illumination within minutes of shutting off. These lamps remained in the study because they would likely remain in use by the animal care staff. Some lamps turned a dark shade of yellow, but were still illuminated. When this occurred there was no measurable UVB irradiance. The black plastic sheets did not reflect UVB as was determined using the radiometer. Effects and reflectivity of the fixtures and shades were not determined as they are used in typical captive herpetological settings.

The three PowerSun lamps failed before months 4, 7, and 10, respectively. Two of the UVHeat Spot lamps failed just before month 10 and one of the UVHeat Flood lamps failed during the first month. One UVHeat Spot and two UVHeat Flood lamps remained through the entire study.

Table 1 reports radiometer readings for the incandescent lamps. Within the PowerSun lamp, there were no statistical differences between distances or over time. The PowerSun emitted less irradiance than the UVHeat Flood and UVHeat Spot irradiance at 0.9 m for the entire study ($P<0.05$).

Within UVHeat Flood, irradiance was greater at 0.9 m compared with 1.5 m until month 9 ($P<0.05$). The UVHeat Flood irradiance at 0.9 and 1.5 m diminished 94 and 91%, respectively, by the end of the study. The UVHeat Spot irradiance at 0.9 and 1.5 m diminished 79 and 78%, respectively, by the end of the study. After month 9 at 0.9 m, the UVHeat Spot was 2–7 times higher in irradiance ($P<0.05$) than the UVHeat Flood. At 1.5 m, there were no differences between UVHeat Flood and UVHeat Spot for the entire 12 months ($P<0.05$).

Table 2 lists ampoule conversion rates for the incandescent lamps. Ampoules for month 9 were lost in transit and were not included in the results. Again, within PowerSun there were no statistical differences between distances or over time with one exception—the 1.5 m reading at 7th month was lower than all prior readings at that distance ($P<0.05$).

For UVHeat Flood at 0.9 m, a negative reading was obtained at month 9 and the data were not used. Within UVHeat Flood ampoule, conversion was consistently higher at 0.9 m compared with 1.5 m until month 7 ($P<0.05$). UVHeat Spot conversion was higher at 0.9 m compared with 1.5 m for month 0, 1, 3, and 6 ($P<0.05$). For both UVHeat Flood and Spot lamps at 0.9 m the initial conversion rate was the same, but then UVHeat Flood had a consistently higher conversion until month 10 ($P<0.05$).

Fluorescent Lamps

Reptisun 5.0 was consistently higher in UVB irradiance than Sylvania BL 350 at both 30.5 and 45.7 cm distances (Table 3). Sylvania Blacklight 350BL promoted approximately 1.5 $\times$ the conversion of the Reptisun lamp between 3 and 7 months;

TABLE 1. Solarmeter® 6.2 Readings (μW/cm²) From Incandescent Lamps at Different Distances

Month	Powersun 0.9 m	Powersun 1.5 m	UVHeat flood 0.9 m	UVHeat flood 1.5 m	UVHeat spot 0.9 m	UVHeat spot 1.5 m
0	$7.0 \pm 3.42^{a,1}$	3.0 ± 3.42^{1}	$50.7 \pm 3.59^{a,2}$	$18.3 \pm 3.59^{a,3}$	$104.7 \pm 3.59^{a,2}$	$39.7 \pm 3.59^{a,3}$
1	$4.0 \pm 3.42^{b,1,2}$	1.7 ± 3.42^{2}	$33.7 \pm 3.77^{b,3}$	$13.7 \pm 3.77^{b,1,4}$	$38.0 \pm 3.59^{b,3}$	$14.7 \pm 3.59^{b,4}$
2	$3.3 \pm 3.42^{b,1,2}$	1.7 ± 3.42^{2}	$31.7 \pm 3.77^{b,3}$	$12.2 \pm 3.77^{b,c,1,4}$	$31.7 \pm 3.59^{c,3}$	$13.0 \pm 3.59^{b,c,4}$
3	$2.7 \pm 3.42^{b,1,2}$	1.0 ± 3.42^{2}	$27.2 \pm 3.77^{c,3}$	$12.2 \pm 3.77^{b,c,1}$	$31.0 \pm 3.59^{c,d,3}$	$12.0 \pm 3.59^{b,c,d,1}$
4	$3.4 \pm 3.52^{b,1}$	1.6 ± 3.52^{1}	$25.7 \pm 3.77^{c,2}$	$10.2 \pm 3.77^{b,c,d,1}$	$28.0 \pm 3.59^{d,e,2}$	$10.7 \pm 3.59^{c,d,e,1}$
5	$2.4 \pm 3.52^{b,1}$	1.6 ± 3.52^{1}	$23.7 \pm 3.77^{c,d,2}$	$10.2 \pm 3.77^{b,c,d,1}$	$27.0 \pm 3.59^{e,f,2}$	$10.0 \pm 3.59^{c,d,e,1}$
6	$2.4 \pm 3.52^{b,1}$	1.1 ± 3.52^{1}	$21.2 \pm 3.77^{d,e,2}$	$8.7 \pm 3.77^{c,d,e,1}$	$28.3 \pm 3.59^{d,e,f,2}$	$10.7 \pm 3.59^{c,d,e,1}$
7	$1.5 \pm 3.79^{b,1}$	0.7 ± 3.79^{1}	$19.7 \pm 3.77^{d,e,2,3}$	$8.2 \pm 3.77^{c,d,e,f,1}$	$26.7 \pm 3.59^{e,f,g,2}$	$10.3 \pm 3.59^{c,d,e,1,3}$
8	$0.5 \pm 3.79^{b,1}$	0.0 ± 3.79^{1}	$17.2 \pm 3.77^{e,2,3}$	$6.7 \pm 3.77^{d,e,f,g,1}$	$23.0 \pm 3.59^{h,2}$	$8.3 \pm 3.59^{e,1,3}$
9	*	*	$12.7 \pm 3.77^{f,1}$	$5.7 \pm 3.77^{e,f,g,h,1}$	$23.0 \pm 3.59^{h,2}$	$8.3 \pm 3.59^{e,1}$
10	*	*	$10.7 \pm 3.77^{f,1}$	$4.2 \pm 3.77^{f,g,h,1}$	$23.1 \pm 3.99^{f,g,h,2}$	$8.6 \pm 3.99^{c,d,e,1}$
11	*	*	$8.7 \pm 3.77^{f,1}$	$3.7 \pm 3.77^{g,h,1}$	$22.1 \pm 3.99^{g,h,2}$	$7.6 \pm 3.99^{d,e,1}$
12	*	*	$3.2 \pm 3.77^{g,1}$	$1.7 \pm 3.77^{h,1}$	$22.1 \pm 3.99^{g,h,2}$	$8.6 \pm 3.99^{c,d,e,1}$

[a,b,c,d,e,f,g,h]Denotes differences within lamp across months ($P < 0.05$).
[1,2,3,4]Denotes differences across lamps within a month ($P < 0.05$).
*Lamp failed.

TABLE 2. Percent Previtamin D_3 Formed in Incandescent Lamps at Different Distances

Month	Powersun 0.9 m	Powersun 1.5 m	UVHeat flood 0.9 m	UVHeat flood 1.5 m	UVHeat spot 0.9 m	UVHeat spot 1.5 m
0	0.11 ± 0.08^{1}	0.04 ± 0.08^{1}	$1.21 \pm 0.08^{a,2}$	$0.39 \pm 0.08^{a,3}$	$1.40 \pm 0.08^{a,2}$	$0.49 \pm 0.08^{a,3}$
1	$0.08 \pm 0.08^{1,2}$	0.03 ± 0.08^{1}	$0.98 \pm 0.10^{b,3}$	$0.33 \pm 0.10^{a,b,2,4,5}$	$0.47 \pm 0.08^{b,4}$	$0.20 \pm 0.08^{b,1,5}$
2	0.08 ± 0.08^{1}	0.03 ± 0.08^{1}	$1.10 \pm 0.10^{a,b,2}$	$0.44 \pm 0.10^{a,b,3}$	$0.46 \pm 0.08^{b,c,3}$	$0.23 \pm 0.08^{b,1,3}$
3	0.07 ± 0.08^{1}	0.03 ± 0.08^{1}	$1.39 \pm 0.10^{c,2}$	$0.42 \pm 0.10^{a,b,3,5}$	$0.54 \pm 0.08^{b,c,3}$	$0.19 \pm 0.08^{b,1,5}$
4	0.03 ± 0.09^{1}	0.04 ± 0.09^{1}	$1.42 \pm 0.10^{c,2}$	$0.51 \pm 0.10^{a,c,d,3}$	$0.21 \pm 0.08^{d,1}$	$0.13 \pm 0.08^{b,1}$
5	0.05 ± 0.09^{1}	0.03 ± 0.09^{1}	$1.33 \pm 0.10^{a,c,2}$	$0.63 \pm 0.10^{d,3}$	$0.37 \pm 0.08^{b,c,e,f,4}$	$0.19 \pm 0.08^{b,1,4}$
6	0.04 ± 0.09^{1}	0.02 ± 0.09^{1}	$1.26 \pm 0.10^{a,c,2}$	$0.43 \pm 0.10^{a,b,c,3}$	$0.43 \pm 0.08^{b,c,f,3}$	$0.17 \pm 0.08^{b,1}$
7	$0.03 \pm 0.11^{1,2}$	0.003 ± 0.11^{2}	$0.62 \pm 0.10^{d,3}$	$0.39 \pm 0.10^{a,b,c,3,4}$	$0.29 \pm 0.08^{d,e,1,4}$	$0.23 \pm 0.08^{b,1,2,4}$
8	*	*	*	*	*	*
9	**	**	*	$0.12 \pm 0.10^{e,1,2}$	$0.24 \pm 0.08^{d,e,2}$	$0.10 \pm 0.08^{b,1,2}$
10	**	**	$0.38 \pm 0.10^{f,1}$	$0.08 \pm 0.10^{e,2}$	$0.26 \pm 0.11^{c,d,e,f,1,2}$	$0.12 \pm 0.11^{b,1,2}$
11	**	**	$0.20 \pm 0.10^{g,1}$	$0.03 \pm 0.10^{e,1}$	$0.25 \pm 0.11^{d,e,f,1}$	$0.12 \pm 0.11^{b,1}$
12	**	**	$0.24 \pm 0.10^{f,g,1}$	$0.09 \pm 0.10^{e,1}$	$0.38 \pm 0.11^{b,c,d,e,f,1}$	$0.16 \pm 0.11^{b,1}$

^{a,b,c,d,e,f,g}Denotes differences within lamp across months ($P < 0.05$).
^{1,2,3,4}Denotes differences across lamps within a month ($P < 0.05$).
*Ampoules were lost.
**Lamp failed.

TABLE 3. Solarmeter® 6.2 Readings ($\mu W/cm^2$) From Linear Fluorescent Lamps at Different Distances

Month	Blacklight 30.5 cm	Blacklight 45.7 cm	Reptisun 5.0 30.5 cm	Reptisun 5.0 45.7 cm
0	$9.0^{a,1}$	$6.0^{a,2}$	$16.3^{a,3}$	$10.3^{a,1}$
1	$5.1^{b,1}$	$4.0^{b,2}$	$12.0^{b,c,d,3}$	$8.7^{b,4}$
2	$6.0^{b,c,1}$	$4.0^{b,2}$	$13.3^{b,3}$	$8.7^{b,4}$
3	$8.0^{a,d,1}$	$5.3^{a,b,c,2}$	$13.3^{b,3}$	$8.3^{b,c,1}$
4	$8.0^{a,d,1}$	$5.3^{a,b,c,2}$	$13.3^{b,3}$	$8.0^{b,c,1}$
5	$7.7^{a,d,1}$	$5.0^{a,b,c,2}$	$12.3^{b,c,d,3}$	$8.0^{b,c,1}$
6	$8.7^{a,d,1}$	$6.0^{a,c,2}$	$13.3^{b,c,3}$	$8.3^{b,c,1}$
7	$8.0^{a,d,1}$	$5.3^{a,b,c,2}$	$12.0^{b,c,d,3}$	$8.0^{b,c,1}$
8	$7.7^{a,d,1}$	$5.0^{a,b,c,2}$	$11.7^{d,3}$	$7.3^{b,c,1}$
9	$7.7^{a,d,1}$	$4.7^{a,b,c,2}$	$11.7^{d,3}$	$7.0^{c,1}$
10	$7.3^{c,d,1}$	$5.0^{a,b,c,2}$	$11.7^{d,3}$	$7.0^{c,1}$
11	$7.7^{a,d,1}$	$4.7^{a,b,c,2}$	$11.3^{d,3}$	$7.0^{c,1}$
12	$7.7^{a,d,1}$	$4.7^{a,b,c,2}$	$11.0^{d,3}$	$7.0^{c,1}$
SEM	±0.53	±0.53	±0.53	±0.53

[a,b,c,d]Denotes differences within lamp across months($P<0.05$).
[1,2,3]Denotes differences across lamps within a month ($P<0.05$).

TABLE 4. Percent Previtamin D_3 Formed in Linear Fluorescent Lamps at Different Distances

Month	Blacklight 30.5 cm	Blacklight 45.7 cm	Reptisun 5.0 30.5 cm	Reptisun 5.0 45.7 cm
0	0.09	0.07	0.07	0.06
1	0.06	0.05	0.07	0.04
2	0.08	0.05	0.07	0.05
3	0.11	0.10	0.07	0.06
4	0.09	0.10	0.08	0.06
5	0.10	0.07	0.08	0.04
6	0.10	0.08	0.06	0.05
7	0.09	0.11	0.06	0.06
8	*	*	*	*
9	0.07	0.04	0.04	0.03
10	0.05	0.04	0.03	0.03
11	0.05	0.03	0.03	0.02
12	0.07	0.04	0.02	0.04
SEM	±0.09	±0.09	±0.09	±0.09

No differences were detected within lamp across months or between lamps within a month ($P<0.05$).
*Ampoules were lost.

however, there were no statistical differences in ampoule conversion between the lamps at either distance (Table 4). Ampoules for month 9 were lost in transit and were not included in the results. Owing to cost, ampoules were only used for testing the centers of the linear fluorescent lamps.

Differences in irradiance levels were determined within lamp when comparing the center and 15.2 cm in from each end ($P<0.05$), which were identified as ‘‘cord’’ (i.e., the end near the light fixture’s electrical cord) or ‘‘other’’ (Table 5). The

TABLE 5. Solarmeter® 6.2 Readings (μW/cm^2) From Linear Fluorescent Lamps at Center and Both Ends at Different Distances

	Blacklight 30.5 cm			Blacklight 45.7 cm			Reptisun 5.0 30.5 cm			Reptisun 5.0 45.7 cm		
Month	Center	Cord	Other	Center	Cord	Other	Center	Cord	Other	Center	Cord	Other
0	$9.0^{a,1}$	$6.7^{a,2}$	$8.0^{a,1,2}$	$6.0^{a,1}$	$4.3^{a,2}$	$5.0^{a,1,2}$	$16.3^{a,1}$	$13.0^{a,2}$	$13.0^{a,2}$	$10.3^{a,1}$	$8.0^{a,2}$	$8.0^{a,2}$
1	$5.1^{b,1}$	$3.7^{b,2}$	$4.7^{b,1,2}$	$4.0^{b,1}$	$3.0^{a,b,1}$	$3.7^{a,b,1}$	$12.0^{b,c,d,1}$	$9.0^{b,c,d,2}$	$9.7^{b,c,2}$	$8.7^{b,1}$	$6.3^{b,2}$	$6.7^{b,c,2}$
2	$6.0^{b,c,1}$	$4.7^{b,1}$	$5.3^{b,c,1}$	$4.0^{b,1}$	$2.7^{b,1}$	$3.0^{b,1}$	$13.3^{b,1}$	$10.3^{b,2}$	$10.3^{b,2}$	$8.7^{b,1}$	$6.0^{b,2}$	$6.0^{c,d,2}$
3	$8.0^{a,d,1}$	$6.7^{a,1}$	$6.7^{a,c,d,1}$	$5.3^{a,b,c,1}$	$3.7^{a,b,2}$	$4.3^{a,b,c,1,2}$	$13.3^{b,1}$	$10.3^{b,2}$	$10.3^{b,2}$	$8.3^{b,c,1}$	$6.0^{b,2}$	$6.0^{c,d,2}$
4	$8.0^{a,d,1}$	$6.0^{a,b,2}$	$7.3^{a,d,1,2}$	$5.3^{a,b,c,1}$	$3.3^{a,b,2}$	$4.3^{a,b,c,1,2}$	$13.3^{b,1}$	$10.7^{b,2}$	$9.0^{b,c,d,3}$	$8.0^{b,c,1}$	$5.0^{b,2}$	$6.0^{c,d,2}$
5	$7.7^{a,d,1}$	$5.7^{a,b,2}$	$6.3^{c,d,1,2}$	$5.0^{a,b,c,1}$	$3.0^{a,b,2}$	$4.0^{b,c,1,2}$	$12.3^{b,c,d,1}$	$9.7^{b,c,2}$	$9.7^{b,c,2}$	$8.0^{b,c,1}$	$5.7^{b,2}$	$6.0^{c,d,2}$
6	$8.7^{a,d,1}$	$6.7^{a,2}$	$7.0^{a,d,2}$	$6.0^{a,c,1}$	$4.0^{a,b,2}$	$4.7^{a,c,1,2}$	$13.3^{b,c,1}$	$10.0^{b,c,2}$	$10.0^{b,c,2}$	$8.3^{b,c,1}$	$6.3^{b,2}$	$5.7^{c,d,2}$
7	$8.0^{a,d,1}$	$6.0^{a,b,2}$	$7.3^{a,d,1,2}$	$5.3^{a,b,c,1}$	$4.0^{a,b,1}$	$4.0^{a,b,c,1}$	$12.0^{b,c,d,1}$	$9.3^{b,c,d,2}$	$9.3^{b,c,d,2}$	$8.0^{b,c,1}$	$5.3^{b,2}$	$6.0^{c,d,2}$
8	$7.7^{a,d,1}$	$5.3^{a,b,2}$	$6.3^{c,d,1,2}$	$5.0^{a,b,c,1}$	$3.0^{a,b,2}$	$4.0^{a,b,c,1,2}$	$11.7^{d,1}$	$8.7^{c,d,2}$	$9.0^{b,c,d,2}$	$7.3^{b,c,1}$	$5.3^{b,2}$	$5.3^{c,d,2}$
9	$7.7^{a,d,1}$	$5.0^{b,2}$	$6.3^{c,d,1,2}$	$4.7^{a,b,c,1}$	$3.0^{a,b,2}$	$3.3^{b,c,1,2}$	$11.7^{d,1}$	$8.7^{c,d,2}$	$9.0^{b,c,d,2}$	$7.0^{c,1}$	$5.0^{b,2}$	$5.0^{d,2}$
10	$7.3^{a,d,1}$	$5.0^{b,2}$	$6.3^{c,d,1,2}$	$5.0^{a,b,c,1}$	$3.0^{a,b,2}$	$3.3^{b,c,1,2}$	$11.7^{d,1}$	$8.3^{c,d,2}$	$9.0^{b,c,d,2}$	$7.0^{c,1}$	$5.0^{b,2}$	$5.0^{d,2}$
11	$7.7^{a,d,1}$	$5.3^{a,b,2}$	$6.3^{c,d,1,2}$	$4.7^{a,b,c,1}$	$3.0^{a,b,2}$	$3.7^{a,b,c,1,2}$	$11.3^{d,1}$	$8.3^{c,d,2}$	$8.7^{c,d,2}$	$7.0^{c,1}$	$5.0^{b,2}$	$5.0^{d,2}$
12	$7.7^{a,d,1}$	$5.0^{b,2}$	$6.3^{c,d,1,2}$	$4.7^{a,b,c,1}$	$3.0^{a,b,2}$	$3.7^{a,b,c,1,2}$	$11.0^{d,1}$	$8.0^{d,2}$	$8.0^{d,2}$	$7.0^{c,1}$	$5.0^{b,2}$	$5.0^{d,2}$
SEM	±0.53	±0.53	±0.53	±0.53	±0.53	±0.53	±0.53	±0.53	±0.53	±0.53	±0.53	±0.53

^{a,b,c,d}Denotes differences within lamp across months ($P<0.05$).
^{1,2,3}Denotes differences across lamps within a month ($P<0.05$).

TABLE 6. Regression Equations Correlating Solarmeter® 6.2 Readings (μW/cm²) With the Formation of Previtamin D_3

Lamp	Distance	Equation	R^2
Powersun	0.9 m*	% pre D3 = 0.0102+0.0155 × UVB reading	0.660
Powersun	1.5 m*	% pre D3 = −0.0032+0.0175 × UVB reading	0.368
UVHeat flood	0.9 m	% pre D3 = 0.9210+0.0095 × UVB reading	0.148
UVHeat flood	1.5 m	% pre D3 = 0.3335+0.0138 × UVB reading	0.136
UVHeat spot	0.9 m*	% pre D3 = −0.0179+0.0137 × UVB reading	0.838
UVHeat spot	1.5 m*	% pre D3 = 0.0636+0.0109 × UVB reading	0.734
Blacklight	30.5 cm*	% pre D3 = 0.0381+0.0089 × UVB reading	0.432
Blacklight	45.7 cm	% pre D3 = 0.0420+0.0108 × UVB reading	0.089
Reptisun 5.0	30.5 cm	% pre D3 = 0.0750+−0.0005 × UVB reading	0.003
Reptisun 5.0	45.7 cm	% pre D3 = 0.0499+0.0005 × UVB reading	0.001

*Denotes significant slope ($P<0.05$).

Reptisun lamp consistently had higher irradiance measurements from the center of the lamp compared with the "other" or "cord" ends at both the 30.5 cm and 45.7 cm distances. For Sylvania Blacklight 350BL, there were no differences at 30.5 cm between the two ends, but the center of the lamp had a higher irradiance than the "cord" end ($P<0.05$) during months 0, 1, and 4–12. At 45.7 cm, the center had a higher irradiance than the "cord" end during months 0, 3–6, and 7–12. The "other" end was never different from the center or "cord" ends.

Regressions equations depicting the percent conversion of vitamin D_3 using radiometer readings are included in Table 6. Powersun at 0.9 and 1.5 m, UVHeat Spot at 0.9m and 1.5 m, and Blacklight 350BL at 30.5 cm had slopes that were significant ($P<0.05$).

DISCUSSION

Because exposing animals to direct sunlight is not always possible, especially in a zoological setting, it is important to find a way to provide the animal with exposure to UVB for vitamin D synthesis. Some lamps, specifically marketed toward herpetologists, are manufactured for the sole purpose of producing UVB radiation for captive animals. These lamps are not tested or regulated by any governmental agencies and are considered nutraceutical in nature. Few reports on quantity or duration of UVB emission exist. Some studies tested UVB lamps several years ago, but most of those lamps were test lamps or are no longer manufactured [Gehrmann, 1987; Gehrmann et al., 2004; Bernard, 1995]. This study was conducted several years ago and the lamps may be quite different from lamps currently available, as was the case with data recently reported by Lindgren et al. [2008].

The UVB band width necessary for vitamin D_3 synthesis is 290–315 nm [Holick, 1999; Webb and Holick, 1988]. The Solartech Solarmeter® 6.2 measures the UVB bandwidth encompassing 280–320 nm. The UVHeat Flood and Spot lamp irradiances were not different at 0.9 m until month 9 when UVHeat Spot began to have a higher UVB reading, leading one to believe that it would promote a higher concentration of previtamin D_3 formation. However, UVHeat Flood had a higher conversion rate of previtamin D_3 from months 2–7, indicating this lamp had a higher level of UVB irradiance in the spectrum, which promotes greater previtamin D_3 synthesis.

Another misleading occurrence in this study was with the linear fluorescent lamps. According to the radiometer readings, Reptisun had a significantly higher UVB output than the Blacklight lamp, but when the ampoule conversion rates were compared, there were no differences. From these two findings, it is important to remember that the UVB readings from a radiometer do not necessarily correlate to previtamin D_3 synthesis, as some of the UVB bands have a higher rate of conversion than others. However, since the initiation of this study, a new radiometer, Solartech's Solarmeter® 6.4, has been manufactured that reportedly has the ability to more accurately reflect the efficiency of vitamin D_3 synthesis by weighing input reflective of the bands' ability for synthesizing vitamin D_3 [Solartech, Inc., 2005; Lindgren et al., 2008].

The ends of the fluorescent lamps were measured, as these lamps are typically used to produce UVB for multiple cages lined side-by-side. Knowing that irradiance levels were different between the ends and centers of the lamp, it may be useful to rotate cage positions under the lamp. However, there were no ampoule data to measure the lamp ends to support this suggestion.

It is difficult to identify when it is time to change a lamp because the animal's requirements for UVB exposure and vitamin D are not known. Some reptiles are more efficient at vitamin D conversion and may only need minimal exposure to UVB [Ferguson et al., 1998, 2005]. Species characteristics that will affect synthesis include degree of skin pigmentation, total amount of skin that can be exposed to UVB, and the skin's concentration of 7-dehydrocholesterol [Bernard et al., 1989].

Gehrmann et al. [2004] used the same Solarmeter® Model 6.2 UVB meter used in this study and report irradiance readings greater than those obtained in this study for the Blacklight, Reptisun 5.0, and UVHeat Spot lamps. However, for that study, ampoule exposure time was 2 hr, which was twice as long as in this study. When using the regression equations reported by Gehrmann et al. to account for exposure time differences, the percent product formed was still greater in their study for all but one comparison. The product synthesized percentages reported by Gehrmann et al. were two–four times higher for the Blacklight lamp, two times greater for the Reptisun lamp at approximately 34 cm, and very similar to concentrations for the Reptisun lamp at 46 cm between months 0–7. When comparing the UVHeat Spot lamp, Gehrmann et al. report product synthesized concentrations of two–three times greater than those obtained in this study. The authors are uncertain as to why there were such marked differences between the study by Gehrmann et al. [2004] and this study. Distances were slightly different between the studies, which may have affected irradiance readings.

Regression equations to predict the percent of previtamin D_3 formed using similar lamps and a Solarmeter® Model 6.2 UVB meter were formulated. Overall, it appeared that as distance from the lamp increased, the ability to predict the percentage of previtamin D_3 was reduced.

Bernard [1995] reports a sharp decline in UVB radiation from fluorescent lamps during the first week of use and a gradual reduction in output over the 4-month study; the findings were similar in this study for both fluorescent and incandescent lamps.

Gehrmann and Ferguson [2005] recommend replacing lamps annually. Since data in the past 12 months has not been reported, it is agreed that lamps should be replaced after 12 months to ensure UVB irradiance is occurring if it is not being measured.

At this point little information is known about the UVB exposure requirements of animals for synthesizing vitamin D_3. Some animals may need very little exposure to meet their vitamin D needs, which makes it difficult to recommend certain lamps over others or times when lamps should be changed.

CONCLUSIONS

1. T-Rex Active UVHeat lamps emitted higher levels of irradiance and had higher ampoule conversion concentrations than ZooMed PowerSun.
2. All incandescent lamps, with the exception of ZooMed PowerSun at 1.5 m, had a significant drop in irradiance from the initial measurement until 1 month.
3. High UVB irradiance measurements do not necessarily correlate to high vitamin D synthesis.
4. Until UVB requirements for vitamin D_3 synthesis in animals are determined, it is not possible to state that any lamp is superior to another.

ACKNOWLEDGMENTS

We thank Westron Corporation and ZooMed Laboratories, Inc. for donating the lights in this study, the Daniel F. and Ada L. Rice Foundation for helping to fund this research, Dr. Robyn Barbiers for her guidance and support during this project, Drs. Gary Ferguson and William Gehrmann for suggestions and help at the start of the project, Ann Ward for proposing this project, and Melissa Friedlund and Marie Perez for their assistance with lamp monitoring.

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