

Predicting small endotherm body temperatures from scalp temperatures

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Abstract

We used 2-d to 3-d-old mallard ducklings (*Anas platyrhynchos*) to test whether remote thermographic measurement of scalp temperature could be used to estimate core (cloacal) temperature from a distance. The scalp was exposed by trimming down from an area of $\leq 1 \text{ cm}^2$, and surface temperature measured to $\pm 0.12^\circ\text{C}$ with a radiometric thermal imager. For wind speeds of up to 2.5 m/s, we found cloacal temperature could be estimated to within 1°C by using a regression model incorporating only scalp temperature and ambient temperature. The inexpensive method of dyeing the scalp black and painting it with temperature-sensitive cholesteric liquid crystal paint is more difficult and provides less accuracy, but appears to be a useful means for monitoring change in body temperature. These methods allow body temperatures of small or young endotherms to be monitored from distances of up to several meters without surgery or encumbering wires, minimizing stress that may alter behavior patterns and physiological parameters.

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1. Introduction

Behavioral and many physiological studies need a non-invasive means to estimate the body temperature of small animals from a distance. A nearby observer may alter behavior, and approaching, handling, or restraining an animal causes an increase in body temperature and heart rate (Southwick, 1973; Heatwole et al., 1979; Cabanac and Gosselin, 1993; Moe and Bakken, 1997; Cabanac and

Aizawa, 2000; Cabanac and Bernieri, 2000; Cabanac and Guillemette, 2001). Radiotelemetry implants can be used with animals large enough to carry them (Aldridge and Brigham, 1988; Amlaner, 1989) but require a significant incision and postoperative recovery period (Perry, 1981; Pietz et al., 1993; Wang and Adolph, 1995). This limits their usefulness for studies of neonatal animals, whose physiological characteristics change rapidly during the first few days (Starck and Ricklefs, 1998). Temperature-sensitive passive integrated transponders (PIT tags) are very small (ca. 2 mm diameter \times 12 mm long), but still require an incision for implantation and have short transmission ranges ($\leq 5 \text{ cm}$, Kort et al., 1997). Radiotelemetry of skin surface temperature avoids surgery, but accuracy is reduced (Willis and Brigham, 2003) and the transmitter may affect behavior (Perry, 1981; Pietz et al., 1993; Rotella et al., 1993).

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Infrared thermometry can measure the temperature of an exposed surface from distances of several meters. Core temperature can be estimated from skin temperature when the core–skin temperature difference is small and predictable. The difference is determined by surface cooling, tissue thickness and tissue perfusion. Thus, the tympanic membrane is frequently used in clinical medicine because it is located close to the brain in a deep depression that shields it from forced convection (Yaron et al., 1995; Stavem et al., 1997). Unfortunately, the tympanum is not easily imaged from a distance. However, the body temperatures of small reptiles have been estimated from skin temperature successfully because only a small amount of heat flows through a thin layer of tissue (Gates, 1968; Jones and Avery, 1989; Tosini and Avery, 1993, 1996; Shine et al., 2002).

We propose that scalp temperature might similarly be used on small birds by trimming feathers from an area of the scalp directly over the brain. The tissue between the brain and skin is thin (Dawson and Whittow, 2000), and thus brain–skin temperature differences are usually small. Convective cooling is a potential source of error, but down surrounding the trimmed spot provides some convection shielding, and air temperature and wind speed data might be used to make corrections (Audet and Thomas, 1996). Alternatively, the trimmed area could be covered with a polyethylene film convection shield glued to the tips of the surrounding feathers.

We tested this approach using 2-d- to 3-d-old mallard ducklings (*Anas platyrhynchos*). Ducklings were studied while exposed to a range of air temperatures and wind speeds to test for errors caused by convection, and while swimming in cold water to test for errors due to head–body temperature differences. We developed models that estimated cloacal temperatures from thermographic scalp temperatures. Finally, we also tested whether temperature-sensitive cholesteric liquid crystal paints might provide an inexpensive alternative to thermography for remote scalp temperature measurements.

2. Materials and methods

2.1. Duckling measurements

All experimental procedures were approved by the Indiana State University Institutional Animal Care and Use Committee, Protocol 01–08:GB. We hatched ducklings from fertilized mallard eggs (Whistling Wings, Hanover, IL, USA). Parents were derived from wild stock (ca. fifth generation). When ducklings were approximately 24 h old, they were transferred from a brooder to a 1.3 m diameter plastic wading pool filled with 6–8 cm of water and equipped with a brooder on a

central island. Ducklings were maintained at 27 °C and 12:12 L:D photoperiod with poultry starter available ad libitum. We imprinted ducklings on a mallard hen decoy attached to an arm driven by a 3-rpm motor, which towed the decoy around the pool intermittently (1 min on, 4 min off). Ducklings were tested when 2–3 d old.

The main series of experiments was conducted in a wind tunnel respirometry chamber (Bakken et al., 1989) operated at various air temperatures and wind speeds to test for errors caused by convection conditions. A purpose-built optical tachometer attached to the blower shaft was calibrated using a Prandtl-design Pitot tube and electronic hook gauge to give wind speed accurate to ± 0.05 m/s (Prandtl and Tietjens, 1934). Because metabolic heat production might also be a significant covariate affecting brain–scalp temperature differences, we measured respiratory gas exchange. The open-circuit respirometry procedures and instruments are described elsewhere (Bakken et al., 1999; Banta et al., 2004). Air, floor, and duckling cloacal temperatures were measured with type TT thermocouples. A digital data logger (CR-21X, Campbell Scientific, Logan, UT, USA) recorded all data at 1 min intervals, and oxygen consumption was calculated for each consecutive 2-min interval using Z-transform methods (Bartholomew et al., 1981).

Each duckling was randomly assigned to 1 of 4 air temperatures (5, 15, 25 or 35 °C). Data were collected during 4 consecutive 15 min runs at 4 wind speeds in randomized order (0.5, 1.7, 2.0 and 2.5 m/s) under room illumination (300 lux) during the active phase. A few ducklings were tested again the following day at a new air temperature using a different sequence of wind speeds.

A second series of measurements tested for head–body temperature differences using ducklings swimming at 30 cm/s in the plastic respirometry enclosure of a flow tank (Vogel and LaBarbera, 1978; Fish, 1995). The flow tank was housed in a controlled environment room (model 8083, Hotpack Corporation, Philadelphia, PA, USA). Ducklings were tested at 1 of 6 water temperatures (5, 10, 15, 20, 25, and 30 °C) with air temperatures either 10 or 15 °C above water temperature. Procedures were otherwise similar to the wind tunnel experiment, except that water temperature was recorded in place of floor temperature.

Before each experiment, we weighed the duckling and created a thermography target by using fine embroidery scissors to trim the down from ≤ 1 cm² of the scalp at a point directly over the brain. We lubricated the rounded sensing junction of a thermocouple with petroleum jelly, inserted it 1.5–2 cm into the cloaca, and secured it by using Skin Bond[®] adhesive (Smith-Nephew Inc., Largo, FL, USA) to glue several adjacent down feathers over a button attached to the thermocouple. After a 5–10 min recovery period, we placed the duckling in the experimental enclosure. Ducklings were allowed 10 min to

adjust to being placed in the chamber, plus 5 min to adjust to each wind speed in the first experimental series. Data were then recorded for 10 min at each wind speed, or for 60 min in the flow tank. Most ducklings were removed at the end of the experiment after a total of 70 min in the chamber, but a few ducklings were allowed to continue swimming in the flow tank for an additional 3–4 h to examine long-term patterns in body and scalp temperature.

2.2. Thermography

2.2.1. Thermal imager

We used a ThermaCAM PM 575 uncooled microbolometer thermal imager (FLIR Systems, North Billerica, MA, USA) to record digital thermographic images. Images are recorded as digital files (320×240 pixels, $\pm 0.1^\circ\text{C}$ resolution and $\pm 2^\circ\text{C}$ accuracy from -20 to $+350^\circ\text{C}$) for later analysis with IRwin Research 2.01 software (FLIR Systems, North Billerica, MA, USA). The imager was equipped with an 80° wide-angle lens attachment that has a close focus distance < 2 cm from front lens element. We machined apertures in the tops of the enclosures, equipped each with an o-ring seal, and arranged latches to lock the 80° lens attachment firmly in place. The 80° lens attachment thereby served as a close-up lens, imager mount, and sealed window into the respirometry enclosure.

Because thermal radiation indicates surface temperature indirectly, indicated temperatures include effects due to ambient thermal radiation reflected from the object of interest and absorption and emission of thermal radiation in windows or lenses (Gates, 1968). The images must be adjusted for these effects to obtain true surface temperature. To do this, we made a calibration target consisting of an aluminum cylinder painted flat black and insulated with synthetic fur except for a 1 cm diameter opening on the top. This was placed at the point normally occupied by the duckling, electrically heated to 40 – 50°C , and then allowed to cool while synchronized thermocouple and thermographic temperatures were recorded for each combination of experimental conditions used in the duckling experiments.

We also tested the effect of a polyethylene convection shield in the wind tunnel as a way to minimize the effect of air temperature and wind on thermographic temperature measurements. The test shield consisted of a 0.025 mm thick polyethylene film glued over the opening in the insulation.

2.2.2. Thermal image processing

For the wind tunnel data, we selected the best image from among several recorded manually during each 1-min interval. We used IRwin Research 2.01 to record the

highest temperature in the image, which was the shaved spot on the scalp. We corrected for zero drift by adding the difference between thermocouple and thermographic floor temperature to the indicated thermographic scalp temperature, T_1 , to obtain an offset-corrected value, T_o . We averaged 4–5 sequential pairs of thermographic and cloacal temperatures from the last 5–7 min of each run. These averages (4 per 70-min run) were used for statistical analysis to avoid autocorrelation problems (Reynolds, 1994).

Based on the wind tunnel results, we recorded thermal images and other data at 5 s intervals during the flow tank experiments and computed 1-min averages for all recorded variables. Scalp temperatures were corrected for drift using water temperature as a reference. For analysis, we averaged 5 values at the end of each run. Because swimming effort might affect the results, we computed the fraction of each minute spent swimming from a count of the number of images in each 1-min interval where the duckling was resting against the back of the respirometry enclosure.

2.2.3. Temperature-sensitive paint

An inexpensive alternative to infrared thermography is to coat the skin with a temperature-sensitive paint containing microencapsulated cholesteric liquid crystal material. These paints are available in a series of formulations with adjacent 5°C ranges covering a span from 25 to 45°C (Thermal Liquid Crystal Paints, Edmund Scientific, Tonawanda, NY, USA). We tested this alternative by dyeing the trimmed area of the scalp of several ducklings with a black permanent marking pen (Sharpie, Sanford Inc. Bellwood, IL, USA). We then used a fine (#2) camel's hair watercolor brush to paint one side of the spot with paint responding from 30 to 35°C , and the other with a paint responding from 35 to 40°C (Thermal Liquid Crystal Paints CR30543-87 and CR30543-88, Edmund Scientific, Tonawanda, NY, USA). During these experiments, we photographed the scalp using both color film and digital cameras.

2.3. Data analysis

We tested two regression models for correcting indicated surface temperature to true temperature using data from the aluminum cylinder calibration targets. One was a model based on optical physics

$$T_c = [(T_o^4 - \alpha_{\text{eff}} T_a^4) / (1 - \alpha_{\text{eff}})]^{1/4}. \quad (1)$$

The effective thermal infrared absorptance, α_{eff} , of window(s) between the target and the imager was estimated by nonlinear regression. Window temperature was assumed equal to the air temperature, T_a , affecting the window elements. The second calibration model was a linear regression model.

We used the cylinder regression model to correct indicated scalp temperature, and used this in a regression model estimating cloacal temperature. Primary independent variables included T_c , T_a , wind, and $[\text{wind} \times (T_c - T_a)]$. Covariates included hours since hatching, mass, metabolic rate, size of trimmed spot, distance between the culmen and nearest edge of trimmed spot, and, for the flow tank experiments, the activity score. We used all-possible-models analysis to find the best model without overfitting (Draper and Smith, 1981; Ginzburg and Jensen, 2003). Statistical significance is indicated with Fisher's F statistic and probability of type I error, p . Confidence intervals for individual predictions of surface or cloacal temperatures are presented as the standard error of the estimate, s.e.e. The s.e.e. is the standard deviation of the individual points relative to the regression model, and indicates the precision of an individual thermographic temperature estimate. All linear and nonlinear regression calculations were made using SYSTAT 7.0 (Wilkinson, 1996).

3. Results

3.1. Converting indicated to true surface temperature

Indicated infrared temperature T_1 and true temperatures of the bare spot on the aluminum cylinder in the wind tunnel are plotted in Fig. 1A. Air temperature T_a ranged from 5 to 35 °C, while the imager body remained at room temperature (22–24 °C). Over this limited range of temperatures, nonlinear regression to the physically correct model (Eq. (1)) did not converge. The linear

model for surface temperature was

$$T_c = -1.327 + 1.080T_o - 0.0442T_a, \quad (2)$$

$$\text{s.e.e.} = 0.12 \text{ } ^\circ\text{C}, F_{2, 505} = 1.2 \times 10^6, P < 0.0001.$$

To test the effect of ambient temperature on the imager, we repeated the measurements using the flow tank system in the controlled environment room so that temperature of the imager could be varied from 7 to 32 °C. It was important to allow the imager to equilibrate before recording images, as thermal gradients within the imager caused by a 15 °C change in ambient temperature could produce transient errors of several degrees. The best-fit model was

$$T_c = -1.506 + 1.088T_o - 0.0448T_a, \quad (3)$$

s.e.e. = 0.12 °C, $F_{2, 202} = 5.4 \times 10^5$, $P < 0.0001$. The small differences between the model coefficients may result from either different temperature gradients in the 80° lens attachment in the two experimental setups or the effect of ambient temperature on the imager.

3.2. Heated calibration target with convection shield

When a patch of polyethylene film was placed over the bare area of the cylinder to simulate the effect of a similar convection shield on a duckling, data taken at a given chamber air temperature fell along a line that crosses the line of equality at the approximate convection shield temperature (Fig. 1B). For these data

$$T_c = -2.066 + 1.209T_o - 0.144T_a, \quad (4)$$

$$\text{s.e.e.} = 0.19 \text{ } ^\circ\text{C}, F_{2, 229} = 5.9 \times 10^5, P < 0.0001.$$

Nonlinear regression using Eq. (1) estimated the effective overall thermal infrared absorptance of the

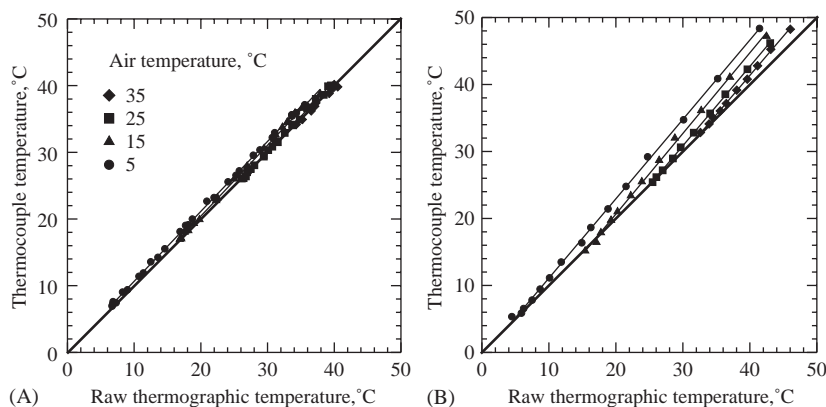


Fig. 1. Surface temperature of calibration target in wind tunnel metabolism chamber vs. thermographic temperature. Data were recorded at four different chamber air temperatures and four different wind speeds from 0.4 to 2.5 m/s. (A) Bare spot uncovered. While wind speed had no effect, the 80° lens attachment (which tracks air temperature) absorbed some radiation from the target and emitted some thermal radiation. This caused data taken at different chamber air temperatures to fall on slightly different lines as described by Eq. (2). (B) Bare spot covered with a 0.025 mm thick polyethylene film convection shield glued to the top of the synthetic fur fibers. The convection shield absorbed radiation from the target and added thermal radiation emitted at air temperature, causing the data taken at different chamber air temperatures to fall on markedly different lines as described by Eq. (3).

convection shield, α_{eff} , to be 0.171. Although physically correct, Eq. (1) predicted surface temperature less accurately (s.e.e = 0.4 °C) than did Eq. (4).

3.3. Duckling

3.3.1. Wind tunnel metabolism chamber

Because the cylinder studies found that a polyethylene convection shield doubled the s.e.e. and thus might create more problems than it solved, we first tested ducklings without a shield to see if $\text{wind} \times (T_c - T_a)$ entered the model. If so, then convective skin cooling significantly changed T_1 and a convection shield might improve accuracy. If not, a convection shield provides no benefits to balance against the increased s.e.e.

Cloacal temperature is plotted as a function of scalp temperature in Fig. 2. The importance of correcting for physical effects associated with the presence of windows is evident in the curvature of the T_b by T_c plot (Fig. 2A), which is absent when T_b is plotted against T_c (Fig. 2B).

Final models rejected all covariates and included only primary variables. The best model predicting duckling

T_b in the wind tunnel experiment was

$$T_b = 1.863 + 0.967T_c, \quad (5)$$

s.e.e = 1.0 °C, $F_{1,150} = 485$, $P < 0.0001$. The relation between measured and predicted cloacal temperature is plotted as the line in Fig. 2C. Wind and $[\text{wind} \times (T_c - T_a)]$ did not enter either forward or backward stepwise analysis, indicating that a convection shield is unnecessary for wind < 2.5 m/s.

3.3.2. Flow tank

The increased smoothing used for the swim tank thermographic data gave somewhat more accurate predictions of body temperature, with s.e.e = 0.7 °C, $F_{2,40} = 23$, $P < 0.0001$.

Interesting relationships among swimming activity, scalp temperature, and cloacal temperatures are evident in the data from ducklings that were allowed to swim for several hours. As an example, scalp temperature, cloacal temperature, and the swimming activity index are plotted for one duckling in Fig. 3. All parameters vary in parallel (indicated by vertical lines in Fig. 3). Time

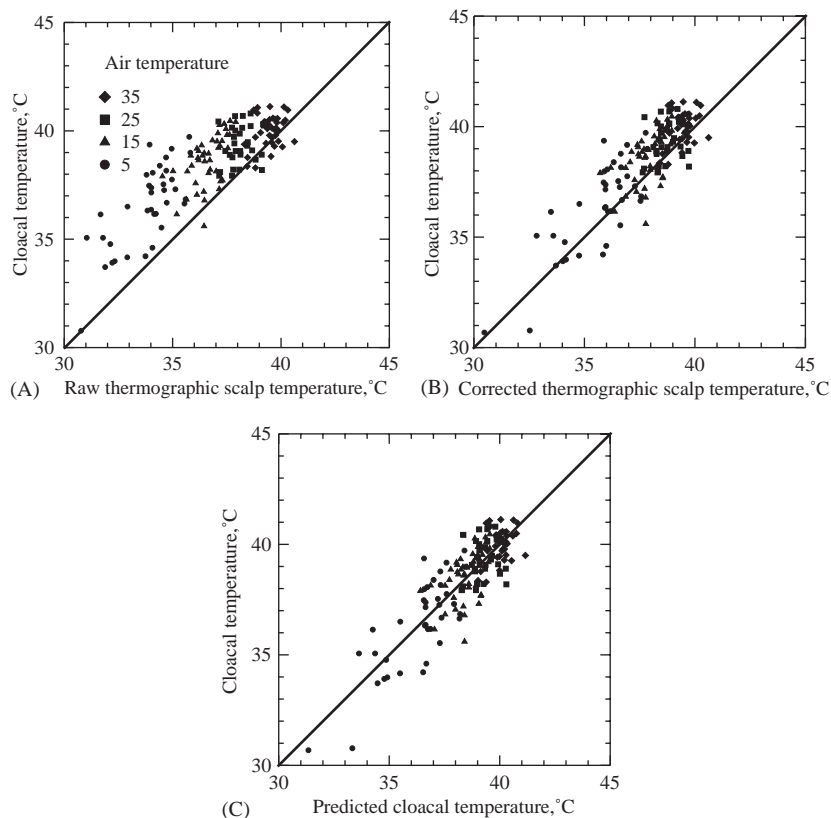


Fig. 2. Cloacal body temperature predicted by thermographic measurements of scalp temperature. (A) Cloacal temperature vs. raw thermographic scalp temperature. (B) Cloacal temperature thermographic vs. true radiometric scalp temperature calibrated using Eq. (3). Scalp temperature averaged about 1 °C lower than cloacal temperature. (C) Measured cloacal temperature vs. cloacal temperature predicted by Eq. (5).

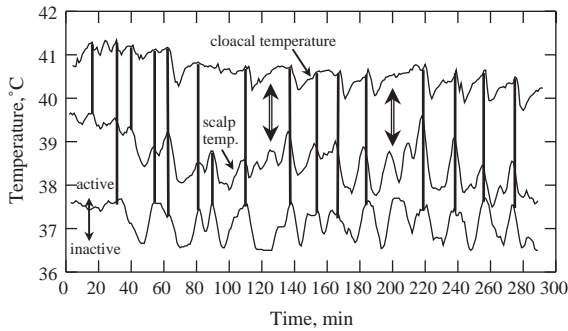


Fig. 3. Cloacal temperature (upper), thermographic scalp temperature (middle), and an index of swimming activity (lower) plotted vs. time. To reduce the noise which results primarily from animal movements, data were recorded at 5 s intervals and smoothed by a 5 min running average. Scalp and cloacal temperatures and swimming activity are significantly cross-correlated ($r = 0.40\text{--}0.45$, $P < 0.001$). The vertical lines indicate concurrent peaks in activity, scalp temperature, and cloacal temperature.

series analysis found that detrended scalp and cloacal temperatures were strongly cross-correlated with each other and with detrended swimming activity ($r = 0.4\text{--}0.45$, $P < 0.001$). However, at 110–140 and 190–220 min, cloacal temperature increased smoothly, whereas scalp temperature increased in a series of surges (Fig. 3) that suggest real variations of up to 1 °C in head–body temperature difference while swimming.

3.3.3. Temperature-sensitive paint

The temperature sensitive paint used was glossy after drying, and diffuse oblique lighting was therefore essential to avoid specular reflections that obscured target color. The colors indicating temperature are saturated but dim, and we found that cameras with automatic exposure severely underexposed the coated area unless the animal is dark-colored and viewed against a black background. When this is not the case, a camera with manual exposure control is necessary. Apparent color varies somewhat with lighting and paint thickness, and it is advantageous to use a uniform coat thickness. Within limits, a thicker application gives stronger color, but introduces more thermal insulation between the surface and the temperature sensing paint and results in lower apparent surface temperature. For the same reason, we found it preferable to dye the scalp than to paint it with the often-recommended black tempera paint.

Paints containing microencapsulated cholesteric liquid crystal material have limited temperature resolution and a narrow range. In film images of the aluminum calibration target, we could distinguish five colors fairly reliably by eye: orange, green, blue-green, blue, and

violet. For the 30–35 °C paint, these steps corresponded to approximately 29, 30, 31, 32, and 33–36 °C. Because of possible color variation introduced by digital camera sensor or film characteristics, lighting, and paint thickness, absolute accuracy will require careful calibration of the specific system used.

4. Discussion

Using the thermal imager, we found that 95% of all individual calibrated surface temperature fell within 0.2 °C of the true value, and better accuracy could be obtained by averaging several values from consecutive images. The imager must be in thermal steady-state with its environment before measurements are made to stabilize internal thermal gradients.

Thermographic estimates of cloacal temperature had a standard deviation of 1.5 °C for individual measurements and of ≤ 1 °C for a series of images averaged to smooth noise. This is greater than or equal to the 0.7–0.8 °C standard deviation documented for human infrared tympanic thermometry. However, the apparent accuracy of thermographic temperature estimates of core temperature may be conservative. Rectal temperature itself is known to be an imperfect indicator of core temperature in humans (Yaron et al., 1995; Stavem et al., 1997), and internal temperature gradients in ducklings subjected to cold stress are likely greater than those in humans in a clinical environment. Thus, the standard deviation of the thermographic estimates of cloacal temperatures likely includes uncertainty in the cloacal estimate of core (heart–lungs–brain) temperature as well as uncertainty in the thermographic estimate of core temperature. This possibility is supported by the observations that cloacal and thermographic temperatures generally varied in parallel, but scalp temperature showed fluctuations independent of changes in cloacal temperature (Fig. 3). Brain–body temperature differences of similar magnitude have been found in adult ducks (Kilgore et al., 1976).

Comparison of the regression coefficients and model statistics for cylinders with and without the convection shield indicate a substantial change in the calibration and a doubling of the standard deviation of individual data points about the model when the convection shield was used (Eq. (3) vs. Eq. (4)). Further, the convection term [$\text{wind} \times (T_c - T_a)$] did not enter the T_b model (Eq. (5)). These results, as well as uncertainties in the α_{eff} of different shield samples and the possibility of condensation on the shield (which would change α_{eff} significantly), leads us to conclude that a polyethylene film convection shield is not useful. However, this result may be specific to our study, and should be tested if this method is to be used at higher wind speeds, or on older

ducklings or other species. Also, that trimming down from an area of the scalp may increase heat loss and thus metabolic rate. If this is a concern, a convection shield may be useful.

Temperature-sensitive paints give a less precise indication of surface temperature than infrared thermography, and this uncertainty should be additive to the uncertainty with which scalp temperature indicates cloacal temperature. However, these paints may be useful in many studies. New analytic methods based on digital image analysis software (Smith et al., 2004) may improve accuracy over visual color judgments. Overall, we expect that the most useful application of temperature-sensitive paints may be in detecting temperature change leading to hyper- or hypothermia during a single experiment, rather than for absolute temperature measurement.

The utility of temperature-sensitive paints in field studies may be restricted by the need to have black background dye under the temperature-sensitive paint. Unless the animal is already very dark, this may increase the local absorption of solar radiation enough to alter surface temperature. The coating may also reduce local evaporative cooling of the skin.

The accuracy of core temperature estimates based on scalp temperatures, however measured, would likely deteriorate as animal size, and hence tissue thickness over the brain, is increased. Thus, thermographic estimates of core temperature are most valuable in providing a much-needed means for obtaining remote body temperature measurements on animals that are too young or too small for implanted temperature recorders or transmitters.

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