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Research article

Effect of different infrared basking lamps on the heating effectiveness and desiccation of gelatine models: Implications for zoo animal husbandry

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Abstract

Artificial heating via lamp technology is a key feature of the husbandry of many captive animals, especially ectotherms. Short wave infrared (IRA) is theoretically more efficient in raising animal core temperature than medium (IRB) and long wave infrared (IRC) as it penetrates deeper into the skin and underlying tissues. However, for historical reasons, lamps emitting predominantly long wave infrared are commonly used, causing superficial heating and dehydration in animals due to shallow tissue penetration and more uneven heating of surface versus core. Few studies have investigated real-world behavioural or physical responses to different infrared wavelengths; therefore, there is a lack of empirical evidence for physiological outcomes under controlled conditions. Here, we investigated the effect of different infrared basking lamps (infrared A, B and C lamps available commercially) on time to reach core target temperature, surface heating, and desiccation rate of ballistic gelatine models in order to link theory to practice. Accounting for variation in air temperature and humidity, infrared A lamps heated models to core target temperature fastest, and demonstrated the lowest desiccating effect, while infrared C lamps caused the highest surface heating. Lamp to model distance influenced time to reach target temperature, while background colour influenced surface temperature changes. Our results provide support that, among commercially available products, lamps emitting infrared A radiation heat the core of animals in captivity more efficiently, with less desiccation and thus confirms the theoretical assertion that such lamps are preferable for use in animal husbandry. This study also develops methods for future infrared heating research.

Introduction

Environmental temperature has a profound influence on the physiology, behaviour, and reproduction of animals (Gillooly et al. 2001). Animals have evolved different behavioural and physiological adaptations to maintain their optimum body temperature for normal functioning of the body (Hertz et al. 1982; de Andrade 2016). Basking, where animals expose themselves to sunlight to absorb heat, is one of the major mechanisms that animals used to thermoregulate, where they expose themselves to sunlight to absorb heat (Baines 2017).

Energy from the sun can be transferred to an animal by radiation, conduction, and convection. Radiation is the primary means by which animals warm up through basking (Ruibal 1961). The sun emits three main types of radiation, ultraviolet (100-400nm), visible light (400-700nm), and infrared (700nm to 1mm). Infra-red radiation (IR) is what humans primarily perceive as heat when exposed to sunlight. IR is divided, according to bandwidth, into IRA (short IR, λ=760–1440 nm), IRB (medium IR, λ=1440–3000 nm) and IRC (long IR, λ=3000 nm–1 mm). In natural sunlight, only IRA and small amounts of IRB reach the Earth's surface, as the atmosphere filters out radiation with wavelengths longer than 2500nm (Jung et al. 2012). IRC may be encountered naturally by animals as radiated wavelengths from objects heated by sunlight. Different bandwidths of IR vary in their penetration of tissue and consequently on their physiological effect on animals basking for warmth. Skin consists of three layers, the superficial epidermis, the deeper dermis and the hypodermis (Rutland et al. 2019a). IRA can penetrate all skin layers (epidermis, dermis and hypodermis),

allowing the blood vessels and underlying tissues to be warmed directly. IRB is mostly absorbed in the epidermis, with a small amount reaching the dermis. IRC can only deliver heat to the surface of the epidermis, which then reaches the dermis and hypodermis through conduction (Svobodová and Vostálová 2010). Animals adjust their thermoregulatory behavior based on core temperatures and IRC may cause thermal burns before animals feel warm, as the skin may reach dangerous temperatures before the core warms (Gartrell et al. 2020).

In captive environments, IR lamps and emitters (henceforth, 'lamps') producing wavelengths absent in natural terrestrial sunlight are commonly used as basking lamps as a result of a lack of understanding of commercially available heating technologies and animal physiology. The suitability of different types of IR lamps remain unclear due to limited empirical data to prove the IR radiation penetration theory on captive animals (Ross et al. 2013; Baines et al. 2016). Keeping animals with inappropriate IR basking options, such as basking lamps emitting IRB and IRC, can exacerbate health issues such as dehydration, abnormal growth, and hair loss (Mendyk et al. 2013; Doneley et al. 2018). For example, captive chelonians can suffer from pyramiding, an abnormal upgrowth of carapace likely caused by prolonged heating of the keratin and bone, and low humidity (Heinrich and Heinrich 2016). Longer wavelengths, IRB and IRC, penetrate into tissue less effectively; therefore, captive animals must bask longer and closer to the lamps to warm their core. Prolonged basking increases body surface heating and water loss through evaporation, resulting in dehydration and related health issues (Doneley et al. 2018).

Although ultraviolet lighting (UV) and the behavioural impacts of IRA and IRB heating in husbandry have been widely studied, few studies have examined the physiological impacts of infrared lamps on basking of captive animals (Baines et al. 2016; Thomas et al. 2019; Kane et al. 2023). The behavioural studies also yielded mixed results. It remains unclear how differences in lamp radiation spectra are relevant for the physiological health of captive animals. Previous studies directly measuring core temperatures in living animals were limited by small sample sizes (e.g. two to three individuals) and number of invasive cloacal temperature measurements that could be taken, measurement of which may influence basking behaviour (Falcón et al. 2018). By conducting experiments on gelatine models, variability between samples can be reduced, manipulation and anlayses will be easier and impact on animal welfare is mitigated. With the growing prevalence of exotic pet keeping and ex-situ conservation, reviewing captive thermal husbandry practices (i.e. heat emitters) is critical for animal welfare.

Here, we investigated the physiological effect of three commonly used IR lamps: incandescent lamps, carbon filament lamps and ceramic lamps, on captive animals by assessing the time to reach core target temperature (CTT), surface to core temperature change ratio, and desiccation effects on ballistic gelatine models. An incandescent lamp produces predominantly short IR wavelengths (IRA) with some visible light (Burgin and Edwards 1970). A carbon filament heater emits predominantly IRB with traces of IRA and visible light. A ceramic lamp produces IRC with negligible amount of visible light, IRA, or IRB (Wunderlich 2021). We repeated the experiments on both black and white backgrounds as background colour influences light absorption and amount of re-radiation (Levinson et al. 2005), and at two vertical distances between the lamp and model to account for variations in radiation irradiance (quantity) (Baines et al. 2016; Arcadia 2022). Specifically, our aims were to empirically evaluate and compare the heating and desiccation effect of IRA, IRB and IRC lamps on captive animals. We hypothesized that incandescent lamps would achieve the fastest heating to CTT, lowest surface temperature changes and least desiccation.

Materials and methods

Raw data files and complete R code for all analyses presented here are available at the repository github.com/CJMichaels/Infrared-Heating-of-gelatine-models.

Infrared lamps

We tested three types of IR lamps commonly used in small enclosures in this study (Table 1). Incandescent lamp (IL) represents IRA lamps, carbon filament heater (CFH) represents IRB lamps, and ceramic lamp (CL) represents IRC lamps. We chose these because each lamp differs greatly in the proportion of IRA, IRB and IRC they emit (Wunderlich 2021; Thomas et al. 2019). A limitation of this study was the lack of available lamps with similar wattages for testing. We did not standardise the lamp per wattage as we aimed to compare the practical purposes of the IR lamps instead of theoretical justification. We did not use mercury vapour and metal halide lamps in this study as they produce lower proportions of IR compared to their total light output (Thomas et al. 2019).

Gelatine models

We conducted the experiments on gelatine models made of 260A ballistic gelatine instead of living animals due to ethical issues. Derived from pig skin through acidic processes, ballistic gelatine closely mimics the density and viscosity of animal muscle tissues (Swain et al. 2014). However, ballistic gelatine does not simulate the keratinous structures on animal skin, such as hair, scales and feathers (Rutland et al. 2019b). Hence, the gelatine models more closely resemble amphibians, whose skin only has one thin keratin layer and is highly permeable to water (Demori et al. 2019). Ballistic gelatine's absorption measurements are reported differently in previous studies (Cook et al. 2011; Nseowo Udofia and Zhou 2020). Nevertheless, the gelatine has a similar transmission spectrum to that of animal skin, allowing most IRA and IRB and only some IRC to pass through (Łopusiewicz et al. 2018; Nseowo Udofia and Zhou 2020), making it one of the best animal tissue simulants available for this study (Lopes et al. 2019). Consequently, these models allowed detailed measurement of surface and core temperatures while avoiding ethical issues and confounding variables (such as behavioural responses to experimental conditions) associated with using live animals.

We made the ballistic gelatine at 10% concentration (0.2kg of ballistic gelatine powder and 1.8kg of 10°C chilled water) as this had previously been found to better represent the mechanical properties of animal muscles and to be more temperature sensitive (Cronin and Falzon 2011). The gelatine was made according to Fackler's calibration method (Jussila 2004), which contains five stages: measuring, mixing, blooming, melting and cooling. We first mixed the powder and water thoroughly to remove clumps. We then placed the mixture in a fridge for two hours for the gelatine to bloom. After that we heated the gelatine to 39°C on a stove until it had completely dissolved with a syrup like structure. While heating, we added 3mL of food colouring to give it a grey colour, resembling the skin colour of most reptiles, some mammals and amphibians (Caro 2013). Finally, we refrigerated the gelatine mould undisturbed for 24 hours before cutting to create cuboid models. Ballistic gelatine has a shelf life of three days and thus we made new models every three days.

Preliminary experiment

We conducted preliminary experiments to determine the amount of food colouring added into the gelatine model, the appropriate heights (cm) at which the IR lamps were placed, the model sizes

Table 1. The three types of infrared lamps that were used in this study (Wunderlich 2021).

Product	E27 Basking Halo Spot	E27 Deep Heat projector	E27 Ceramic lamp
Manufacturer	Reptile Systems	Arcadia	PearlCo
Wattages (W)	60	50	150
Type	Incandescent Lamp	Carbon filament heater	Ceramic Lamp
Shape	BR20 lamp	PAR30 lamp	Conical lamp
Wavelengths	IRA~48%	IRA~3%	IRB~3%
	IRB~34%	IRB~38%	IRC~97%
	IRC~9%	IRC~59%	
	Visible~9%		
			

(cm) and the final CTT (°C) of the models. We first installed a basking lamp in a dome fitting (22cm ZooMed delux porcelain clamp lamp) mounted on an adjustable stand positioned directly above the area where the model is placed (MA). We positioned each lamp such that the top surface of the model was 20cm, 30cm and 40cm from the bottom surface of the lamp, which were distances recommended by lamp manufacturers and husbandry practice guidelines (Arcadia personal communication and information on packaging; Healey 2024; RSPCA 2024). We tested gelatine models measuring 5cm×2.5cm×2.5cm and 10cm×5cm×5cm as they resembled the size of small animals (Inns 2019). We used IR lamps with low wattages in this study which were more suitable for heating small animals. We heated the models to 25°C and 30°C as many small reptiles and amphibians generally have optimum core body temperatures of around 25°C to 30°C (Raske et al. 2012). We conducted all experiments in the absence of sunlight.

Preliminary results showed that some models took more than an hour to reach the CTT and prolonged heating melted the surface of the model. As such, we excluded 10cm×5cm×5cm model size, 40cm lamp-model distance and 30°C model CTT as factors in our analyses.

Experimental setup

We tested the i) heating effectiveness (time taken to reach CTT), ii) surface to core temperature change ratio and iii) desiccation effect of three IR lamps at two different heights from the gelatine

Table 2. Summary of results from preliminary experiment

5cm×2.5cm×2.5cm model size		
Distance (cm)	CTT (°C)	Reached CTT in >1 hour
20	25	No
20	30	No
30	25	No
30	30	Yes
40	25	Yes
40	30	Yes
10cm×5cm×5cm model size		
20	25	Yes
20	30	Yes
30	25	Yes
30	30	Yes
40	25	Yes
40	30	Yes

Table 3. Measurements taken before and after each experiment and equipment used.

Before experiment	After experiment	Equipment (Company & model)	Units
Starting model weight	Ending model weight	Digital Weight scale (AMIR, KA8)	±0.01g
Starting model surface temperature	Ending model surface temperature	Non-contact infrared thermometer (Helect H-1020)	±0.1°C
Starting model core temperature	Ending model core temperature	Digital thermometer (OXO 11181400G)	
Air temperature	-	Alarm thermometer (Electronic Temperature Instruments Ltd 810-090)	±0.1°C
Air humidity	-	Hygrometers (Thlevel TPM-40)	±5%Rh
Time taken to heat the core temperature of the model to 25°C		Mobile phone (iPhone 13)	minute

models on two background colours. The gelatine block was cut into 5cm×2.5cm×2.5cm cuboids. There were ten replicates and one control for each lamp at each height and on each background colour. The basking lamp setup was the same as the preliminary experiment. We conducted all experiments in the absence of sunlight, with a background of either black or white paper to assess the effects of high and low light absorption basking surfaces (Figure 1). We kept the environmental conditions as consistent as possible across all treatments, keeping windows and doors closed and drawing curtains to block IR radiation from sunlight.

Before starting the experiments, we pre-heated the MA to 30°C in all trials to maintain a consistent starting temperature and animals typically approach a site already warmed by sunlight to bask. We chose this temperature based on husbandry guidelines and previous experiments (Poole 2008; Divers 2020; Willis et al. 2021; Kane et al. 2022). We held a non-contact IR thermometer (Helect H1020, ±0.1°C) above the centre of the MA to measure the site's temperature. We warmed the refrigerated gelatine models at room temperature to a core temperature of 20°C, the lowest active body temperature of various reptile and amphibian species for which data were available (Brattstrom 1965; Rowley and Alford 2007). We gently inserted a thin-probed food thermometer (OXO, ±0.1°C) into the centre of the model to measure the core temperature. We then scraped any pieces of gelatine adhering to the probe back onto the model to avoid unnecessary weight loss. We also measured air temperature (°C) and humidity (%) by placing the alarm thermometer and hygrometer adjacent to the adjustable stand to account for their impact on the temperature change rate, time taken to reach CTT and water evaporative rate (Table 3) (Foley and Spotila 1978).

We placed the gelatine model on the MA and heated the model using the IR lamps detailed above. We measured the time taken (minutes) to heat the CTT of the model to 25°C. We set a cut-off time of 30 minutes, even if 25°C was not achieved. Once the CTT or the 30-minute cut-off was reached, we recorded the model's final weight and, surface temperature and core temperature after their readings stabilised (Table 3). For the control treatment, the setup was identical except that we removed the basking lamp and all models stood undisturbed for 30 minutes.

Statistical Analysis

All statistical analyses were conducted in R v.4.2.1 (R Core Team, 2022) or later. We visually inspected boxplots of air temperature, air humidity, and model starting weight for outliers. We excluded four data points with exceptionally high or low model starting weight, which is likely caused by uneven cutting of the gelatine block, to keep the model weight constant across replicates.

We investigated the relationship between different IR lamps and time to reach CTT by running the survival analysis with the survival package (Therneau 2024). The outcome was the time taken for the gelatine models to reach the CTT (25°C), with observations censored if the CTT was not reached by the cut-off time. Due to non-proportional hazards detected via Schoenfeld residuals and primary interest in time to event rather than relative hazards, we employed an Accelerated Failure Time (AFT) model with the survival package with i) lamp types, ii) distance between lamp and gelatine models, iii) background colour, iv) air temperature (centred) and v) air humidity (centred) as covariates. We included air temperature and humidity in models to account for their uncontrolled effects on the response variables. AFT models assume the effect of the covariates accelerates or decelerates the time to event and does not assume proportional hazards. The AFT model was specified with a lognormal error distribution, selected through comparison of models with other available distributions using Akaike Information Criterion (AIC), assessment of deviance residuals, deviations of beta (reflecting the influence of each data point on estimated coefficients), and residuals against time, which were considered optimal and acceptable under the lognormal distribution.

To examine the relationship between different IR lamps and the water evaporative rate and surface temperature change of gelatine models, we first calculated the surface to core temperature change ratio using the following equation:

$$\text{Surface temperature change of replicate} - \text{surface temperature change of control} \div 30 \times \text{duration}) \div (\text{Core temperature change of replicate} - \text{core temperature change of control} \div 30 \times \text{duration})$$

where duration was the time taken in minutes for the core temperature of the model to reach 25°C. A surface to core

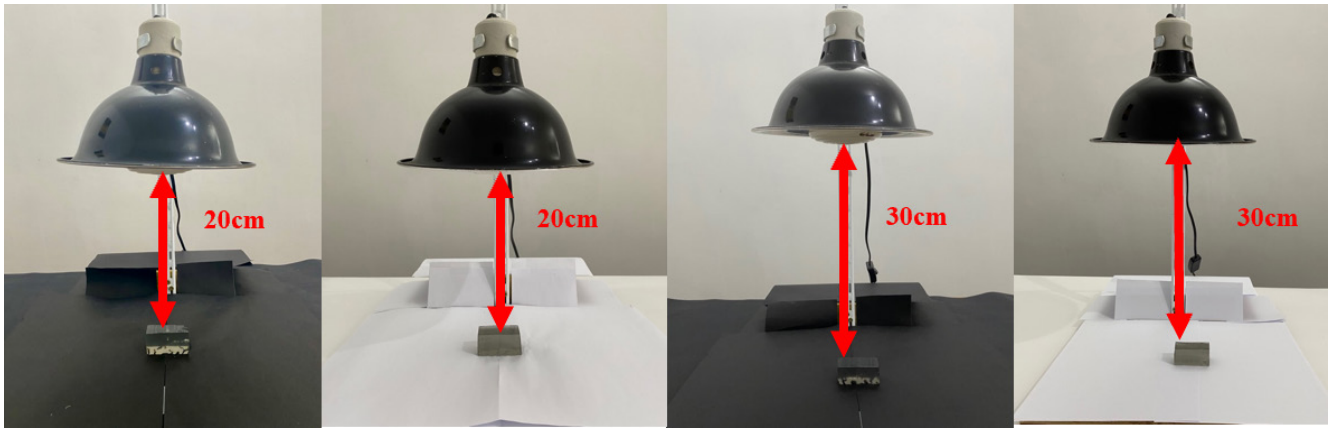

Figure 1. Examples of experimental setup: infrared lamps heating gelatine models at distances of 20cm and 30cm with either a white or black background.

temperature change ratio of one means that the model had the same changes in temperature on the surface as in the core. A ratio of greater than one indicates a higher temperature change on the surface than the core, and vice versa for a ratio of less than one. We then calculated total desiccation using the equation:

$$\left(\frac{\text{Difference in weight of replicate}}{\text{Starting weight of replicate}} - \frac{\text{Difference in weight of control} \div 30 \times \text{duration}}{\text{Starting weight of control}}\right)$$

We assumed the rate of temperature change and water evaporation to be constant at controlled room conditions.

After calculating the temperature change ratio and desiccation, we ran two linear models with the lm() function. These two models have identical covariates with the survival analysis and had surface to core temperature change ratio and total desiccation as response variables, respectively. We calculated variance inflation factors (VIF) (R package *car*) to check for collinearity among air temperature and humidity, and they were not collinear with

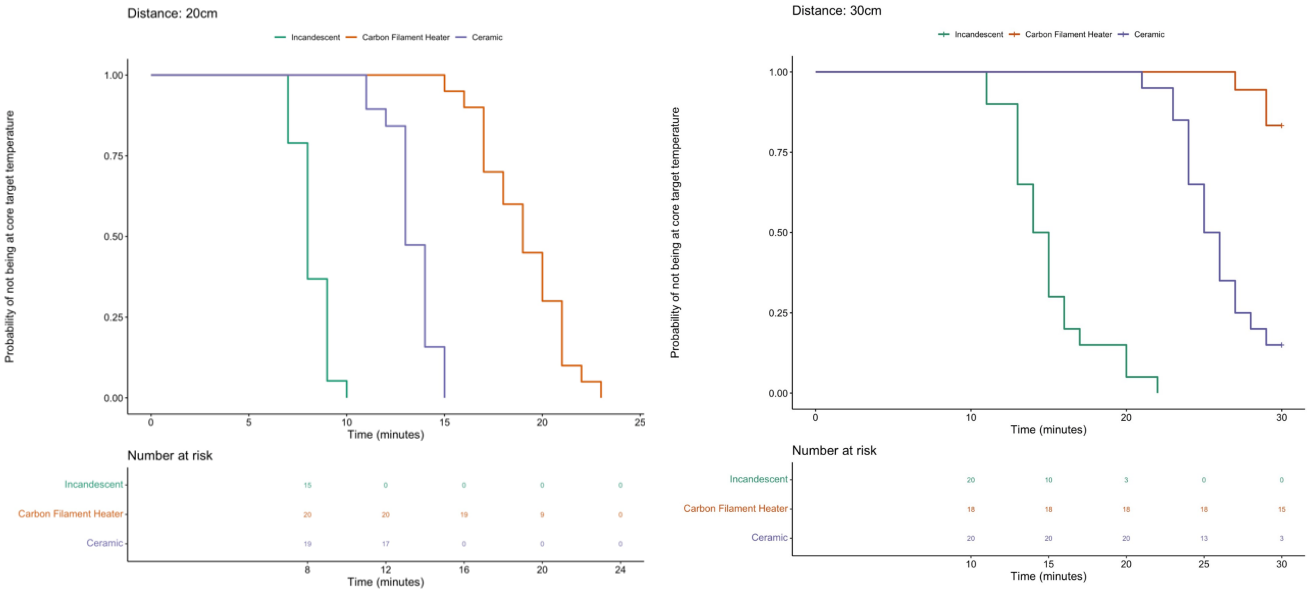

Figure 2. Kaplan-Meier curves showing the probability of models not yet having reached CTT under each lamp type, stratified by lamp-model distance. Both lamp type and distance were significant predictors of time to reach CTT.

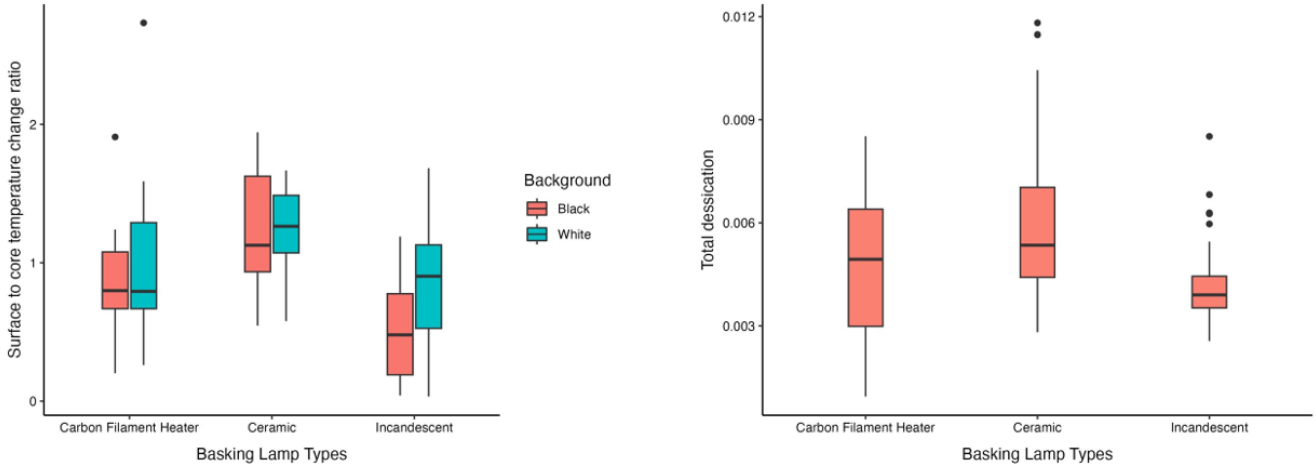

Figure 3. Comparison of a) surface to core temperature change ratio and b) total desiccation of gelatine models under three infrared lamps.

each other (all VIF<3). We also carried out AIC comparison and inspection of residulals to evaluate model fit, confirming that including air temperature and humidity as parameters increased the fit of the model.

A pairwise post hoc Tukey test (R package *emmeans*) was subsequently conducted on the linear models to determine if the three lamp types had significantly different surface to core temperature change ratio and total desiccation. Finally, the effect sizes of the explanatory variables in the linear model (R package *effectsize*) were examined. The effect sizes were calculated using omega squared, a more conservative and robust measure for small sample sizes (Keselman 1975).

Results

Time to reach CTT

The AFT model revealed several significant predictors of the time to event (i.e. time taken for the gelatine models to reach the CTT (25°C)). AFT models generate coefficients reflecting acceleration or deceleration of events relative to a reference, where positive coefficients (on the log scale) indicate the event happened slower, and negative coefficients indicate faster. Relative to the

Table 4. Summary of a) AFT model for time to reach CTT, and pairwise post-hoc Tukey test from linear model showing b) surface to core temperature change ratio and c) total desiccation.

a) Time to reach CTT					
	Estimate	S.E.	z-value		P
Intercept	2.75	0.03	90.28		$<2.00\times10^{-16}$
Ceramic— Incandescent	-0.70	0.04	-18.92		$<2.00\times10^{-16}$
Ceramic—Carbon Filament Heater	0.20	0.03	6.36		2.00×10^{-10}
Log(scale)	-2.24	0.07	-31.46		$<2.00\times10^{-16}$
b) Surface-to-core temperature change ratio					
	Estimate	S.E.	t	d.f.	P
Ceramic— Incandescent	0.42	0.12	3.57	105	1.50×10^{-3}
Ceramic—Carbon Filament Heater	0.42	0.10	4.26	105	1.00×10^{-4}
Carbon Filament Heater— Incandescent	-6.70×10^{-6}	0.08	0.00	105	1.00
c) Total desiccation					
	Estimate	S.E.	t	d.f.	p
Ceramic— Incandescent	1.40×10^{-3}	5.20×10^{-4}	2.72	108	0.02
Ceramic—Carbon Filament Heater	3.30×10^{-4}	4.30×10^{-4}	0.77	108	0.72
Carbon Filament Heater— Incandescent	1.10×10^{-3}	3.70×10^{-4}	2.95	108	0.01

CL, gelatine models under the CFH had a significantly longer time taken to reach 25°C, while models under the IL had a significantly shorter time taken (Table 4, Figure 2). Lamp-model distance was also a significant factor, with a longer distance (30 cm) associated with a longer time for the gelatine models to reach 25°C (coefficient=0.55, P<0.001). Background colour and air humidity had no significant effect on the time taken to reach CTT (coefficient=-0.02, P=0.44; coefficient=2.50×10^{-5}, P=0.72). Higher air temperatures were associated with shorter times to reach CTT (coefficient=-0.53, P<0.001).

In terms of real-world effects, time ratios were calculated by exponentiating model coefficients. The results indicated that the IL reduced the time for the gelatine model to reach core target temperature by approximately 50% (time ratio=0.50) compared to the CL, while the CFH increased the time to reach the target temperature by 22% (time ratio=1.22) compared to the CL. A 30cm distance resulted in reaching the core target temperature 73% slower (time ratio=1.73) compared to a 20cm distance for all lamp types, and a one-unit increase in air temperature above mean decreased the time to reach the target temperature by 5% (time ratio=0.95) within the observed range. The combination of a significant negative log(scale) and significant covariates suggested that the model explained the majority of variability in time to event through the covariates with minimal remaining variation. The significant, positive Kaplan-Meier plots showing the number of gelatine models that failed to reach core target temperature over time, stratified by lamp type and lamp-model distance, are shown in Figure 2.

Surface to core temperature change ratio

Lamp type had a medium effect on surface to core temperature change ratio (ω^2=0.13). Gelatine models heating under IL and CFH had significantly lower surface to core temperature change ratio than CL, whereas no statistically significant difference was found between IL and CFH (Table 4, Figure 3). Background colour had a small significant effect on surface to core temperature change ratio (t=2.10; P=0.04, ω^2=0.03), with white background having a 0.13±0.06 higher ratio than black background. Distance between lamp and model had no significant effect on the ratio (t=-1.79, P=0.08). Air humidity and temperature had a medium and large significant positive effect on surface to core temperature change ratio (t=3.72, P<0.001, ω^2=0.10; t=4.34, P<0.001, ω^2=0.14). 1% increase in humidity led to 2.30±0.62 increase in ratio when temperature was kept constant at the mean value. While 1°C increase in temperature caused a 0.11±0.03 higher in ratio when humidity was constant at the mean value.

Total desiccation

Lamp type had a medium significant effect on water evaporation of gelatine models (ω^2=0.07). IL had a significantly lower proportion of weight loss by water evaporation than CFH and CL (Table 4, Figure 3). There was no significant difference in total desiccation between CFH and CL (Table 4, Figure 3). Background colours and lamp – model distances also had no significant effect on desiccation of models (t=-0.97, P=0.34; t=-1.48, P=0.14). Air humidity and temperature had strong significant negative effects on desiccation (t=-8.63, P<0.001, ω^2=0.39; t=-5.33, P<0.001, ω^2=0.19). 1% increase in air humidity led to a 0.02± 2.69×10^{-3} decrease in the proportion of weight loss from water evaporation when temperature was constant at the mean value. Similarly, 1°C increase in temperature caused a $6.21\times10^{-4}\pm1.17\times10^{-4}$ decrease in the amount of desiccation when humidity was constant at the mean value.

Discussion

We investigated how IR lamps emitting different spectra of IR can affect the physiology of animal models using empirical data. Theoretically, IRA is the most effective in heating the models to CTT as it can penetrate deepest into the skin (Barolet et al. 2016). IRA also causes lower desiccation rate and surface heating as animals bask for a shorter period of time to warm up their core.

Time to reach CTT

According to the IR radiation penetration theory, IRA can penetrate all skin layers, while IRB and IRC only deliver heat to the skin surface which then reaches deeper layers of the skin through conduction (Svobodová and Vostálová 2010). IL was found to be the most efficient at warming the model core despite having a much lower wattage than the CL, suggesting that spectrum differences but not intensity of IR radiation emitted cause the significant difference in heating time. Our findings provide direct evidence that predominantly IRA emitting lamps are more effective at warming animals than lamps emitting IRB and IRC (Svobodová and Vostálová 2010), and are consistent with the changes in behaviour observed under different IR lighting products in a preceding study (Thomas et al. 2019). The shorter time to reach CTT achieved by the CL versus the CFH could be due to the substantially higher wattage of the CL (150W), which might have over-compensated for its less skin-penetrating spectrum.

Distance between lamp and model strongly influenced heating effectiveness, which was in line with previous studies (Nowak and Lewicki 2004) that IR emitters have a higher heating efficiency at closer distances to the heating surface. As the lamp was moved away from the models, IR radiation spread out, reducing the amount of radiation and heat energy reaching the model surface (Brownson 2014). Less heat was absorbed by the model per time, lengthening the warming process. Background colour did not affect the heating effectiveness, likely because the intensity of IR radiation emitted by the lamps in this study was too low, and insufficient IR radiation was reflected from the background to induce a significant difference in heating time between background colours (Cheng et al. 2005).

Surface to core temperature change ratio

Theoretically, IRA penetrates deeper into the gelatine and thus the heat will be distributed more evenly between the surface and the core, whilst IRB and IRC are absorbed mostly at the surface, leading to slower core heating and higher surface temperature changes. Our results indicate that IR lamps exhibit significant differences in surface to core temperature change ratio, but the lamp effect was possibly confounded by air temperature. The CL had the highest ratio, suggesting that it caused the highest surface temperature changes, given core temperature change was constant across all treatments (20°C-25°C). This corroborates the theory that IRC is exclusively absorbed on the skin surface, whereas IRA and IRB penetrate into deeper layers of tissues (Schieke et al. 2003; Svobodová and Vostálová 2010). Surprisingly, the IL and CFH produced no difference in surface to core temperature change ratio. One possible reason is that ballistic gelatine does not have a keratin layer like animal skin, resulting in different absorption properties to the skin and underlying tissues. Moreover, 63% of the CFH replicates failed to reach 25°C within 30 minutes. There could be a significantly higher surface to core temperature change ratio in CFH if the experiment time was extended.

Background colour had a small effect on surface to core temperature change ratio. White colour reflected more radiation from the lamp, leading to more heat being absorbed on the surface of the models and higher surface temperature changes (Cheng et al. 2005). Distance between lamp and model had no effect on surface to core temperature change ratio, which contradicted previous findings by Nowak and Lewicki (2004). This can be attributed to the confounding effect of air temperature.

Replicates at 30cm distance were exposed to lower ambient temperatures than 20cm, which counteracts the effect of heating longer (Motevali et al. 2018).

Total desiccation

Lamp type had a significant effect on water evaporation of gelatine models, with the IL causing a significantly lower amount of water evaporation than the CL and CFH. This result was in line with a preceding experiment showing the shorter the heating time under IR emitters, the less water was lost by water evaporation (Nowak and Lewicki 2004). The IL predominantly emitted IRA, which heated up the model core faster, resulting in the lowest desiccation (Svobodová and Vostálová 2010). IRC lamps can dehydrate outer skin layers and the environment more than IRA lamps, which could explain the often patchy fur, dry skin condition and shell pyramiding found in captive animals housed with IRC lamps. One might argue the higher wattages (higher IR irradiance) in CL contributed to higher water evaporation as more heat was absorbed on the surface (Motevali et al. 2018). This is unlikely as the CFH had the same total desiccation as the CL despite a much lower wattage.

The lack of difference between the CFH and CL was a surprise, as previous literature showed that IRC was mostly absorbed by the surface (Schieke et al. 2003). The higher the surface temperature, the greater the water evaporative rate and total desiccation. The similarity could be due to the lower wattage of and thus longer heating time under the CFH. The CFH models absorbed less heat on the surface (lower surface to core temperature change ratio), and thus had lower water evaporative rate. Yet this was counteracted by the longer heating time, resulting in a similar total amount of water loss with the CL. Further research comparing desiccation effect of IR lamps at similar wattages is required.

Interestingly, background colour and lamp – model distance had no effect on desiccation, contradicting previous literature (Withers 1995). One possible explanation is that the gelatine model had reached a maximum level of water evaporation due to its small surface area and low surrounding air movement (windows closed). Surrounding air was saturated with water vapour and the water molecules on the surface of the model could not escape into the air, reducing water loss (Foley and Spotila 1978).

Significance and future studies

This study is the first to examine the heating and desiccation effect of IR technology commonly used to provide basking opportunities for animals in captive enclosures. Body temperatures are generally difficult to measure in living animals; by using gelatine models, repeated measurements could be taken, resulting in a larger sample size. Body size, starting and ending core temperatures could also be kept constant, reducing confounding impacts that were commonly found in previous studies (Falcón et al. 2018; Thomas et al. 2019). This study provides evidence that ILs, emitting predominantly IRA, are the most effective in heating animals to the required core temperature and resulting in the lowest desiccation.

It is unclear whether the CFH or CL generally performed better, due to several limitations in the study. Ballistic gelatine is not a perfect replica of animal skin and tissue, and is homogenous, i.e. it cannot simulate the nervous and vascular tissues of living animals. It also has a different absorption property and has higher water evaporation than animal skin due to the absence of a watertight keratin structure. Future experiments could add shed skin pieces on the gelatine model surface or use dead animal specimens or tissue samples to better mimic animal skin. All replicates should also be heated under the three different IR lamps at the same time, so that all models are exposed to the same variation in ambient temperature, humidity and air movement. Finally, it is difficult to control for the beam angle and wattages between lamps when relying on commercially available IR lamps. Our study focused on comparing the practical purposes of the IR lamps instead of theoretical justification, acknowledging that the inherent differences between available lamps contribute to the observed variability. It is crucial to extend this research by testing different IL, CFH and CL of varying wattages and reflector angles to provide a more comprehensive understanding.

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References

Arcadia. (2022) The Revolutionary Infrared A and B Deep Heat Projector. Arcadia Reptile. https://www.arcadiareptile.com/heat-projector/.

Baines F.M. (2017) *Lighting.* In: Doneley B., Monks D., Johnson R. Carmel B. (eds.). Reptile Medicine and Surgery in Clinical Practice. Hoboekn, NJ: Wiley Publishing, 75–90.

Baines F.M., Chattell J., Dale J., Garrick D., Gill I., Goetz M., Skelton T. Swatman M. (2016) How much UVB does my reptile need? The UV-Tool, a guide to the selection of UV lighting for reptiles and amphibians in captivity. *Journal of Zoo and Aquarium Research* 4(1): 42–63.

Barolet D., Christiaens F. Hamblin M.R. (2016) Infrared and skin: friend or foe. *Journal of Photochemistry and Photobiology B* 155: 78–85. doi:10.1016/j.jphotobiol.2015.12.014.

Brattstrom B.H. (1965) Body temperatures of reptiles. American Midland Naturalist 73: 376–422.

Brownson J.R.S. (2014) *Solar Energy Conversion Systems.* Oxford, UK: Academic Press.

Burgin R., Edwards E.F. (1970) The tungsten halogen lamp decade. *Lighting Research & Technology* 2(2): 95–108. doi:10.1177/147715357000200 20901.

Caro T. (2013) The colours of extant mammals. *Seminars in Cell & Developmental Biology* 24(6): 542–552. doi:10.1016/j. semcdb.2013.03.016.

Cheng V., Ng E. Givoni B. (2005) Effect of envelope colour and thermal mass on indoor temperatures in hot humid climate. *Solar Energy* 78(4): 528–534. doi:10.1016/j.solener.2004.05.005.

Cook J.R., Bouchard R.R. Emelianov S.Y. (2011) Tissue-mimicking phantoms for photoacoustic and ultrasonic imaging. *Biomedical Optics Express* 2(11):, 3193–3206. doi:10.1364/BOE.2.003193.

Cronin D.S. Falzon C. (2011) Characterization of 10% ballistic gelatin to evaluate temperature, aging nd strain rate effects. *Experimental Mechanics* 51(7): 1197–1206. doi:10.1007/s11340-010-9438-z.

de Andrade D.V. (2016) Temperature effects on the metabolism of amphibians and reptiles. In: de Andrade D.V., Bevier C.R., de Carvalho J.E. (eds.). *Amphibian and Reptile Adaptations to the Environment; Interplay between Physiology and Behavior*. Boca Raton, FL: CRC Press, 129–254.

Demori I., el Rashed Z., Corradino V., Catalano A., Rovegno L., Queirolo L., Salvidio S., Biggi E., Zanotti-Russo M., Canesi L., Catenazzi A. Grasselli E. (2019) Peptides for skin protection and healing in amphibians. *Molecules* 24(2): 347. doi:10.3390/molecules24020347.

Divers S.J. (2020) *Management and husbandry of reptiles - exotic and laboratory animals, MSD Veterinary Manual*. Available at: https:// www.msdvetmanual.com/exotic-and-laboratory-animals/reptiles/ management-and-husbandry-of-reptiles#Enclosure_v3307174 (Accessed: 28 December 2024).

Doneley B., Monks D., Johnson R., Carmel B. Wiley J. (eds.). (2018). *Reptile Medicine and Surgery in Clinical Practice*. Oxford, UK: Wiley Blackwell.

Falcón W., Furrer S., Bauert M., Hatt J.-M., Hansen D.M. Clauss M. (2018) Evaluation of artificial heating sources for the thermoregulation of Aldabra giant tortoises (*Aldabrachelys gigantea*) in Zurich zoo. *Zoo Biology* 37(6): 458–465. doi:10.1002/zoo.21449.

Foley R.E. Spotila J.R. (1978) Effect of wind speed, air temperature, body size and vapor density difference on evaporative water loss from the turtle *Chrysemys scripta. Copeia* 1978(4): 627–634. doi:10.2307/1443689.

Gartrell B., Ahn J., Khude R., Dougherty N., Johnson K., McCutchan J., Clarke A. Hunter S. (2020) Thermal burns of the spectacle associated with supplementary heating in native New Zealand geckos. *New Zealand Veterinary Journal* 68(2): 126–133. doi:10.1080/00480169.2019.1674747.

Gillooly J.F., Brown J.H., West G.B., Savage V.M. Charnov E.L. (2001) Effects of size and temperature on metabolic rate. *Science* 293(5538): 2248–2251. doi:10.1126/science.1061967.

Healey M. (2024) Collared Lizard Care Sheet ReptiFiles. Available at: https://reptifiles.com/collared-lizard-care-sheet/ (Accessed: 13 March 2025).

Heinrich M.L. Heinrich K.K. (2016) Effect of supplemental heat in captive African leopard tortoises (*Stigmochelys pardalis*) and spurred tortoises (*Centrochelys sulcata*) on growth rate and carapacial scute pyramiding. *Journal of Exotic Pet Medicine* 25(1): 18–25. doi:10.1053/j.jepm.2015.12.005.

Hertz P.E., Huey R.B. Nevo E. (1982) Fight versus flight: Body temperature influences defensive responses of lizards. *Animal Behaviour* 30(3): 676–679. doi:10.1016/S0003-3472(82)80137-1.

Inns H. (2019) *Britain's Reptiles and Amphibians: A Guide to the Reptiles and Amphibians of Great Britain, Ireland and the Channel Islands*. Hampshire, UK: WILDGuides Ltd.

Jung T., Höhn A., Lau A.-M., Piazena H. Grune T. (2012) An Experimental setup for the measurement of nonthermal effects during water-filtered infrared A-irradiation of mammalian cell cultures. *Photochemistry and Photobiology* 88(2): 371–380. doi:10.1111/j.1751-1097.2011.01072.x.

Jussila J. (2004) Preparing ballistic gelatine—review and proposal for a standard method. *Forensic Science International* 141(2): 91–98. doi:10.1016/j.forsciint.2003.11.036.

Kane D., Tapley B., Carter K. Michaels C. (2022) Reproduction of the Ethiopian mountain adder, *Bitis parviocula* Böhme, 1976 (Reptilia: Viperidae), at ZSL London Zoo. *Herpetology Notes* 15: 423–429.

Kane D., Stapleton H., Griffiths T. Michaels C.J., (2023) Effects of different heat and light sources on the behaviour of captive reptiles. *The Herpetological Bulletin* 166: 1-9.

Keselman H.J. (1975) A Monte Carlo investigation of three estimates of treatment magnitude: epsilon squared, eta squared, and omega squared. *Canadian Psychological Review/Psychologie Canadienne* 16(1): 44.

Levinson R., Berdahl P. Akbari H. (2005) Solar spectral optical properties of pigments—Part II: survey of common colorants. *Solar Energy Materials and Solar Cells* 89(4): 351–389. doi:10.1016/j.solmat.2004.11.013.

Lopes P.A., Santaella G.M., Lima C.A.S., Vasconcelos K. de F. Groppo, F.C. (2019) Evaluation of soft tissues simulant materials in cone beam computed tomography. *Dentomaxillofacial Radiology* 48(1): 20180072. doi:10.1259/dmfr.20180072.

Łopusiewicz Ł., Jędra F. Bartkowiak A. (2018) New active packaging films made from gelatin modified with fungal melanin. *World Scientific News* (101): 1–30.

Mendyk R.W., Newton A.L. Baumer M. (2013) A retrospective study of mortality in varanid lizards (Reptilia:Squamata:Varanidae) at the Bronx Zoo: implications for husbandry and reproductive management in zoos. *Zoo Biology* 32(2): 152–162. doi:10.1002/zoo.21043.

Motevali A., Jafari H. Hashemi J.S. (2018) Effect of IR intensity and air temperature on exergy and energy at hybrid infrared-hot air dryer. *Chemical Industry and Chemical Engineering Quarterly* 24(1): 31–42.

Nowak D. Lewicki P.P. (2004) Infrared drying of apple slices. *Innovative Food Science and Emerging Technologies* 5(3): 353–360. doi:10.1016/j.ifset.2004.03.003.

Nseowo Udofia E. Zhou W. (2020) 3D printed optics with a soft and stretchable optical material. *Additive Manufacturing* 31: 100912. doi:10.1016/j.addma.2019.100912.

Poole V.A., Grow S. (2008) Amphibian Husbandry Resource Guide. Associations of Zoo and Aquariums. Available at: https://aszk.org.au/wp-content/uploads/2019/03/amphibian_husbandry_resource_guide_1.0-1.pdf (Accessed: 28 December 2024).

Raske M., Lewbart G.A., Dombrowski D.S., Hale P., Correa M. Christian L.S. (2012) Body temperatures of selected amphibian and reptile species. *Journal of Zoo and Wildlife Medicine* 43(3): 517–521.

R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www. R-project. org/.

Ross M.R., Gillespie K.L., Hopper L.M., Bloomsmith M.A. Maple, T.L. (2013) Differential preference for ultraviolet light among captive birds from three ecological habitats. *Applied Animal Behaviour Science* 147(3): 278–285. doi:10.1016/j.applanim.2013.05.006.

Rowley J.J. Alford R.A. (2007) Non-contact infrared thermometers can accurately measure amphibian body temperatures. *Herpetological Review* 38: 308–316.

RSPCA (2024) Bearded Dragons: How to Care for Your Bearded Dragon. Available at: https://www.rspca.org.uk/adviceandwelfare/pets/other/beardeddragon (Accessed: 13 March 2025)

Ruibal R. (1961) Thermal relations of five species of tropical lizards. *Evolution* 15(1): 98–111. doi:10.2307/2405846.

Rutland C.S., Cigler P. Kubale V. (2019a) Reptilian skin and its special histological structures. In: Rutland C.S., Kubale V. (eds.). Veterinary Anatomy and Physiology. London, UK: IntechOpen. http://dx.doi.org/10.5772/intechopen.73942.

Schieke S.M., Schroeder P. Krutmann J. (2003) Cutaneous effects of infrared radiation: from clinical observations to molecular response mechanisms. *Photodermatology, Photoimmunology & Photomedicine* 19(5): 228–234. doi:10.1034/j.1600-0781.2003.00054.x.

Svobodová A., Vostálová J. (2010) Solar radiation induced skin damage: Review of protective and preventive options. *International Journal of Radiation Biology* 86(12): 999–1030. doi:10.3109/09553002.2010.501842.

Swain M.V., Kieser D.C., Shah S. Kieser J.A. (2014) Projectile penetration into ballistic gelatin. *Journal of the Mechanical Behavior of Biomedical Materials* 29: 385–392. doi:10.1016/j.jmbbm.2013.09.024.

Therneau T. (2024) *A Package for Survival Analysis in R*. R package version 3.7-0, https://CRAN.R-project.org/package=survival.

Thomas O., Kane D. Michaels C. (2019) Effects of different heat sources on the behaviour of blue tree monitors (*Varanus macraei*) in captivity. *The Herpetological Bulletin* 149: 41–43. doi:10.33256/hb149.4143.

Willis N.J., Quayle A. Brereton J.E. (2021) Rethinking Captive Heating: Effect of Infrared Radiation on the Radiated Tortoise (*Astrochelys radiata*). *Captive and Field Herpetology Journal* 5(1): 21–46.

Withers P.C. (1995) Evaporative water loss and colour change in the Australian desert tree frog *Litoria rubella* (Amphibia: Hylidae). *Records-Western Australian Museum* 17: 277–282.

Wunderlich S. (2021).thermo:waermestrahler [Licht im Terrarium]. Available at: http://www.licht-im-terrarium.de/thermo/waermestrahler (Accessed: 21 August 2022).