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Infrared thermography – a non-invasive tool to evaluate thermal status of neonatal pigs based on surface temperature

T. S. Kammersgaard†, J. Malmkvist and L. J. Pedersen

[1]*Department of Animal Science, Faculty of Science and Technology, Aarhus University, DK-8830 Tjele, Denmark*

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Hypothermia is a major cause of mortality in neonatal pigs. Infrared (IR) thermography is a promising non-invasive method to assess thermal status, but has not been evaluated for use on neonatal pigs from birth. The aim of this study was to evaluate the application of IR thermography as a non-invasive tool to estimate body temperature and assess the thermal status in newborn pigs by (1) estimating the relationship between surface temperature and rectal temperature (RT) in neonatal pigs; and (2) estimating the influence of air temperature (AT), birth weight and the time from birth on the relationship between surface temperature and RT. The method was evaluated on the basis of 1695 thermograms and 915 RTs on 91 neonatal pigs born in loose farrowing pens with floor heating at 34°C, and three different ATs (15°C, 20°C and 25°C). Full-body thermograms of the back and the side of the pigs and RT were acquired at 11 sampling times between birth and 48 h after birth. The maximum (IR_{max}), minimum, average of the full body and ear minimum IR surface temperatures were derived from the thermograms. IR_{max} had the highest correlation with RT (0.82) and was therefore used in the statistical analysis. The relation of RT by IR_{max} depended on time at: 0 h (slope: 0.20°C, $P < 0.001$), 0.25 h (slope: 0.42°C, $P < 0.01$), and 0.5 and 1 h after birth (slope: 0.68°C, $P < 0.001$). After the 1st hour (1.5 to 48 h) the relation of RT by IR_{max} was no longer affected by time (slope: 0.63°C, $P < 0.001$). The agreement between RT and IR_{max} was improved ($P < 0.001$) after the 1st hour (RT – IR_{max} 0 to 1 h: 2.02 (1.44)°C; 1.5 to 48 h: 0.95 (0.85)°C). IR_{max} below 30°C was indicative of piglets having RT < 32°C (91.3%). The location of IR_{max} was identified predominantly at the base of the ears (27/50), other sites in the region of the head (12/50) and the axilla area (8/50). There was a small but significant effect of the angle as IR_{max}_side–IR_{max}_back: mean 0.20°C ($P < 0.001$). On the basis of the low difference between IR_{max} from back and side view thermograms, and the location of IR_{max}, the angle seems less important and thus the method has the potential to be used without the need for manual restraint of the pigs. On the basis of the results of this study, we propose that IR_{max} temperature from full-body thermograms has implication as a valid tool to assess the thermal status in neonatal piglets but not as an identical substitute for RT.

Keywords: hypothermia, thermography, neonatal pigs, rectal temperature, surface temperature, infrared

Implications

The evaluation of infrared thermography as a non-invasive tool to assess the thermal status in neonatal pigs holds implications in applied research and the swine industry. In research, applying minimally invasive procedures minimizes the risk of affecting the results. The evaluated procedure provides a swift and easily applicable method to assess the thermal status of neonatal pigs.

Introduction

Hypothermia is a major cause of neonatal pig mortality under commercial production conditions where the use of straw and other nesting materials is usually scarce (Tuchscherer *et al.*, 2000; Edwards, 2002; Herpin *et al.*, 2002). Hypothermic neonatal pigs are also more prone to die from other causes such as starvation, crushing and disease (Pedersen *et al.*, 2011). After birth, the pig must rapidly recover from postnatal hypothermia to avoid a fatal outcome. Assessing pigs' thermal status is commonly done by rectal thermometry, which in most cases requires each pig to be handled by an experimenter. This method is laborious and might influence pig behaviour, which in turn affects pig thermoregulation (Kammersgaard *et al.*, 2011). A non-invasive method to assess the thermal status of pigs with good accuracy, without manual handling of individual pigs, would therefore have great potential both in research and in monitoring farrowing facilities on farms. Infrared (IR)

† E-mail: trines.kammersgaard@agrsci.dk

thermography measures heat radiation from the surface of a subject and translates the radiation into a point-specific surface temperature. Others have used IR surface temperatures to predict body temperature in older pigs (Loughmiller *et al*., 2001; Chung *et al*., 2010). However, the unique thermal conditions of the newborn make it different from older pigs, because of evaporation of birth fluids and a wider span in the biological relevant temperatures. The two methods are essentially different not just in technique, where rectal thermometry is based on conductive heat transfer to the sensor, whereas thermographic equipment measures radiation. In addition, thermography measures the temperature on the body surface, which is constantly engaged in heat exchanges with the surroundings, whereas the rectum cavity is dependent on the situation closer to or is an integrated part of the body core. The aim of this study was to evaluate the application of IR thermography as a non-invasive tool to estimate body temperature and assess thermal status in newborn pigs by (1) estimating the relationship between surface temperature on the basis of IR thermography and rectal temperature (RT) in neonatal pigs; and (2) estimating the influence of AT, birth weight and the time from birth on the relationship between surface temperature on the basis of IR thermography and RT.

Material and methods

Animals

The experiment was conducted at the agricultural research facilities of the Department of Animal Science at Aarhus University, situated in Tjele, Denmark. The experimental set-up was part of a larger study on the effects of air temperature (AT) and floor-heating strategies on sow and pig thermal behaviour and physiology. We refer to Pedersen *et al.* (2013) and Malmkvist *et al.* (2012) for the results on these issues. The experimental subjects in the present study were 91 pigs from 45 litters born in 2009. The dams were crossbred Landrace and Yorkshire sows of 1st and 2nd parity, and the sires were Duroc. The pigs included in the present study were the 5th and 10th pigs in the order of birth from each litter of six batches (each consisting of eight sows). If the 5th or 10th pig was stillborn, the next pig in the birth order was included instead.

Housing and climate treatments

The pigs were born in a climate-controlled farrowing unit with room for eight farrowing sows in individual pens. These were loose housing pens as described by Malmkvist *et al.* (2012). Each batch of farrowing sows was assigned to a temperature treatment in which the AT was maintained at 15°C, 20°C or 25°C through automatic adjustments of: the ventilation rate, supplementary heating and high-pressure water cooling of the air in the farrowing unit. The AT was controlled within the nearest 0.1°C at a relative humidity of 60 ± 2% during the entire experimental period by a Skov A/S climate control system (Skov A/S, Roslev, Denmark). Floor heating to a surface temperature close to 34°C in the area of the pen with concrete solid floor (1.80 × 2.23 m) was switched on by the start of nest-building behaviour or no later than day 115 of pregnancy in all pens. Within each batch of eight farrowings, half of the pens had floor heating switched off by 12 h and the other half by 48 h after birth of the 1st pig in the litter. The number of pigs on each combination of both AT and floor heating treatments were: AT 15°C: 31 pigs (floor heating 12 h: 15 and 48 h: 16), AT 20°C: 31 pigs (floor heating 12 h: 16 and 48 h: 15) and AT 25°C: 29 pigs (floor heating 12 h: 13 and 48 h: 16).

Data collections

IR thermograms and rectal temperature (RT) were acquired at birth, 15, 30, 60, 90, 120, 180 and 240 min after birth of the individual pig and at 12, 24 and 48 h after birth of the 1st pig in the litter. RT was taken manually by picking up the pig from the floor of the pen and inserting a digital thermometer (Kruuse, Digi-Temp Digital Thermometer, Langeskov, Denmark; range 32°C to 42°C accuracy ± 0.10°C) ~1.5 cm into the rectum of the pig. Immediately after measuring RT, the thermograms were acquired. For procedures and specifications on the collection of IR thermograms data, see section on IR thermography. Individual pig data on pig weight in kg 1 h after birth (weight) was collected using a calibrated digital scale (OHAUS (Parsippany, NJ) of maximum 6000 ± 2 g). The procedure lasted no longer than 1 min. After these procedures, the pigs were returned to the pen at the same spot from where they had been picked up.

IR thermography

IR thermographic cameras measure the IR radiation from the surface of an object, and with the input of the emissivity factor of that surface it translates the radiation into temperatures. The thermographic camera used in the current study was a Testo thermografic camera model T880-3 (33 Hertz, firmware version v.1.22, 160 × 120 pixels, accuracy ± 2°C, ©Testo AG, Lenzkirch, Germany, www.testo.de). After completing data collection, a stability test was conducted using a bucket of icy water as target and comparing IR_{max} of the water surface with water temperature close to the surface measured by a PT100 thermal sensor probe as reference temperature. The difference between IR and reference was compared on the basis of simultaneous recording over a period of 90 min, acquiring thermograms every 5 min. On the basis of the results of this stability test, the maximum differences between IR_{max} and reference temperature was +0.4°C and −1°C. After 15 min, the maximum differences between IR_{max} and reference were +0.2°C and −0.5°C. On average (full 90 min period), the maximum IR temperature was 0.21°C higher than the temperature reference. The stability test therefore suggests better accuracy of the thermographic device than promised by the manufacturer (see above). The emissivity was set to 0.98, based on data from humans (Steketee, 1973), as we presumed the hair coverage and skin characteristics to be similar between man and pig. Other manual settings of the thermographic camera were: relative humidity: 60%; surrounding AT: 20°C; and reflection temperature: 20°C. To evaluate the importance of which part of the piglet's body was thermographed, the pigs were thermographed both from the side and from the back. To do so precisely, the pig was held by the legs by one person and another person acquired the thermogram. The distance to target was ~1 m, allowing for a full view of the pig from the snout to the tail (see Supplementary Figure S1a and S1b). Strong radiant heat sources within field of view were avoided. The IR temperature data were derived from the thermograms using IRSoft software version 2.5 (©Testo AG,). The data derived from the thermograms came from manually (using the drawing tool included in the software) drawing a line on the inside of the edge of the pigs. This method excluded the legs of the pig that were covered by the hands of the person holding the pig (see Supplementary Figure S1a and S1b). The software then identified the pixel with the maximum IR temperature (IR_{max}), the minimum IR temperature and calculated the average IR temperature. The data further included the minimum IR temperature of the pig's ear. Minimum ear temperature was included, because the ear as a highly vascularized extremity is used by pigs and elephants as a thermoregulatory organ (Andersen *et al.*, 2008; Weissenböck *et al.*, 2010), from which they can minimize blood flow by vasoconstriction in response to cold, or increase blood flow in response to heat, by vasodilation. We therefore suspected that minimum ear temperature could hold valuable information with regard to thermal status. However, this suspicion could not be confirmed by our analysis. For an example of the RT data and surface temperature data from side view of one representative pig over the full duration of the experimental period (see Figure 1). In total, lower rectal than IR_{max} temperatures were found in 182 of the 1641 thermograms, or 11.1% of all thermograms included in this study. A subsample of 50 randomly selected thermograms (with in the original 1695 thermograms) were analysed to identify the location of the pixel-representing IR_{max}. This assessment of location of the pixel-representing IR_{max} was performed by means of the thermal hot spot identifier within the software and a manual visual categorization of the location.

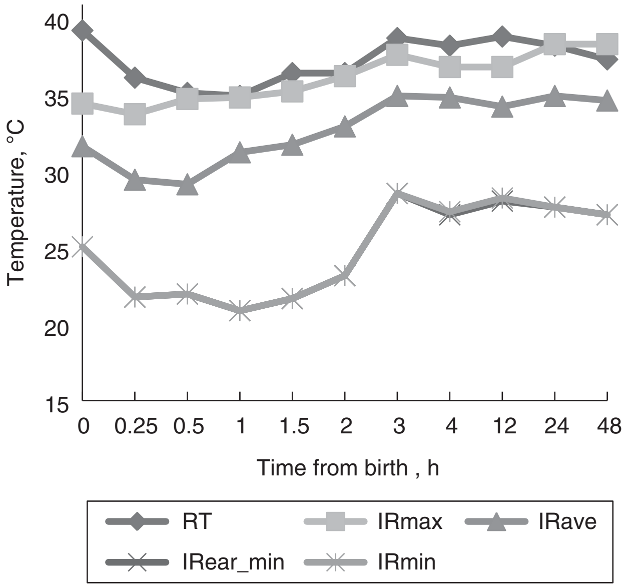

Figure 1 The development in rectal temperature (RT) and infrared (IR) temperatures: IR maximum, IR average, IR minimum and IR minimum ear temperature over time of one representative pig at air temperature treatment: 20°C.

Handling of data and statistical analysis

To avoid unstable models because of closely correlated covariates, only one IR parameter was included in the model. IR_{max} was chosen over average, minimum and minimum ear temperature as initial data inspection showed IR_{max} as having the highest correlation (Pearson's) with RT ($IR_{max} = 0.82$, average = 0.77, minimum = 0.67, ear minimum = 0.67). It proved difficult to include IR temperature data from both the thermogram taken from the back and from the side of the pig in the same statistical model. Also because statistical models become unstable when including closely related covariates such as in this case IR_{max} from side and back view. Therefore, the means of the IR_{max} from the two views was included in the model of RT. The effect of view was subsequently treated separately in a pairwise *t*-test. Only IR_{max} data where RT was above 32°C were included in the primary analysis. The IR_{max} measurements, where corresponding RT was below 32°C, were analysed separately and only descriptive statistics are included in the results.

On the basis of initial data inspection, it was evident that the time from birth affected the relationship between RT and IR_{max}. The data set was therefore split into two parts: one containing data from the 1st hour after birth, and the other containing data collected after the 1st hour. Both data sets were analysed using the same initial linear mixed model with RT as the response variable. AT treatment and time of sampling (TIME) were included as fixed categorical effects, whereas maximum IR temperature (IR_{max}) and pig weight (weight) were included as continuous covariates. The initial model also included all six possible two-way interactions of the four main effects variables: TIME and IR_{max}, TIME and AT, TIME and weight, IR_{max} and AT, IR_{max} and weight, and between weight and AT. Litter and pigs within litter were included as random effects. The nlme package (Pinheiro and Bates, 2000) in the statistical language R (R Development Core Team, 2012) version 2.15.2 was used for data analysis.

Model selection was carried out by stepwise reduction in the number of parameters in three steps. In the 1st step, the initial model was reduced starting with interactions followed by main effects by means of classical maximum likelihood, removing the non-significant effects ($P < 0.05$). In the 2nd step, the effect of time was simplified by testing whether the number of parameters on time could be reduced. This was also tested by maximum likelihood ($P < 0.05$). In the 3rd step, the model was further reduced by a stepwise simplification and reduction in the number of parameters on the basis of the Bayesian information criterion (BIC) of each model. BIC relates to maximum likelihood but favours the simpler model by adding an additional penalty for the number of parameters that makes it an effective method to avoid over parameterization. The model with the best fit is the model with the lowest BIC value. On the data set from the 1st hour, the reduced model with the best fit included: the interactions of TIME and IR_{max}, and of TIME and weight. The effect of TIME was reduced to: time of birth; 15 min after birth; and 30 and 60 min after birth were combined. After the 1st hour, the reduced model of RT with the best fit included only the effect of IR_{max}.

We further applied the method described by Bland and Altman (1986) for the assessment of agreement between RT and IR_{max}. In this step, the data set was again split into two, the 1st including the 1st hour after birth, and the 2nd the subsequent hours, and compared in a pairwise *t*-test. The effect of time on the difference between RT and IR_{max} was also compared using the individual sampling times in a honest significant difference test.

Results

From birth to 1 h after birth

The relationship between RT and IR_{max} at different time points including scatter plot of data at each sampling time are shown in Figure 2a to c. The effects and the parameter estimates during the 1st hour were (parameter estimates are given with s.e. in parentheses; RMSE = 0.70):

$$\text{TIME 0 } (°C_{RT}) = 31.62(1.94) + IR_{max} \times 0.20(0.06) + \text{weight(kg)} \times 0.1(0.03)$$

$$\text{TIME 15 } (°C_{RT}) = 19.81(2.60) + IR_{max} \times 0.42(0.08) + \text{weight(kg)} \times 1.5(0.03)$$

$$\text{TIME 30 and 60 } (°C_{RT}) = 11.59(2.13) + IR_{max} \times 0.68(0.06) + \text{weight(kg)} \times 0.6(0.03)$$

All TIME-specific intercepts and interactions of IR_{max} and TIME were significant in the model with $P < 0.01$. Birth weight had no effect on RT at the time of birth ($P = 0.73$), although it influenced RT at 15 min ($P < 0.001$, 0.15°C increase in RT for every 100 g increase in weight) and at 30 and 60 min after birth ($P < 0.05$; 0.06°C increase in RT per 100 g increase in weight). The effect of weight did not interact with the effect of IR_{max}.

After 1 to 48 h after birth

After the 1st hour and until 48 h after birth, the model with the best fit included only IR_{max} as an explanatory variable.

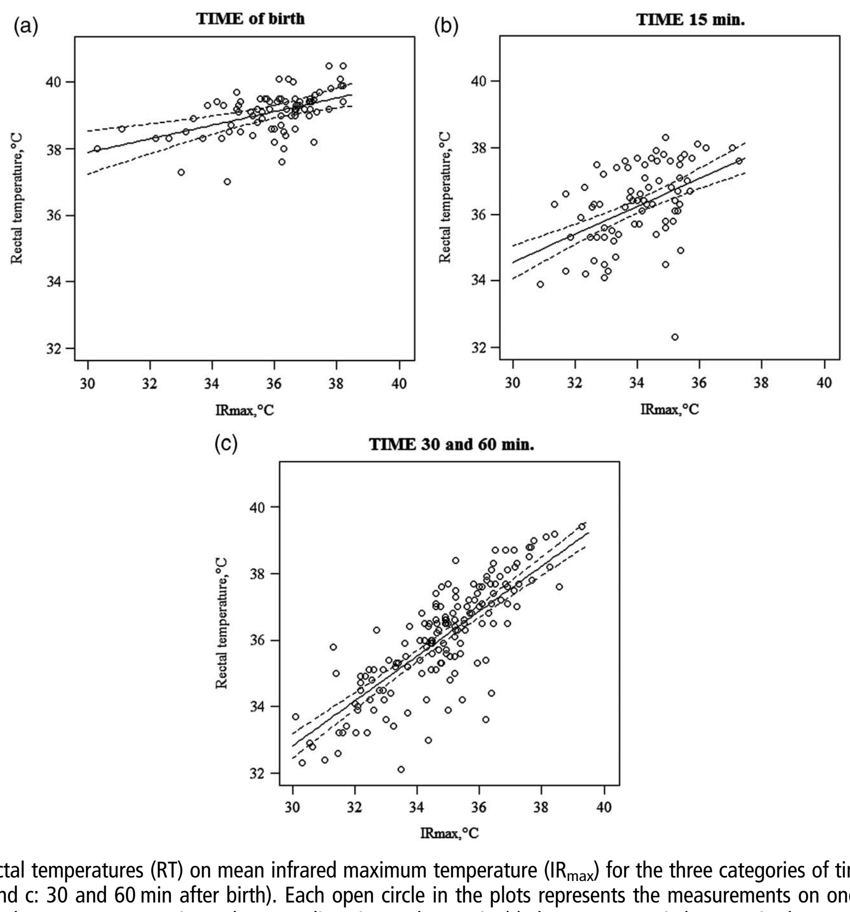

Figure 2 Scatterplots of rectal temperatures (RT) on mean infrared maximum temperature (IR_{max}) for the three categories of time during the 1st hour after birth (a: 0 min, b: 15 min and c: 30 and 60 min after birth). Each open circle in the plots represents the measurements on one pig at one sampling time. In plots (a) and (b), each circle represents one pig at that sampling time, whereas in (c) there are two circles per pig, because it includes data from both 30 and 60 min. The solid lines within each of the plots represent the parameter estimates for the interaction of TIME and IR_{max} (at the average weight of 1330 g) at that time and the dashed lines define the 95% confidence interval for the parameter estimates.

Parameters of the model were (parameter estimates are given with s.e. in parentheses; RMSE = 0.72): TIME 1.5 h to 48 h, $°C_{RT} = 14.72\ (0.97) + IR_{max} \times 0.63\ (0.03)$. Both intercept and slope were significant in the model with $P < 0.001$. The relationship between RT and IR_{max} including the scatterplot of the data from 1.5 to 48 h after birth can be seen in Figure 3. Neither AT, TIME or weight improved the fit of the model after the 1st hour and were therefore excluded. After the 1st hour, there was also no interaction of IR_{max} and TIME or of weight and TIME as was seen partly in the 1st hour after birth.

Agreement between RT and IR_{max}

The limits of agreement were calculated for the 1st hour and after the 1st hour, separately. For measurements during the 1st hour (0, 15, 30 and 60 min from birth), the mean difference (s.d. in parentheses) between RT and IR_{max} was 2.02 (1.44)°C. After the 1st hour to 48 h after birth (1.5, 2, 3, 4, 12, 24 and 48 h after birth), the mean difference between RT and IR_{max} was 0.95 (0.85)°C. See Figure 4a and b for the visual assessment of agreement by the Bland–Altman plot. The difference $RT - IR_{max}$ gradually declined over time. Parameter estimates are given in parentheses, the estimated honest significant difference was 0.53°C; therefore, only the differences between any two estimates larger than 0.53°C are significantly different. Time in hours: 0 h (3.2°C); 0.25 h (2.3°C); 0.5 h (1.4°C); 1 h (1.1°C); 1.5 h (1.2°C); 2 h (1.0°C); 3 h (0.7°C); 4 h (0.9°C); 12 h (0.7°C); 24 h (0.8°C); and 48 h (0.5°C).

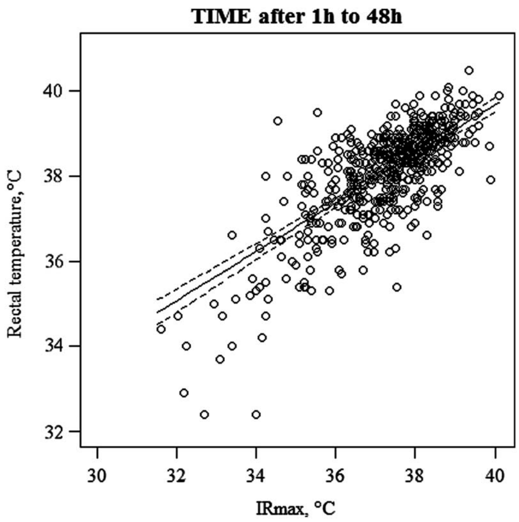

Figure 3 Scatterplot of mean infrared maximum temperature (IR_{max}) and rectal temperature (RT) of data from 1.5 to 48 h after birth. Each open circle in the plot represents the measurement on one pig at one sampling time. Thus, there are up to seven repeats per pig in the plot because of repeated measurements. The solid line represents the parameter estimate for the model of RT during the time after the 1st hour, and the dashed lines define the 95% confidence interval for the parameter estimate.

Identifying pigs with very low RTs (<32°C) based on IR_{max}

The rectal thermometers used in this study were unable to display exact RTs below 32°C. In 54 of the 1695 thermograms (3.2%), the corresponding RT was below 32°C. These 54 thermograms originated from eight of the original 91 piglets. When IR_{max} measured below 30°C (based on 46 thermograms), 91.3% of the thermograms were of pigs, with a corresponding RT below 32°C. When IR_{max} measured in the interval 30°C to 32°C, only 21.7% of the thermograms (also based on 46 thermograms) were of pigs, with a corresponding RT below 32°C. However, the average RT of the pigs with IR_{max} between 30°C and 32°C but RT above 32°C (remaining 78.3% of the 46 thermograms where IR_{max} was between 30°C and 32°C) was still very low at 34.4°C.

The influence of back or side view

In a pairwise comparison based on data from the period one to 48 h after birth, the average difference between IR_{max} from side and back was 0.20°C and different from zero (*t*-test, $P < 0.001$, 95% confidence interval: 0.14–0.25°C). The simple linear regressions of RT on IR_{max} for the two views were: back: $°C_{RT} = 15.66 + IR_{max} \times 0.60$ and side:

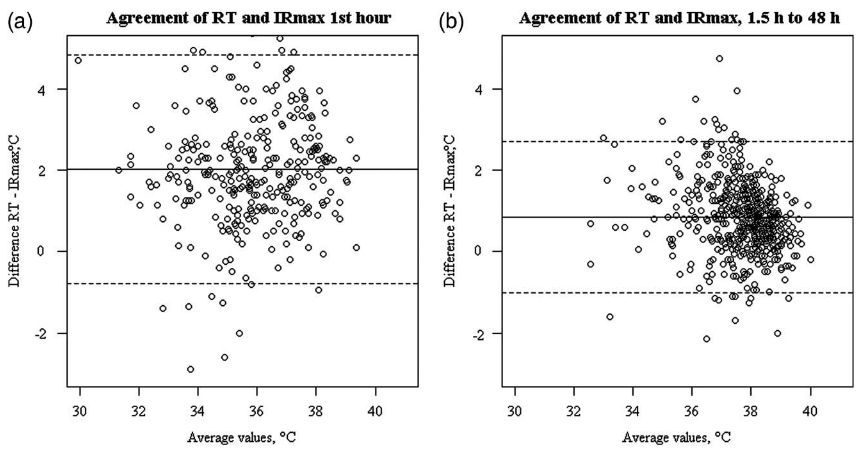

Figure 4 Bland–Altman plots of the agreement between rectal temperature (RT) and IR_{max} during the 1st hour after birth (a) and after the 1st hour to 48 h after birth (b). Each circle represents the difference between RT and IR_{max} from the same pig at the same sampling time, plotted against the mean of the two samples. The solid horizontal line shows the mean of the paired means, and the dashed horizontal lines show the mean ± 2 × s.d. of the mean, respectively. These represent the limits of agreement (Bland and Altman, 1986).

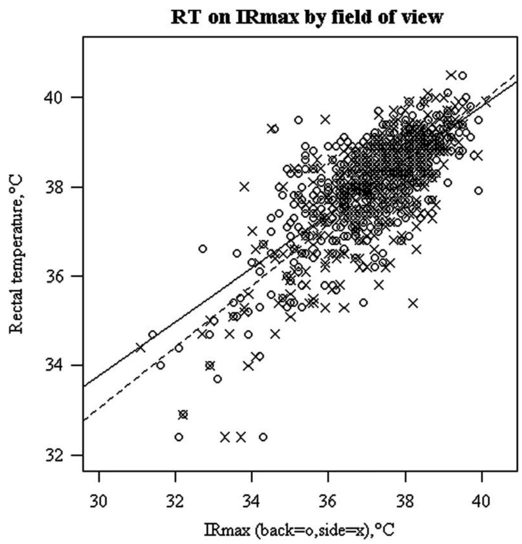

Figure 5 Scatter plot of rectal temperature (RT) on infrared maximum temperature (IR_{max}) from back (circles) and IR_{max} from side (x's) from 1.5 to 48 h after birth. Each circle or x represents one pig at one sampling time. Therefore, there are up to 14 repeats per pig. The lines are based on simple linear regression of RT and the IR_{max} data from back (solid line) and side (dashed line).

$12.49 + IR_{max} \times 0.69$. These are shown in Figure 5 with scatterplots of data from the two views.

Location of IR_{max}

The location of IR_{max} in 50 randomly selected thermograms were identified in seven different areas of the body: the ear basis (27), front leg axilla area (8), neck below the ear (6), in the ear (4), mid back (3), top of the head (1) and the eye region (1). The location of IR_{max} was not random between these seven regions (χ^2, $P < 0.001$).

Discussion

The relationship between IR_{max} and RT was independent of time in pigs older than 1 h, but strongly dependent on time since birth during the 1st hour after birth. The agreement between RT and IR_{max} was in addition much improved after the 1st hour. To the best of our knowledge, this is the 1st study to relate IR surface temperature to RT in newborn pigs from birth. Others have used the technique to relate surface temperatures to RTs in young pigs (Chung *et al*., 2010), growing pigs (Loughmiller *et al*., 2005) and farrowing sows (Zinn *et al*., 1985), and to detect fever in growing pigs (Loughmiller *et al*., 2001). The relationship between surface temperature and RT, as given by the parameter estimates and correlations in this study, are stronger than in previous studies. The parameter estimates at the time of birth were comparable to the linear regressions of surface temperature and RT in the previous studies; however, from 30 min onwards, we achieved a much closer relationship than seen in previous studies. All of these previous studies have two main things in common as opposed to the current study. First, in previous studies, the experimental subjects were in a situation resembling steady state where there is little variation in RT, or in a fever condition where RT is elevated above normal. Many of the pigs in the current study suffered from hypothermia, or were in the recovery phase from acute hypothermia. The hypothermic situation rendered a much wider span in not only the IR surface temperature, which was also seen in previous studies, but also in RT. Statistically, the wider range automatically improves the correlation between the data from the two methods. Second, the IR equipment used differs between studies. Zinn *et al.* (1985) and Chung *et al.* (2010) both used IR spotmeters, which typically cover an area and calculate the mean temperature of that area. Chung *et al.* (2010) used an IR spot thermometer on eight different locations on young gnotobiotic pigs. They found that, of the eight areas only three had significant correlations with RT, and still the linear regression of data from these three areas explained only 9.6% to 34.1% of the variation in RT (Chung *et al*., 2010). In farrowing sows, Zinn *et al.* (1985) compared IR temperatures acquired by an IR spotmeter to RTs and found no or only very poor evidence that the IR data could explain any part of the variance in RT. Loughmiller *et al.* (2005) and Loughmiller *et al.* (2001) used thermographic cameras as in the current study; however, using the mean of a 15 by 25 cm area on the side of the pig. Thus, the previous studies used average of the area in one form or another, whereas in the present study we used the maximum temperature, IR_{max}. Using maximum temperature instead of average increases the probability of acquiring the skin temperature and not the temperature of the hair on top. When the AT in the surroundings is lower than body temperature, the hair on the body surface is colder than the skin surface underneath. This is an important part of the thermal insulation properties of the pelage for pigs (Mount, 1963) and other mammals. In a study on sows in the farrowing unit, Traulsen *et al.* (2010) also found that in all measuring sites maximum temperature had the highest correlation to RT. This supports the finding in the current study and emphasizes the superiority of IR_{max} over average IR surface temperature as an indicator of body temperature.

In both the model for the 1st hour and the model for the subsequent hours, all interactions with AT, including IR_{max} and AT and the general effect of AT, were insignificant ($P > 0.05$) and thus excluded from the model. This is in contrast to our expectations as Loughmiller *et al.* (2005) found that AT had a significant effect on mean body surface temperature in four pigs of 30 kg. We find that the cause of the difference in results could again be the use of the maximum temperature in the current study in favour of the average temperature used in the study by Loughmiller *et al.* (2005). When using the average IR temperature of an area, the average catches the thermal insulation properties of the body surface. Alternatively, using IR_{max} as in the present study, and retaining it from the thermograms with a good resolution and short distance to target gives a very different result, which according to the results in the present study is independent of AT. This could explain why we found no interactions of IR_{max} and AT in the current study.

Other means of heat exchanges in addition to evaporative heat loss that affects the relationship between skin temperature and RT immediately after birth also include convective heat loss. Convective heat loss is increased by increased air movement and drafts in the farrowing environment removing heat from the surface of the piglet (Mount, 1966). This cools down the surface of the piglet increasing the temperature gradient between surface and RT. In this study, we did not monitor convection in the farrowing environment. The difference in AT, as part of the design of the study, might in theory generate a higher convective heat loss in the piglets born in colder ATs, as a result of drafts caused by larger difference in temperatures within the pen and higher ventilation rates. Therefore, differences in the relationship between IR_{max} and RT between AT treatments could have been indicative of the difference in convective heat loss between AT treatments. However, such a difference was not seen in this study, as we found no general effect of AT on the relationship between IR_{max} and RT, and thus no indication of difference in convective heat loss between piglets of different AT treatments in this study. However, in the experimental setup of the current study, we also had floor heating. Floor heating in farrowing pens aims to stabilize and improve the micro climate around the piglet. On the basis of the current study where all pigs were subjected to floor heating for at least 12 h, we cannot discard the possibility that heating the floor is what masks a possible effect of AT in the farrowing unit, because the micro climate around the pig may not have been significantly affected by AT, because all pigs had floor heating regardless of AT.

The development of the interaction of TIME and IR_{max} during the 1st hour after birth is most likely caused by the dynamics of postnatal hypothermia and the parallel development in heat and energy balance during the 1st hour after birth. At birth, the pig's RT is largely reflected by the body temperature of the farrowing sow. However, evaporation of foetal fluids covering the surface of the pig instantly starts to cool down the skin. In addition, the large temperature gradient between the surface of the newborn pig and the surroundings facilitates a substantial heat loss by radiation. This explains the situation at birth where we report a large variation in IR_{max} temperature and only a small variation in RT. This is reflected in the parameter estimates seen as the flatness of the slope and high intercept at the time of birth. At 15 min after birth, the pig is losing energy from the evaporation of foetal fluids, and the surface temperature drops even further. The pig is unable to keep up with the heat loss by increasing heat production, and the negative energy balance causes both the body and surface temperature to drop. This is seen in the lower RTs 15 min after birth and in the parameter estimates as an increase in the slope of IR_{max} and a decrease in the intercept. At 30 and 60 min after birth, most or all of the foetal fluids have been evaporated, and as evaporation declines so does heat loss because of it. The energy balance starts to shift and become more positive that causes the body and surface temperature to rise. At 30 and 60 min after birth, there was also a large difference between pigs but at the same time a strong relationship and small differences between RT and IR_{max} in the individual. This is seen in the parameter estimates and plot as a steep slope and low intercept.

On the basis of the Bland–Altman assessment of agreement between measurements of RT and IR_{max}, we find that the agreement between the two methods was much improved after the 1st hour after birth, as implied by smaller mean difference and lower standard error of mean. The theoretical effect of wetness on the results is supported by the declining difference between RT and IR_{max} over the course of the 1st hour and the more stable difference between RT and IR_{max} after the 1st hour. This is in agreement with the results from the mixed model, where the model with the best fit during the 1st hour was based not only on IR_{max} but also including the interaction of time and weight of the piglet. However, the effect was additive, which makes the interaction of time and IR_{max} independent of weight. After the 1st hour after birth, the model with the best fit is based only on IR_{max}, indicating that IR_{max} could be used to estimate RT without any other prior knowledge, except that the pig is in the age range of 1.5 to 48 h.

In a recent study, Thomas *et al.* (2012) applied the Bland–Altman method in comparing skin temperature by zero heat flow method and axillary temperature (both acquired with probe thermal sensors) to RT in hypothermic babies. From their study, they concluded that the agreement between methods was insufficient for skin temperature to replace RT, on the basis of the clinically acceptable limits of agreement of ±0.3°C being less than the limits of agreement found in their study (Thomas *et al.*, 2012). This high resolution on thermal status is necessary with regard to monitoring therapeutic hypothermia in human infants. However in the application of monitoring or assessment of thermal status in neonatal piglets in a production environment the levels of agreement would likely be acceptable to have a much wider range. Therefore, acceptable limits of agreement should be evaluated on the basis of the application of the technique, and the possible gains of using the less-invasive technique within this application.

The accuracy of the IR thermografic camera, as promised by the manufacturer, was ±2°C and this is comparable to other IR devices of this type. Within the relatively small range of biologically relevant temperatures, this is a very large margin of error. However, on the basis of the stability test conducted after completing data collection, we suggest that the errors in the IR data are much less than ±2°C, as promised by the manufacturer. With the thermographic equipment as with all scientific equipments, familiarization with the technique, its limitations and the specific product is essential, and calibration should be carried out routinely to produce valid data.

The results showed an effect of birth weight on RT at 15, 30 and 60 min after birth, but no effect of birth weight at the time of birth or after the 1st hour. Birth weight is well established as an important factor in early thermoregulatory success of neonatal pigs (Mount and Stephens, 1970; Herpin *et al.*, 2004). However, in this study, RT seems to be completely explained by IR_{max}, except during the period where the pigs are still wet from birth fluids. A possible explanation for this difference in results is the difference in the energy balance during evaporation of foetal fluids and energy balance later when the surface is dry. BW determines the maximum heat production capacity, which gives the heavier piglets the 1st advantage over the lighter piglets with regard to energy balance. During the evaporation of foetal fluids, the lighter pigs have an additional misfortune and come into a more negative energy balance faster than the larger pigs because of their greater surface to volume relationship. The body temperature therefore becomes lower in lighter pigs than in the heavier pigs, as it is shown in the results of the present study during the 1st hour. However, the insignificance of body weight after the 1st hour suggests that, after evaporation has commenced, the recovery phase is less affected by the difference in heat production capacity caused by birth weight. It seems that in the thermal environment in the present study, the pigs were able to adjust their heat production to match the heat loss from the dry surface, and therefore weight was not a limiting factor for heat production after the 1st hour. This would explain why birth weight did not affect RT beyond the 1st hour after birth in the present study.

In the present study, 11.1% of all thermograms had IR_{max} above RT. To the best of our knowledge, this is the 1st study to document skin temperatures above RT. In 50 randomly selected thermograms, IR_{max} was found mainly at the base of the ear and generally in the region of the head (39/50 thermograms) and in addition front leg axilla area (8/50). Thermography and probe temperature of the axilla area in relation to RT has been studied with the aim of detecting fever in human infants (Hughes *et al.*, 1985). Both the head and the axilla are close to or directly above the brain and heart, which are the central organs of the body core, which is given the highest priority during hypothermia in terms of maintaining normotherm body temperature. The consistently high priority of the heart and brain during hypothermia has been demonstrated by Mayfield *et al.* (1986), who induced hypothermia in 3- to 4-day-old piglets and monitored blood flow and oxygen delivery to the different areas/organs during hypothermia. On the basis of the location of IR_{max}, we therefore suggest that maximum skin temperature on a site directly above the central organs can be higher than RT at a depth of 1.5 cm, and explain the findings of $IR_{max} > RT$. Given the dynamic nature of the temperature gradient across the body during hypothermia (Kiley *et al.*, 1984), RT is not necessarily an accurate substitute of body temperature during hypothermia. The results of this study ($IR_{max} > RT$ and the location of IR_{max}) could suggest that IR_{max} might be closer to core temperature than RT in some situations. However, more tests are necessary to confirm this. We found no other systematic explanations of $IR_{max} > RT$ caused by the levels of time, IR_{max}, RT, AT or the progression of hypothermia.

On the effect of angle from which the thermogram was taken, we found that IR_{max} from a thermogram of the side was slightly higher than IR_{max} from a thermogram of the back of the pig. Intuitively this finding makes sense based on the anatomy of the pig, as the side view of the pig exposes more of the areas close to the heart and areas above the central arteries than the back view does. However, the results also show that back or side view only explain a very small part of the variation as compared with the effect of IR_{max}. The minor difference in predicted RT based on IR_{max} from side view and IR_{max} from back view gives great potential for the method to be used without the need for manual restrained. It gives the possibility to acquire the thermogram in the pen without manual handling of the pig, and then the option of either adjusting for the angle or simply using the model based on the mean of the two different views applied in this study. This conclusion is supported by a recent study where thermograms were acquired in the pen, without handling the piglets (Tabuaciri *et al.*, 2012). Tabuaciri *et al.* (2012) found that the areas most easily accessible from thermograms acquired in the pen were: the back, tips of the ear and base of the ear, in set order, while it proved very difficult to get a clear picture of the eye of the pigs. Tabuaciri *et al.* (2012) further found that the correlation between surface and RT temperature were strongest at the base of the ear. This is similar to the identified location of IR_{max} in the subsample from the current study, and in combination these results support the use of thermografic assessment of thermal status without manual handling of the piglets. What is missing from the former study is the effect of time from birth that is covered by the present study.

In this study, where the floor of the farrowing pen was heated to 34°C, eight of the 91 piglets included in the study had on one or more occasions during the sampling period a recorded RT below 32°C. This finding suggests that even when floor heating is applied in the aim to improve the thermal micro climate surrounding the piglets at birth, severe hypothermia is still common. Therefore, common veterinary practice thermometers with a lower limit of 32°C are essentially insufficient in this application. However, although a large part of the piglets had recorded RT below 32°C, this covered only a small part of the data included in the present study. We further found that the piglets with $RT < 32°C$ could be identified by IR_{max} from full-body thermograms, with sufficiently good accuracy.

In conclusion, IR_{max} from a full-body thermogram can be used in the assessment of thermal status of neonatal piglets in pens with heated floor, without adjusting for AT. During the 1st hour after birth, the relationship between IR_{max} and RT is affected by time from birth. After the 1st hour to 48 h after birth, adjusting for birth weight or time from birth does not improve the method, and IR_{max} from full-body thermograms can be used to asses the thermal status and estimate RT without further adjustment. IR_{max} from a full-body thermogram can be used to identify piglets with low RT. There are significant but minor differences in IR_{max} derived from thermograms of the back and the side of the piglet. The location of IR_{max} based on a subsample from the original data set was identified mainly in the region of the head and the axilla area. On the basis of the results of this study, we propose that IR_{max} temperature from full-body thermograms can be applied as a valid tool to assess the thermal status in neonatal piglets but not as an identical substitute for RT.

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Supplementary material

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