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Accuracy of an inexpensive, compact infrared thermometer for measuring skin surface temperature of small lizards

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ABSTRACT

Studies of thermal sensitivity in ectotherms require accurate measurements of body temperature using a reliable device, including in field situations. In this study, we tested the accuracy of a compact and inexpensive mini-infrared thermometer (mini-IRT, 22.3 g) at close distance (within 5 mm) for measuring skin surface temperature of small lizards or their models (painted copper bars). First, we used copper bars to assess the effect of model width on the accuracy of the measurement. We placed the heated models on a cool background, and then surface temperatures were measured with a mini-IRT for comparison with a thermogram from an infrared camera (IRC). We also assessed the accuracy of the mini-IRT for measuring skin temperature for two species of small lizards in the laboratory and in the field, in comparison with the skin surface temperature measured with the IRC and with cloacal temperature measured with a thermocouple thermometer. Our results with inanimate models show that the accuracy of the mini-IRT at a distance within 5 mm is biologically acceptable (within ± 1.0 °C of the mean value obtained using a more expensive, calibrated device) when the width is ≥ 7 mm. For live lizards, we observed highly significant relationships between skin surface temperature measured with the mini-IRT and temperatures measured with the two other devices. The mean discrepancies between the mini-IRT and other devices were acceptably small for geckos but larger for the smaller and more slender skinks. Taken together, our results suggest that skin temperature measured with the mini-IRT at a close distance is acceptable for field studies on lizards with an abdominal width ≥7 mm, serving as an inexpensive proxy for core body temperature in situations where portability and affordability of equipment and minimal animal handling are paramount. Nonetheless, calibration of mini-IRTs before use is strongly recommended.

1. Introduction

Temperature is a determinant of all biological processes and physiological functions in animals (Angilletta et al., 2002). In ectotherms, body temperature (T_b) has a pervasive influence on an organism's behaviour (Abram et al., 2017), performance (Gangloff and Telemeco, 2018) and overall well-being and fitness (Angilletta, 2009; Huey, 1982; Huey and Slatkin, 1976). Thus, eco-physiologists often seek to measure T_b in field and laboratory situations (Meiri et al., 2013), and the value of such information is only likely to increase as the global climate continues to warm (Deutsch et al., 2008; Huey et al., 2012; Sinclair et al., 2016).

The body temperature of ectotherms such as lizards has been measured in the past by inserting a quick-response mercury thermometer (Brooks, 1968; Mueller, 1969), or more recently a thermocouple thermometer with digital display (Sepúlveda et al., 2008; Vickers and Schwarzkopf, 2016) into the cloaca. Most recently, skin surface temperature has been examined as an alternative to core body temperature using infrared technology or by attaching temperature-sensitive data loggers or thermocouple probes to the reptile's dorsum or abdomen (Berg et al., 2015; Camacho et al., 2018; Dubois et al., 2008; Vickers and Schwarzkopf, 2016). Infrared technology gives a good indication, with minimal handling, of cloacal temperature in small reptiles (Barroso et al., 2016; Halliday and Blouin-Demers, 2017; Hare et al., 2007; Rowley and Alford, 2007; Werner et al., 2005).

To date, the infrared devices used for measuring skin temperature of small lizards include "gun-style" non-contact infrared thermometers (Carretero, 2012; Christian et al., 1998; Garrick, 2008; Halliday and

Abbreviations: T_b, Body temperature; T_{sk}, Skin surface temperature of an animate object (e.g. lizard); T_{surf}, Surface temperature of an inanimate object; T_{cl}, Body temperature measured from the cloaca using thermocouple thermometer; Mini-IRT, Compact mini-infrared thermometer; IRC, Infrared camera; SVL, Snout-vent length

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Table 1
A comparison of temperature-measuring devices used in this study.

	Mini-infrared thermometer (mini-IRT)	Infrared camera (IRC	Thermocouple thermometer (TC)
Model and Manufacturer	Compact Non-Contact IR IP67 Thermometer - QM7218, Digitech[a]	Flir i60, Flir Systems Inc. USA	Digi-Sense 8528-20 Type K, Thermocouple Digital Thermometer Cole-Parmer
Mass (with battery)	22.3 g	600 g	231.5 g
Battery type	LR44.2 1.5v (2pcs)	Li/ion 7.2, 2.2 Ah Rechargeable	9 v, Alkaline 625mAh Non- rechargeable
Temperature range	−33 to 110 °C	−20 to 350 °C	−346 to 1372 °C
Resolution/sensitivity	0.2 °C @ −9.9–110 °C	0.1 °C @ 25 °C	0.1 °C
Manufacturer's accuracy	Above 0 °C: ± 2.5% of reading	± 2 °C or ± 2% of reading, whichever is greater[c]	Above 1.0 °C: ± 0.5% of reading [b]
Cost (USD)	$28	$3500	$150
Emissivity	0.95 fixed	variable	not applicable
Distance-to-spot ratio	1:1	30:1	not applicable

[a] Subsequent to this study, a newer device with the same model number has become available in New Zealand. It is blue rather than yellow, and slightly heavier (29 g), with a wider operating range (−35 to 230 °C) and improved resolution (0.1 °C) and accuracy (± 2% of reading or 2 °C).
[b] This is for a newer available model, Type J/K/T, NIST-Traceable Calibration, as the model used in our study has been phased out by the manufacturer.
[c] We conducted additional validations for our own device, within the temperature range of biological interest, by comparing the temperatures measured over water with temperature of the water measured with a reference thermometer. Mean differences in temperature between the devices were 0.8 °C at 8 °C, 0.1 °C at 18 °C, 0.5 °C at 24 °C and 1.1 °C at 31 °C.

Blouin-Demers, 2017) and infrared cameras (Barroso et al., 2016; Tattersall, 2016). Although these devices are increasingly popular in laboratory situations, they are bulky and can involve significant cost; thus, they are not always practical for field situations. Here, we tested the accuracy of a compact and inexpensive (USD $28) mini-infrared thermometer (mini-IRT) for measuring skin temperature from a close distance in small lizards and lizard models. The device we used is sufficiently compact to be attractive in field situations (mass 22.3 g, length 82 mm, diameter 17 mm; Table 1); it is easy to carry by hand, in a pocket or with the hand strap. The temperature output, which can be converted from °C or °F, is captured within 1 s and displayed on the LCD screen. The sensor has a distance: spot (D:S) ratio of 1:1 meaning that a distance of 5 mm, the sensor takes a measurement with a spot of 5 mm in diameter; the spot becomes correspondingly larger at greater distances (and there is no laser pointer). Thus, for small lizards, the device must be brought in virtual contact with the animal's surface and would not be suitable for use from a distance.

In this study, we investigated the accuracy of this commercially available mini-IRT for measuring skin surface temperature (T_{sk}) of small lizards. We predicted that the accuracy of measurement at a close distance would depend on the width of the object being examined, a prediction that we tested experimentally with models. To guide fellow biologists, especially field ecologists working with small terrestrial ectotherms, we assessed the accuracy of the mini-IRT for measuring skin temperature in adults of two species of lizards, the larger-bodied gecko *Woodworthia* "Otago/Southland" and the smaller and more slender McCann's skink, *Oligosoma maccanni.* For the gecko (a nocturnal forager that also basks and thermoregulates under rocks by day), we examined the use of the device in both fields (daytime and nighttime) and laboratory situations. For the heliothermic skink, we examined the use by day in a laboratory situation only. To assess accuracy, we compared T_{sk} measured with the mini-IRT with temperatures measured using two calibrated devices. The comparisons were with T_{sk} measured with an infrared camera (IRC), which has been established as a proxy for core body temperature in small ectotherms (Barroso et al., 2016), and with cloacal temperature (T_{cl}) measured with a thermocouple thermometer. Our results enable us to make recommendations on the use of the mini-IRT in studies of lizard thermoregulation, including on other species.

2. Materials and methods

2.1. Description and calibration of temperature-measuring devices

The three types of devices used for the study and their specifications are presented in Table 1. We used two different mini-IRT devices (of the same model) for obtaining measurements in different parts of the study. To check the calibrations, we compared surface temperatures measured with the mini-IRTs for a terracotta tile with those measured using an infrared camera (IRC, Table 1). The tile was heated or cooled to different temperatures between −18 and 50 °C. We observed that mean temperature for both mini-IRTs were highly correlated with mean temperatures for the IRC ($r^2 \geq 0.95$); the overall mean temperatures were also within 0.8 °C of those for the IRC and each other (see supplementary information, Fig. S3). From this, we concluded that no calibration adjustments for the mini-IRTs used in our study were required (but see Discussion).

2.2. Effect of the width of a rectangular copper bar on the accuracy of the mini-IRT relative to the IRC

We made rectangular copper bars of 7 different widths (3, 5, 7, 9, 11, 13 and 15 mm, n = 5 per width) with a uniform length of 75 mm and depth of 4 mm. The models were painted grey-brown (Café-Royale, Resene Paints™) to simulate the colour of live geckos (Hare et al., 2009; Penniket and Cree, 2015). For each trial, we placed one model of each width in an incubator (Orbital, Selby Australia) for 2 h at 35 °C. The models were then removed from the incubator and placed on a ceramic tile at room temperature (18 °C). We chose this background temperature to provide an obvious contrast with the temperature of the models; thus, if the device was reading the temperature of the background rather than the model, the discrepancy should be obvious (Hare et al., 2007). Surface temperature (T_{surf}) of the models was immediately recorded in the mid-point of the length and width with a mini-IRT positioned vertically at ≤ 5 mm above the model. Immediately afterward (within 30 s) we took an infrared photo (thermogram) with the infrared camera. We repeated the trial four more times, each time with a different set of models.

The thermograms were loaded into Flir® ExaminIR software for analysis. The emissivity of the object was set at 0.95 while the background reflected temperature was set at 18 °C (room temperature during the experiment) (Tattersall, 2016). A free-hand tool on the software was used to draw a region of interest (ROI) in the centre of the model, in the same spot where the temperature had been recorded with the mini-IRT. For the larger models (width ≥ 7 mm) the diameter of the ROI (7 mm) was the same as for the mini-IRT sensor, but for the models of width 3–5 mm the diameter of the ROI was correspondingly smaller. The mean temperature recorded within the ROI was recorded as the surface temperature of the model.

2.3. Accuracy of the mini-IRT for recording skin surface and body temperatures of Otago/Southland geckos

We tested the accuracy of a mini-IRT relative to the IRC for obtaining skin surface temperature (T_{sk}) using adult *Woodworthia* "Otago/Southland" geckos (mass 9–19 g; snout-vent length (SVL) 66–88 mm) of different sexes (male and female) and female reproductive conditions (pregnant and non-pregnant). Otago/Southland geckos are rock-dwelling, primarily nocturnal lizards that also sometimes bask cryptically during the day (Gibson et al., 2015). We limited our sampling to adults, for which abdominal width (estimated retrospectively) is ~9–22 mm (cf. abdominal width in neonates can be as small as ~3 mm, see Fig. S1 Supplementary information). We collected T_{sk} data in the field at Macraes, Eastern Otago, New Zealand, between September 2017 and June 2018, from 41 geckos sampled from under rocks during the day and from 84 geckos emerged at night. We considered that background temperatures were likely to be more discrepant from T_{sk} by night, and thus that time of day might influence the accuracy of the mini-IRT. For each daytime capture, we caught the geckos by hand (avoiding touching the abdomen) and immediately recorded T_{sk} of the dorsal posterior abdomen with the mini-IRT and then the IRC in quick succession (within 30 s). The mini-IRT was positioned vertically above and within 5 mm of the dorsal posterior abdomen. The maximum of 5 mm distance virtually eliminates many of the atmospheric concerns that are present with infrared technology (Faye et al., 2016). Geckos were returned to their capture rocks. At night, emerged geckos were located by torchlight on rock surfaces within 3–4 h after dusk. For each gecko, a thermogram was first taken with the IRC without disturbing the animal. We then immediately recorded T_{sk} with the mini-IRT as above, avoiding any influence on T_{sk} through handling, before releasing the gecko. To assist analysis of IRC images, we also recorded shade air temperature during fieldwork, at 1 min intervals, with a Thermocron iButton™ (Maxim Integrated CA 95134 USA) hung at 1.2 m above the ground). We assumed the reflected temperature to be equal to air temperature (all our night data were measured under cloudy conditions, without a clear sky). Also, a relatively small amount of radiation is emitted for an object of high emissivity measured from a distance less than 0.5 m (Tattersall, 2019).

For analysis of thermograms, we drew a circular ROI on the dorsal posterior abdomen of the geckos (estimating the area where mini-IRT reading was taken) as described above. The emissivity was set at 0.95 for live animals while the background reflected temperature was set at the air temperature (Tattersall, 2016). We set the humidity with data recorded hourly at the Otago Rural Fire Authority weather station about 3 km from the field site. In the same species, we also compared the accuracy of T_{sk} measured with the mini-IRT relative to cloacal temperature (T_{cl}) measured with the thermocouple thermometer. Paired data (T_{sk}, then T_{cl} within ~30 s) were obtained by day (November 2016) from 24 adult geckos in the field, and from 23 adult geckos in a laboratory colony at the University of Otago over a range of body temperatures.

2.4. Accuracy of the mini-IRT for recording skin surface and body temperatures of McCann's skink

McCann's skink is a small diurnal, rock-dwelling species (mass: 2–4 g; SVL 48–67 mm). Our measurements were obtained from adult skinks (males and non-pregnant females) held in temporary captivity for other studies (abdominal width, estimated retrospectively from its correlation with SVL, was ~5–7 mm for these individuals, see Fig. S1 Supplementary information). Skinks were held in individual enclosures and measurements were taken in March/April 2018. Measurements were taken across a range of body temperatures, achieved by including times at which skinks did or did not have access to a heat lamp. For each skink, we recorded three measurements in quick succession: T_{sk} using the IRC, T_{sk} using the mini-IRT (both before the skink was handled for T_{cl}) and then T_{cl}. We obtained 36 sets of measurements from 28 skinks (repeat sampling was on different days under different thermoregulatory conditions).

2.5. Data analysis

All data were analysed in R (R Core Team, 2018) and statistical significance was assumed at $P < 0.05$. For the effect of model width on the accuracy of the mini-IRT, we examined temperature differences (ΔT) measured between the two devices ($T_{surf(mini\text{-}IRT)} - T_{surf(IRC)}$). We fitted a linear model to examine ΔT as a function of model width, followed by post-hoc tests to examine pairwise differences (Tukey HSD). We examined the plot of residuals and Cook's distance using the "autoplot" in R package, "tidyverse". For models with widths of 7 mm and above, we plotted a linear regression between $T_{surf(mini\text{-}IRT)}$ and $T_{surf(IRC)}$ using "lmodel2′ R package and used paired t-tests to compare the mean temperatures.

With live lizards, we examined the relationships between $T_{sk(mini\text{-}IRT)}$ and $T_{sk(IRC)}$, and between $T_{sk(mini\text{-}IRT)}$ and T_{cl}, using ordinary least square (OLS) linear regression ("lmodel2′ R package). We use paired t-tests to compare mean temperatures between each device. To understand the effect of time of day on mini-IRT values measured in the field, we fitted a linear model with $T_{sk(mini\text{-}IRT)}$ as the dependent variable and the time of day (daytime or nighttime) as an independent variable. We compared the mean temperature difference with non-paired Student's t-test.

3. Results

3.1. Effect of the width of a rectangular copper bar on the accuracy of the mini-IRT relative to the IRC

The overall effect of model width on ΔT accuracy of mini-IRT was statistically significant ($F_{6,26} = 41.92$, $P < 0.001$). Post-hoc tests (Tukey HSD) showed that the mean discrepancy between devices (ΔT, $T_{surf(mini\text{-}IRT)}–T_{surf(IRC)}$) for the model size of 3 mm was high and significantly different from other model sizes (for 3 mm, mean: 7.12 ± 1.67 °C, $P < 0.001$). Although post-hoc tests did not identify ΔT for the 5 mm model (−1.24 ± 0.38 °C) as different from the wider models, the variation was greater with this model width and beyond our target consistency of being within ± 1.0 °C. For models of width 7 mm and above, the relationship between individual values for $T_{surf(mini\text{-}IRT)}$ and $T_{surf(IRC)}$ was significant ($r^2 = 0.40$, $P < 0.01$) (Fig. 1 insert). Although the mean temperatures between the two devices differed significantly (paired $t = 4.124$, $df = 24$, $P = 0.001$), the mean discrepancy was very small (less than ± 0.3 °C; Fig. 1).

3.2. Accuracy of the mini-IRT for recording skin surface and body temperatures of Otago/Southland geckos

In the field, we observed a highly significant relationship between $T_{sk(mini\text{-}IRT)}$ and $T_{sk(IRC)}$ during both daytime ($r^2 = 0.98$, $P = 0.01$, N = 40, OLS) and night-time ($r^2 = 0.93$, $P < 0.01$, N = 83, OLS) (Fig. 2a). The mean differences between $T_{sk(mini\text{-}IRT)}$ and $T_{sk(IRC)}$ measured by daytime (paired $t = -2.592$, $df = 39$, $P >$ 0.01) and at nighttime (paired $t = 18.41$, $df = 82$, $P < 0.001$) were both statistically significant, and the effect of time of day was also significant ($t = -9.353$, $df = 52.73$, $P < 0.001$). However, the mean discrepancies between $T_{sk(mini\text{-}IRT)}$ and $T_{sk(IRC)}$ were very small (−0.37 ± 0.91 °C by day and 1.07 ± 0.53 °C by night). Combining both times of day, the mean discrepancy recorded was only 0.60 °C (maximum 2.8 °C) and 53% of the values were within ± 1.0 °C of values for the IRC (Fig. 3).

The regression between $T_{sk(mini\text{-}IRT)}$ and T_{cl} was also highly significant ($r^2 = 0.98$, $P < 0.01$, N = 28, OLS) (Fig. 2b) and mean temperatures recorded with the two devices differed significantly (paired

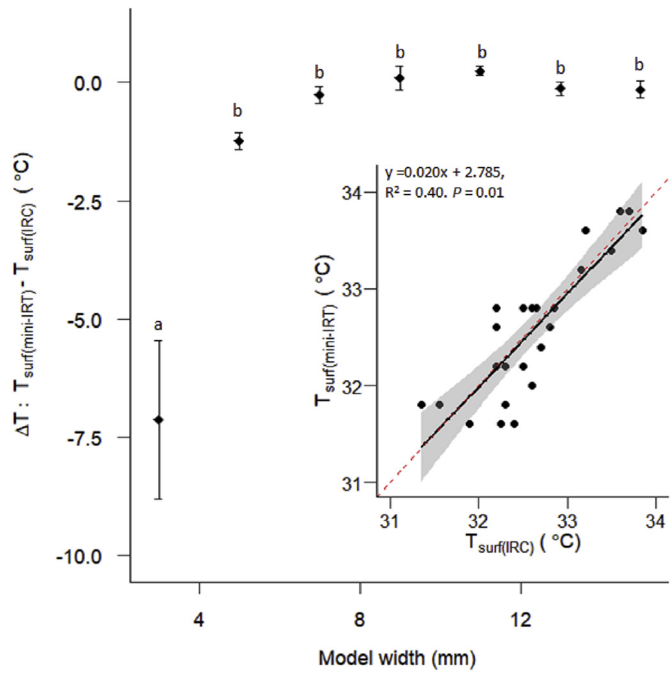

Fig. 1. Main Figure: Effect of width of copper models (rectangular bars) on discrepancy between surface temperatures measured with a mini-IRT and with an IRC (mean ± SE, n = 5 per model width, $P < 0.01$, Tukey HSD). The model width with letter 'a' differed significantly from models with letter 'b'. Insert: Relationship between the surface temperatures measured for each device for copper models ≥7 mm in width. Each dot represents one copper model. The grey shaded area is the 95% confidence interval on the fitted line. Broken red line represents the isothermal line.

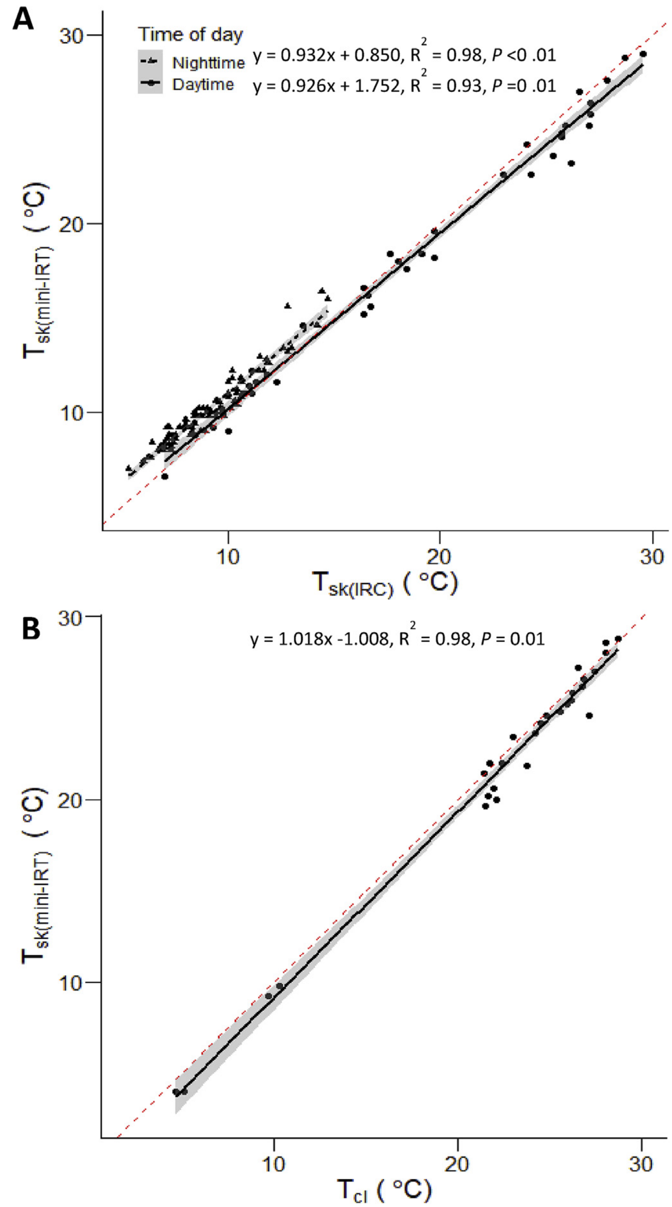

Fig. 2. Regression plots for body temperatures of adult geckos (*Woodworthia* "Otago/Southland") measured with different devices. A) Skin temperature (T_{sk}) measured with a mini-IRT and from thermograms taken by an infrared camera, by daytime (n = 40) and by nighttime (n = 84). B) Skin temperature (T_{sk}) measured with a mini-IRT and cloacal temperature (T_{cl}) measured with a thermocouple thermometer (n = 47). Broken red line represents the isothermal line.

$t = -3.96$, $df = 27$, $P < 0.001$). However, the mean discrepancy between $T_{sk(mini\text{-}IRT)}$ and T_{cl} was small (−0.6 °C; maximum −2.5 °C), and 75% of mini-IRT values were within ± 1.0 °C of the temperature recorded with a thermocouple thermometer (Fig. 3).

3.3. Accuracy of the mini-IRT for recording skin surface and body temperatures of McCann's skink

Although the regression between skin temperature measured with the mini-IRT and with the IRC was highly significant ($r^2 = 0.95$, $P < 0.01$, $N = 36$, OLS; Fig. 4A), the mean discrepancy (−2.0 °C) was also significant (paired $t = -9.20$, $df = 35$, $P < 0.001$) and the line fell below the isothermal line. The maximum discrepancy was −4.9 °C, and only 31% of mini-IRT values fell within ± 1.0 °C of IRC values (Fig. 3). The mean discrepancy was also significantly greater for McCann's skink than for the Otago/Southland gecko (Fig. 3A).

For McCann's skink, we recorded a significant relationship between skin temperature measured with the mini-IRT and cloacal temperature that was closer to the isothermal line ($r^2 = 0.92$, $N = 36$, $P < 0.01$, OLS; Fig. 4B). The mean discrepancy was significant (−1.1 °C; $t = -6.28$, $df = 35$, $P < 0.001$); the maximum was −3.0 °C, and only 50% of values were within ± 1.0 °C (Fig. 3).

4. Discussion

Our study provides information on the value of a mini-IRT for estimating mean body temperatures of small lizards. In practice, the mini-IRT is easy and quick to use, and when care is taken with positioning and animals are sufficiently large, it can provide mean values for skin temperature that are comparable with those obtained using more expensive and bulky devices. It can also provide mean values for skin temperature that are comparable with those for cloacal temperature measured with a thermocouple, in a manner that requires less training and animal handling. The device is also inexpensive and has a longer battery life than an IRC.

Nonetheless, there is a lower limit to animal width below which results will be unreliable. Our tests with inanimate models (painted copper bars) showed that the discrepancies were uniform and small (± 0.3 °C) for the models with widths of 7–15 mm. At 5 mm wide, the variation increased, and for the 3 mm width, the discrepancy was unacceptably large, probably reflecting the influence of background temperature during the measurement. Therefore, even when used at a close distance, we highly recommend against using this device on organisms less than 5 mm wide.

When tested with the live adult geckos studied here (*Woodworthia* "Otago/Southland", ~9–19 g), for which abdominal width is likely to

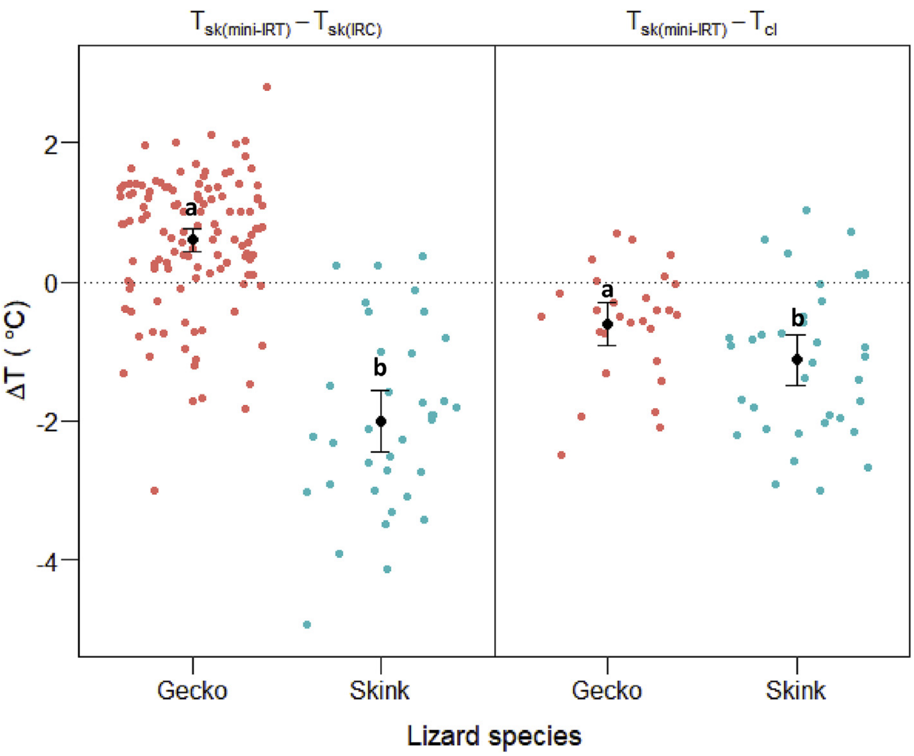

Fig. 3. Differences between body temperatures measured with different devices for two species of lizards: adult geckos (*Woodworthia* "Otago/Southland") and adult McCann's skinks (*Oligosoma maccanni*). A). Difference between skin temperatures (T_{sk}) measured with a mini-IRT and those measured with an infrared camera. B). Difference between skin temperature measured with a mini-IRT and cloacal temperature (T_{cl}) measured with a thermocouple thermometer. Mean discrepancy (± SE) is shown for each group. Lizard species with letter 'a' differed significantly from those with letter 'b' within each comparison. The data shown here are the discrepancy between the two devices plotted in Figs. 2 and 4. Broken red line represents the isothermal line.

have been between ~ 9 and 22 mm, the skin surface temperatures measured with the mini-IRT were undoubtedly associated with temperatures obtained with the infrared camera (for skin) or thermocouple (for the cloaca). In both field and laboratory settings for geckos, the coefficient of determination for all regressions was above 90%. These values are similar to those of Barroso et al. (2016), who recorded correlation coefficients (R^2) of 0.838–0.968 between skin surface temperature (as measured with an infrared thermal camera) and cloacal temperature for the lacertid lizard species. Our values for geckos are also better than the correlations obtained by Carretero (2012) when comparing skin temperatures measured with a larger infrared thermometer and cloacal temperature measured with thermocouple thermometer for small lacertids (*Podarcis* sp.). Although the infrared devices used for these studies are different from our mini-IRT, all work on the same principle. We also found, for geckos, that time of day had a small effect on the accuracy of the mini-IRT device (relative to the IRC) in the field; however, mean discrepancies were less than or equal to 1 °C in both daytime and nighttime. The lower variance at night may arise because the background temperature is likely to be more similar to the gecko's body temperature at night than by day.

We also examined the performance of the mini-IRT for non-pregnant females and male individuals of a smaller species, McCann's skink (*Oligosoma maccanni*, ~2–4 g), for which abdominal width ranges from ~5 to 7 mm. For the skinks, we observed highly significant correlations between skin surface temperatures measured with the mini-IRT and the infrared camera, and between skin temperatures measured with the mini-IRT and cloacal temperatures measured with the thermocouple. However, the discrepancies were larger than for the gecko, and more than we might have expected from the inanimate models of similar width. In a previous study with McCann's skinks using a more expensive "gun-style" IRT, the mean discrepancy between the infrared thermometer (when correctly positioned) and cloacal temperature measured with a thermocouple was about 0.6 °C (Hare et al., 2007). In the present study with the less expensive mini-IRT, the discrepancies may have been greater than in the earlier study with McCann's skinks, and greater than in the present study for the geckos and the copper bars, because of a greater influence of background temperature. Live McCann's skinks have narrower abdomens than the geckos studied here, and are also more inclined to squirm; thus, it is harder to position the mini-IRT over the abdomen without the influence of background temperature. As suggested by Jones and Avery (1989) in a study with *Lacerta vivipara* of 3–5 g, in which a maximum discrepancy of 0.2 °C was observed, the discrepancy may also be attributed to a real difference between the surface and core body temperature. Overall, we suggest that reliable mean values for skin temperature may be obtained using the mini-IRT at close distance for lizards with an abdominal width of ≥7 mm; results may be useful for species with abdominal widths of 5–7 mm (depending on the purpose) but need to be validated against another method, whereas below about 5 mm measurements should not be attempted.

One of the limitations of the mini-IRT is the 1:1 distance: spot ratio, which means maintaining the device close to the animal, yet preferably not touching it so that disturbance is minimised. Furthermore, as handling can influence an ectotherm's T_b through heat conduction from the researcher's hand (Halliday and Blouin-Demers, 2017), care must be taken to minimise handling and to avoid touching the abdomen where T_{sk} is to be measured (we recommend holding the animal by the limbs or around the shoulders). In addition, as with many thermometers, the compact mini-IRT only measures spot temperature. For changes in body temperature over time, researchers may wish to consider attaching bio-loggers (Virens and Cree, 2018) or implanted devices (Halliday and Blouin-Demers, 2017). These will, of course, introduce additional welfare considerations.

Nonetheless, the mini-IRT may hold value for field studies where spot body temperatures are being sought. Data on activity temperatures in wild lizards are of interest to ecologists and eco-physiologists for many reasons (Andrews et al., 1999; Ibargüengoytía, 2005; Huey et al., 2009). However, such activity temperatures are available for only about 861 of the world's 6512 + species of lizards (Meiri et al., 2013). To illustrate for an understudied fauna, in New Zealand field body temperatures have been reported (for spring-summer) in only 14 of more than 100 proposed species (Hare and Cree, 2016). Many species for which data are currently lacking live in remote and infrequently visited areas (e.g. mountains, offshore islands) and are sparsely distributed, and when surveys are conducted, team members often split up

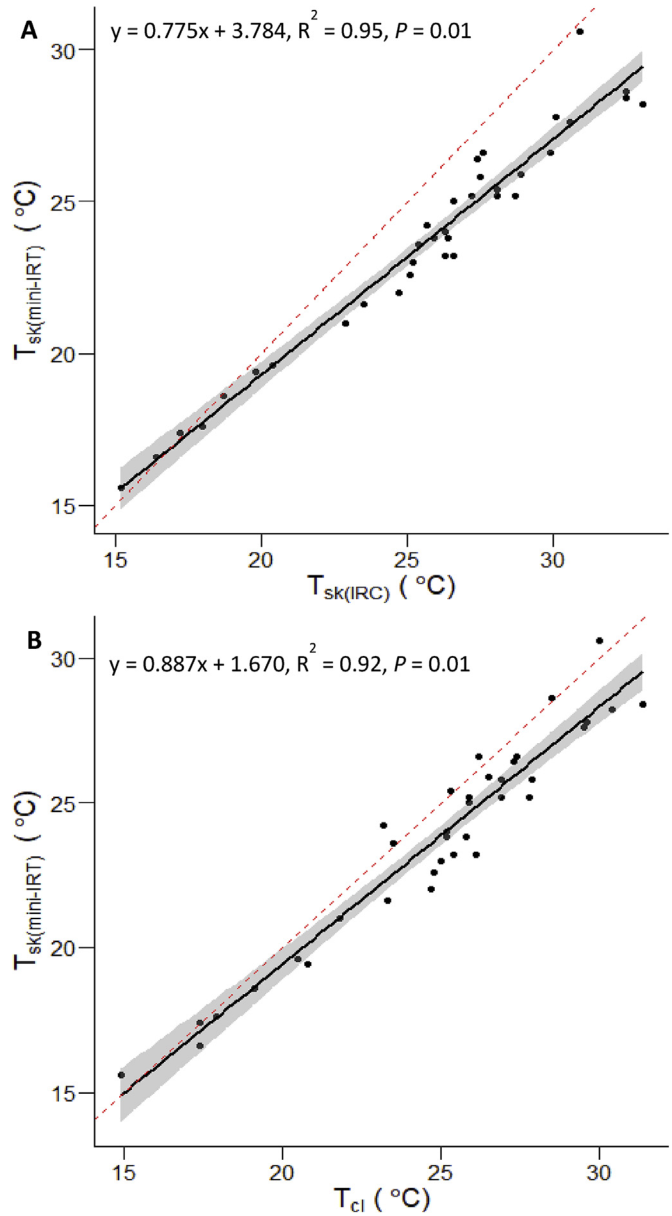

Fig. 4. Regression plot for body temperatures of adult McCann's skinks (*O. maccanni*) measured with different devices. A). Skin temperature (T_{sk}) measured using a mini-IRT and from thermograms taken by an infrared camera. B). Skin temperature measured with a mini-IRT and cloacal temperature (T_{cl}) measured with a thermocouple thermometer (n = 36 for each group). Broken red line represents the isothermal line.

to cover difficult terrain. We recommend the inclusion of mini-IRTs as part of the standard field kit for future surveys. The mini-IRT may also be useful in laboratory teaching exercises as it is inexpensive, does not require technical knowledge and is easy to handle. However, we recommend periodic calibration against a standard reference temperature tool, such as an infrared camera or mercury thermometer, to be sure that results are accurate and can be pooled from different devices.

Conflicts of interest

There are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2019.07.016.

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