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Determining the emissivity of pig skin for accurate infrared thermography

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ABSTRACT

Infrared thermography may be used for pig health screening and fever detection. In order to achieve the necessary accuracy for this purpose, it is necessary to know emissivity of the skin surface. Previous investigations attempting to find the emissivity of pig skin revealed numbers from 0.8 to 0.955. Such discrepancies can result in measured surface temperatures differing by several degrees Celsius. An unacceptable discrepancy if used for fever screening.

In this study we determined the emissivity of three skin locations in ten sows when they were alive and dead: the ear base, udder and shoulder. The shoulder was investigated with and without (clipped) hairs.

Emissivity for ear base, udder, and shoulder (hairy) was 0.978 ± 0.006, 0.975 ± 0.006 and 0.946 ± 0.006, respectively. Clipping the hairs of the shoulder tended to increase the emissivity ($p = 0.07$). Emissivity of the hairy shoulder was significantly lower than for the ear base ($p < 0.001$) and the udder ($p < 0.005$). Emissivity of the three skin areas with no blood perfusion (after euthanasia) tended to be lower ($p = 0.06$) compared with the emissivity of the skin areas when perfused with blood. The results of this study confirm that it is valid to use the human skin emissivity value of 0.98 for infrared skin measurements on sows. However, when studying hairy skin areas or skin with no blood perfusion, the emissivity value is lower.

1. Introduction

Automatic and rapid evaluation of pig health is of increasing interest in the pig production industry. Infrared thermography (IRT) is one of the promising technologies for performing automatic surveillance of pigs for health screening. IRT offers major advantages for measuring temperature in pigs compared to other techniques, such as rectal and contact skin thermometers or ingestible/implantable thermal sensors. It is a non-obtrusive, non-invasive method, where restraint of the pigs is unnecessary with no risk of infection spread during the screening process.

Knowing the emissivity (ε) of the skin is required for correct, absolute temperature measurements using IRT. This number describes a materials ability to emit energy by radiation. Using an incorrect emissivity value when measuring, for example, pig skin temperature with an IR camera (IRC) can result in serious measurement error. Only a few studies have investigated the emissivity of pig skin. Metternick-Jones and Skevington (1992) found the emissivity of pig skin to be between 0.92 and 0.93 using auto-emissivity adjustment in an IR thermometer based on surface temperature measured by an RTD thermal sensor, while it was 0.8 using the manual emissivity adjustment in the IR thermometer until matching surface temperature measured by the aforementioned RTD thermal sensor. Gariepy et al. (1989) found the skin in the dorsal area to have an emissivity of 0.95. Kelly et al. (1954) used a radiometer and found the emissivity of a hairy pig skin area to be 0.93, a value they later decided to adjust to 0.955, based on findings on human skin (Hardy, 1934). Actually, many of the studies measuring the skin temperature in pigs using IRT have used the emissivity of human skin, observed to range between 0.93 and 1.00 (Gartner et al., 1964; Hardy, 1934; Sanchez-Marin et al., 2009; Steketee, 1973; Togawa, 1989; Villasenor-Mora et al., 2009). It is fair to say that the consensus is that the emissivity of human skin is 0.98, which is also the value most researchers have used in the pig studies.

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The aforementioned study by Metternick-Jones and Skevington (1992) investigated the emissivity of pig skin using dead pigs and reported the lowest pig skin emissivity of 0.8. Human studies investigated the skin emissivity changes due to blood perfusion (Gartner and Gopfert, 1964; Gartner et al., 1964) and showed a reduction in emissivity by as much as 0.04 when restricting blood perfusion to the human forearm. This raises the question if blood perfusion affects the pig skin emissivity?

Some studies investigated the correlation between rectal temperature and IRT measured surface temperatures at various sites, including the eyes, ears, vulva, udder, axilla, side, loin/back, shoulder, and snout (Chung et al., 2010; Dewulf et al., 2003; Loughmiller et al., 2001; Magnani et al., 2011; Malmkvist et al., 2012; Schmidt et al., 2013; Sykes et al., 2012; Tabuaciri et al., 2012; Traulsen et al., 2010; Warriss et al., 2006; Wendt et al., 1997; Zinn et al., 1985). The relationship between ambient air temperature and pig surface temperatures at different sites, including eyes, ears, loin/lumbal area, shoulder region, legs, abdomen, udder, and snout, have also been investigated (Collin et al., 2002; Henken et al., 1991; Loughmiller et al., 2001; Malmkvist et al., 2012; Nanni Costa et al., 2010; Savary et al., 2008; Wendt et al., 1997). However, some of the mentioned studies were, in part (Wendt et al., 1997) or completely (Collin et al., 2002; Henken et al., 1991; Loughmiller et al., 2001; Magnani et al., 2011; Nanni Costa et al., 2010; Tabuaciri et al., 2012), performed on pigs weighing 35 kg or below, which have different thermoregulatory mechanisms than those of sows and therefore may not be a good model for sow studies. From the surface areas chosen in the mentioned studies, the most reliable and accessible in practical measurement scenarios for sows are probably the ear base, shoulder and udder. Especially during the lactation period, which is arguably the most interesting period for sow health screening. The orbital area (inner canthus) may be a better site as suggested for humans in the International Electrotechnical Commission 80601-2-59 standard (IEC, 2008). However, it is impractical in sow studies, since sows are usually stalled facing toward walls when in farrowing crates, making it difficult to get good measurements with an IRC. Furthermore, sows move their heads quite frequently, and slight movements during IRT acquisition will cause averaging of the relatively small area covering the inner canthus and the surrounding area.

The purpose of this study was to determine the emissivity of adult pig skin at the shoulder, ear base, and caudal part of the udder, and determine if there is an effect of hairiness and blood perfusion on the emissivity.

2. Materials and methods

The basis for determining the emissivity of pig skin in this study was by measuring the skin temperature with an accurate reference PT-100 sensor (model Dostmann sharp tip 6000-1023S sensor, ThermoWorks Inc., Lindon, UT, USA) and comparing it to the corresponding skin temperature measured by IRT. Ideally, the difference would be attributed to the emissivity of the skin. All temperature measurement devices used in this work were calibrated accredited at the Danish National Reference Laboratory for Non-contact Thermometry at The Technical University of Denmark, Roskilde, Denmark.

2.1. Infrared camera calibration

To ensure accurate IR measurements the recommendations described in the International Electrotechnical Commission 80601-2-59 standard (IEC, 2008) were followed wherever possible. IRCs require, like other electronic measurement equipment, regular calibrations and corrections (Plassmann et al., 2006). Issues like stability, start-up drift, long-term drift, offset variation over temperature measurement range, image non-uniformity and flooding are known to affect infrared thermography measurements (Jiang et al., 2005; Machin and Chu, 2000; Plassmann et al., 2006; Ring et al., 2007). Measurements prior to the experiments had shown that the IRC required an hour to stabilize after being turned on. Before any IRC measurements in this study, the IRC had been on for more than an hour.

Calibration using a black body cavity ($\varepsilon > 0.999$) at the Danish National Reference Laboratory for Non-contact Thermometry (Technical University of Denmark, Roskilde, Denmark) revealed that the IRC measured 0.20 °C less than the black body cavity at 40.00 °C in the center of the field of view (FOV). As the skin area region of interest (ROI) was in the center of the FOV in all measurements, a correction factor of 0.20 °C was added to all thermal images in the post processing analyses.

2.2. Measurements

2.2.1. Animal handling

Multiparous Danish Landrace × Yorkshire sows (4–8 parturitions, $N = 10$) were selected for this study. The study was approved by the Danish Animal Experiments Inspectorate according to the permission given September 2013 (J.nr.: 2013-15-2934-00932/JANNI).

The sows were anesthetized by intramuscular injection with a mixed solution consisting of 1 bottle of Zoletil dry matter (mix of 125 mg Tilematin and 125 mg Zolazepam) dissolved in 2.5 ml Torbugesic, 1.25 ml Ketaminol (100 mg/ml), and 6.25 ml Rompun. The dosage was 1 ml/10 kg. Knowing that stress reduces the impact of the anesthesia, the sows were led calmly into the room where the experiments were undertaken prior to the injection. The sows were allowed to walk freely in the room (approx. 3 by 5 m) until the anesthesia took effect and they lied down. If their eyes and/or eyelids moved after an additional wait time of 15 min, the sows were injected with an additional 5–10 ml of Zoletil-mix. When the eyelids were no longer moving and the breathing was relaxed, the sow was moved away from the wall if necessary and laid on their side allowing visual access to the ear base, shoulder and the caudal part of the udder for the IRC and also to provide space for the IR acquisitions. If any of the measurement sites were dirty or otherwise deemed unsuited for the measurements, the sow was turned to the other side. All measurement sites were dry when measured.

2.2.2. Ambient setting

All experiments were conducted in the same room. The windows were covered with sheets of cloth to minimize the effect of incoming sun radiation, that when absorbed, may heat up the irradiated surfaces. Most experiments were conducted on cloudy days. The room size was approx. 5 m × 7 m, but a large 1 m high double-plated plastic wall was set up to reduce the size of the area to 3 m × 5 m and to further reduce the sunlight radiation impact to a minimum and to prevent draft from the windows. All doors were kept shut and there were no ventilation ducts in the room. The room was clean, with no visible dust or perceivable odor of ammonia in the air. Ammonia has an absorption peak at approx. 10 μm, which could influence the IR measurements (Soerensen et al., 2011). Air movement was minimal (<0.02 m/s), which was confirmed by measurement taken approx. 5 cm above the concrete floor using a hot wire anemometer (Testo 425, Testo AG, Lenzkirch, Germany) before start of the measurements on each sow. Relative humidity was logged every minute (THS-296-061 ThermaData Logger, ThermoWorks, Lindon, UT, USA). This logger has a humidity accuracy of ±2%RH. The logged data was retrieved after each

experiment (ThermaData Logger version 3.4.9, ThermoWorks, Lindon, UT, USA).

Room temperature was measured by a temperature reference as described in previous work (Soerensen et al., 2011) in which the tip of a stainless steel probe thermometer (Traceable Digital Thermometer model 4000, Control Company, TX, USA – accuracy of ±0.05 °C) was inserted. It was held next to the ROI in the FOV of the IRC, approx. 3–4 cm from the skin so it was not heated up by the sow. Lowest and highest ambient temperatures observed during the measurements were 16.2 and 24.3 °C, respectively.

2.2.3. Reference temperature sensors

Three accurate platinum resistance thermometer needle probes (model Dostmann sharp tip 6000-1023S sensor, ThermoWorks Inc., Lindon, UT, USA) were inserted into the outer layers of the skin at each of the 3 measurement locations; the ear base, the upper part of the shoulder, and the caudal part of the udder (see Fig. 1). Inserted needle probes under the skin were found advantageous over normal surface contact thermometers, which do not allow for optical access to the skin area required by the IRC, necessary for simultaneous measurements. In addition to that, it can be very difficult to achieve good contact between a thermo probe and the skin surface.

To minimize the damage of the skin tissue, a syringe needle (18G 1½″, 1.2 mm × 40 mm BD Microlance 3, Becton Dickinson and Company, NJ, USA) was first inserted into the skin, approx. 2–3 cm in the outer layers of the skin, as close to the surface as possible. The syringe needle tip was pushed through so each end of the needle was outside the skin. The tips of the needle thermo probes were then inserted into the lumen of the syringe needle tip. While holding the thermo probe and slowly withdrawing the syringe needle, the tip of the thermo probe ended up under the skin very close to the inner surface. An example of an inserted needle probe in the skin at the ear base is depicted in Fig. 2.

The needle temperature sensor probes were connected to a data logger (Model LogMaster QuadRTD 4-channel precision RTD data logger, ThermoWorks, Lindon, UT, USA). The needle probes were 3-point calibrated by the manufacturer (at 0, 25, and 50 °C, NIST traceable) with paired channels on the LogMaster QuadRTD, giving high accuracies with maximum error at the three measurement points $\leqslant |0.03|$ °C. Furthermore, the measurements were corrected using the second order correction from the calibration results of the sensors performed at The National Reference Laboratory for Non-contact Thermometry (Technical University of Denmark, Roskilde, Denmark). The QuadRTD logger was set up to record temperatures every 5 s. The logged data was retrieved after each experiment (ThermoWorks Data Recorder Software version 2.05, ThermoWorks, Lindon, UT, USA).

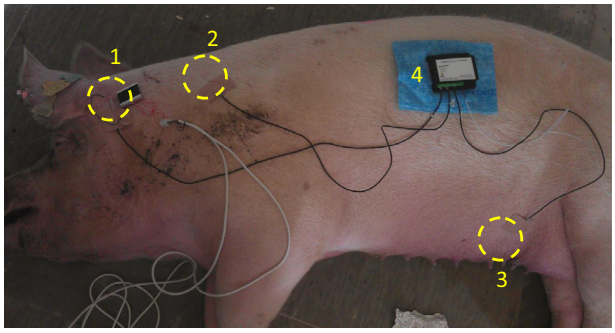

Fig. 1. Experimental setup. The three skin areas investigated are shown with circles numbered 1–3. Circles 1, 2, and 3 are the ear base, shoulder and caudal third of the udder, respectively. The QuadRTD 4-channel temperature logger is marked with the number 4.

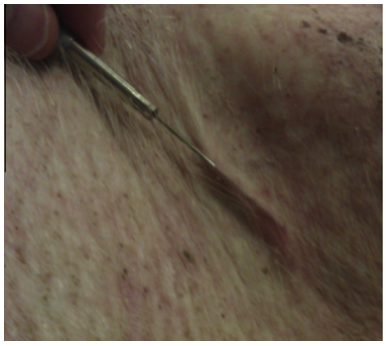

Fig. 2. An example of an inserted needle temperature probe. The probe was inserted in the outer layers of the skin with the measurement sensor immediately under the skin.

2.2.4. Acquisition of infrared thermographs

Emissivity was set to 1.00 in the IRC (model SC660, Flir Systems, Wilsonville, Oregon, USA). Distance was set to 50 cm. The IRC spatial resolution was 640 × 480 pixels. It was equipped with a 24° lens, resulting in a skin surface pixel dimension of 0.325 mm × 0.325 mm at the 50 cm distance. ROI was the skin area at which the temperature needle probe tip was underneath.

A rod with the length 50 cm was held between the IRC and the skin ROI to maintain the correct distance. The IRC was focused at 50 cm distance. This was important, because a blurry thermograph is basically averaging neighboring pixel temperature values. The result of this would be worst when measuring between-hair temperatures, because the colder hair tips would lower the between-hair pixel temperatures.

Three thermal images were acquired almost perpendicularly to the skin ROI. Human skin reflects more specular than Lambertian at wavelengths measureable by the IRC used in this study (Villasenor-Mora et al., 2009). To avoid effects of specular reflection of heat radiation emanating from the camera and operator, the camera was tilted slightly from the perpendicular axis. This measurement procedure was followed for all three skin ROIs: the shoulder, udder, and ear base. The order in which the skin area measurements were performed was randomized.

The sow was then euthanized with an injection of pentobarbital through a major ear vein. After a wait time of at least 5 min, measurements were acquired again in the same way as described above. Again, the order in which the three skin ROIs were measured was random.

To test the effect of hair on emissivity, the hair was clipped on the shoulder ROI. Some sows were clipped before ($N = 3$) and the rest after ($N = 7$) euthanasia. Hair clipping of the shoulder ROI was carried out after the IR measurements were made of the three ROIs (shoulder, udder and ear base). Clipping left only short (<2 mm) hair stubs in a small spot (approx. 1.5 cm × 4 cm) under which the needle probe was located. The clipping procedure did not scrape the skin, removing any of the outer skin layers, which could affect the emissivity. Three thermographs were acquired of the clipped shoulder ROI.

2.3. Infrared measurement parameters

The IRC used in this study was sensitive in the 7.5–13.5 μm spectral band. This band is well-suited for measuring physiologic temperatures. Wien's displacement formula states that the peak radiation intensity emitted from an object with temperature of

30 °C is at the wavelength of 9.6 μm. Based on the measured intensity of this electromagnetic radiation and some parameters describing the measurement scenario, the IRC is able to calculate the temperature of the radiating surface area. The measurement scenario can be described by a measurement formula (Flir Systems, 2010) and isolating the radiation emanating from the object only, the actual voltage measured by the sensor elements becomes:

$$U_{obj} = \frac{1}{\varepsilon\tau}U_{tot} - \frac{1-\varepsilon}{\varepsilon}U_{refl} - \frac{1-\tau}{\varepsilon\tau}U_{atm} \quad (1)$$

In simplified terms, U_{obj} is the calculated output voltage for the object with temperature T_{obj}, U_{tot} is the measured output voltage for the pixel elements, U_{refl} is the voltage output emanating from the radiation reflected in the surface and U_{atm} is the voltage output emanating from the radiation stemming from the molecules in the atmospheric air. ε is the emissivity and τ is the transmission. In this work where the room was near equilibrium, the temperatures of the walls, ceiling and air were equal, resulting in a U_{refl} depending only on ambient room temperature, T_{amb}. This was confirmed in two ways by measuring the reflected apparent temperature prior to the first and after the last measurement on each sow, with correctly adjusted object parameters (distance, T_{amb}, relative humidity, emissivity set to 1.00) in the IRC. This temperature is a good approximation of the radiation emanating from reflection. First, the temperature of the ceiling and walls was measured. Second, a piece of highly reflective aluminum foil (first crumbled then unfolded to ensure a diffuse, Lambertian radiation reflection) was put on the floor area. The average surface temperature of the aluminum foil was measured by a circular ROI with 20 pixel radius. The reflection temperatures of both methods were within 1.5 °C of the measured air temperature T_{amb}.

The IRC requires the following parameters to perform the actual object temperature calculation: object emissivity, the temperature of the object surroundings (usually close to the ambient temperature), air temperature, distance between the object and IRC and relative humidity of the air. The order in which the parameters are listed is usually also the sequence of importance to the actual temperature calculation. One should note that if the emissivity of the object is 1.00, the reflection temperature is irrelevant, since no radiation is reflected in the object surface. The lower the emissivity, the more impact the reflection temperature has on the IR measurements. Basically, the "perfect" scenario to measure with IRT is if there is no medium (vacuum) between the object and IRC, and if the object emissivity is 1.00. Then the only term left on the right side of formula (1) is U_{tot}.

2.4. Data analysis

2.4.1. Emissivity calculation

The stored thermal images were analyzed using ThermaCam Researcher Pro 2.10 (Flir Systems, Wilsonville, Oregon, USA). The correct ambient temperature and relative humidity values were entered according to their values measured during the experiments. With updated object parameters, each thermal image was saved as a Matlab file.

Traulsen et al. (2010) showed that using either the maximum, or averages of the top-10% or top-25% pixel temperature values in the ROI of IR measured surface area exhibits higher correlation to core body temperature in animals than minimum and average pixel temperature values. To avoid using noise values, the max. pixel temperature value was not chosen. Instead the median of the top-5% pixel temperature values (from now on called $T_{top5\%,median}$) was calculated. By doing this, the impact of noise pixels were reduced, or in best case removed, while still using a close to maximum temperature value found inside the ROI. The ThermaCam Researcher Pro 2.10 software does not allow for this calculation. Due to this and that the output of calculated temperatures were limited to one decimal place, a proprietary Matlab (Matlab R2012b, Mathworks, Natick, MA, USA) algorithm was made for subsequent calculations. In the Matlab algorithm, the skin ROI was defined graphically for each thermal image by defining a ROI circle of the skin area under which the needle probe was located. The skin ROI was either 4 or 10 pixels in radius, corresponding to only 1.3 mm and 3.25 mm, respectively. The $T_{top5\%,median}$ in the ROI was calculated and the correction factor of 0.20 °C was added to all calculated $T_{top5\%,median}$. This corrected skin temperature (from now on called $T_{skin,IRT}$) was then subtracted from the needle probe temperatures ($T_{skin,needle}$), which had been corrected with their individual second order calibration. Ideally, the temperature difference between $T_{skin,needle}$ and $T_{skin,IRT}$ was attributed to the emissivity of the skin not being 1.00.

The emissivity (ε) was calculated by changing the emissivity in the following formula (2) until it matched the temperature difference between the skin temperature measured by the needle probes ($T_{skin,needle}$) and the IRC ($T_{skin,IRT}$).

$$T_{skin,needle} - T_{skin,IRT} = \frac{C_2}{\lambda Ln\left(1 - \frac{1}{\frac{\varepsilon}{1-e^{\frac{C_2}{\lambda T_{skin,needle}}}} + \frac{1-\varepsilon}{1-e^{\frac{C_2}{\lambda T_{room}}}}}\right)} - T_{skin,needle} \quad (2)$$

C_2, also known as the second radiation constant and defined as 1.4388×10^{-2} m K in ITS-90 (Preston-Thomas, 1990), is given by $h * c_0/k$, where h is Planck's constant (6.63×10^{-34} J s), c_0 is the speed of light in vacuum (299,792,458 m s^{-1}), and k is Boltzmann's constant (1.38×10^{-23} J K^{-1}). Temperatures in formula (2) are in Kelvins. λ was chosen to 9.5 μm due to the IRC bandwidth being specified by the manufacturer to be sensitive in the 7.5–13.5 μm spectral band. Choosing a specific wave length instead of the spectral range gives a negligible difference in this application.

Three emissivity values were calculated per site per sow. Three sows were measured three times at the ear base, udder, shoulder (unclipped) and shoulder (clipped) while alive and three times at the ear base, udder, shoulder (clipped) while dead (total of 99 measurements). The other seven sows were measured three times at the ear base, udder, shoulder (unclipped) while alive and three times at the ear base, udder, and shoulder (clipped) and shoulder (clipped) while dead (total of 111 measurements). If the calculations resulted in an emissivity above 1.00, it was set to 1.00.

2.4.2. Statistical analysis

The emissivity (based on median of top-5% IR temperatures) was analyzed as continuous dependent variables in a mixed model in PROC MIXED of SAS (v. 9.3, SAS Institute Inc., Cary, NC, USA). Site (udder, shoulder, ear base, and clipped shoulder), state (dead, alive), humidity and ambient room temperature were included as fixed effects.

The emissivity (based on average IR measurements) was analyzed as continuous dependent variables in a mixed model in PROC MIXED of SAS (v. 9.3, SAS Institute Inc., Cary, NC, USA). Site (shoulder and clipped shoulder) and ambient temperature were included as fixed effects.

The interaction between sow, state and site was included as a random variable in both analyses. A pair-wise comparison of means for the included variables was conducted. *P*-values were based on the Satterthwaite approximation for the denominator degrees of freedom. The difference between the three measurements performed at the individual sites was tested with a variance analysis, showing no difference. Data are reported as means ± SE

Table 1
Calculated emissivities (estimates of least square means ± standard errors) for the skin site and alive/dead effects. The calculations were based on median of top-5% IR measured temperatures.

Factor	Level		DF	*p*-value
State	Dead	0.960 ± 0.0042	63	0.062
	Alive	0.972 ± 0.0046		
Site	Ear base [a]	0.978 ± 0.0057	63	0.0018
	Udder [a]	0.975 ± 0.0057		
	Shoulder (hairy)[a,b]	0.946 ± 0.0062		
	Shoulder (clipped)[a,b]	0.964 ± 0.0073		

[a,b] Significance level: $p < 0.05$.

and considered significant when *p*-values were <0.05 and as a tendency when $0.05 < p < 0.1$.

3. Results

The lowest and highest skin temperatures measured by the needle probes inserted under the skin were 25.9 °C (clipped shoulder on a dead sow, T_{amb} = 16.6 °C) and 34.8 °C (ear base on a living sow, T_{amb} = 18.6 °C), respectively.

We found an overall effect of site and a trend for state (see Table 1). A trend of a difference between emissivity of the hairy and clipped shoulder was also found ($p = 0.07$). No effect of T_{amb} or humidity was found.

The importance of including the hairs in the emissivity calculation was tested by calculating the emissivity of the shoulder based on average pixel temperature values instead of on median of top-5% IR temperatures, $T_{top5\%,median}$. When using the average values, the emissivity of the hairy shoulder was lower compared to the clipped shoulder (0.904 ± 0.008 vs. 0.934 ± 0.009; $p = 0.02$).

4. Discussion

The results show that emissivity of bare sow skin is similar to that reported for human skin (Gartner and Gopfert, 1964; Gartner et al., 1964; Hardy, 1934; Sanchez-Marin et al., 2009; Steketee, 1973; Togawa, 1989; Villasenor-Mora et al., 2009).

The degree of hair density varied between the sows used in this study. This may account for some of the variability in calculated emissivity values. This was especially important in the shoulder region, where the hair coat was so dense, that in some cases the actual skin was difficult to see visually through the hairs. This resulted in different temperature values measured by the needle probes and IRT that were not attributed only to the emissivity of the skin. Moreover, the hair may actually increase the emissivity of a skin area due to the cavity effect (Bedford and Ma, 1974; Sapritsky and Prokhorov, 1992). However, the IRC should have an adequate resolution, able to detect the higher temperatures between the hairs, without averaging them with the colder hair tip temperatures as described by Kelly et al. (1954). Sows in this study with high hair density exhibited lower calculated emissivity values than the sows with less shoulder hairs. This was attributed to the hairs being so dense that $T_{top5\%,median}$ also included hairs in the calculation. The cavity effect described may also apply slightly to the ear base in some cases. If the ear base has a "pocket" or a groove, which depends on the angle of the ear flap, this may give a cavity, elevating the emissivity of that particular skin area.

Skin with blood perfusion had higher emissivity than without blood perfusion. The skin with no blood perfusion was not necessarily dead tissue, as the measurements were performed within approx. an hour after the sows had been euthanized. Why the blood perfusion makes a difference in skin emissivity is difficult to say and we cannot explain it. However, if there indeed is an effect as found in humans (Gartner and Gopfert, 1964; Gartner et al., 1964), it will impact the IR temperature measurements for skin areas with much thermoregulation. In colder surroundings, the blood perfusion to these skin areas is lowered. In addition to the skin getting colder, IRT may measure the skin temperature too cold, due to the lower skin emissivity, and incorrect emissivity entered in the IRC. This may explain some of the inconsistent results from other studies investigating pig skin temperatures using IRT.

Changes in skin emissivity due to blood perfusion may be interesting in human studies as well and could be of interest in circulation studies (Sivanandam et al., 2012; Skala et al., 2010; Szentkuti et al., 2011) including diabetes diagnosis using IRT and estimation of time of death in forensic studies (Ammer and Ring, 2005; Edelman et al., 2013).

The impact of room temperature was found to have an insignificant effect on the calculated emissivity values; both when calculation was based on average pixel temperatures as well as $T_{top5\%,median}$. However, hairs themselves could have a very high emissivity. Hammel (1956) reported very high emissivity (most with $\varepsilon \approx 1.00$) of fur in arctic mammals, but to our knowledge, a similar study has not measured the emissivity of pig hair.

The needle temperature probes were so small and near the surface of the skin, that the temperature can be assumed to be the same on the skin as under the skin where the probes were located. This is particularly true in this study, where the sows were treated with Zoletil mix, which is known to have a vasodilating effect, resulting in a lower heat gradient between the needle probe and the outer surface. In some cases, such as shoulder skin, the needle would stretch the outer layers of the skin, potentially changing the properties of the skin, and thus its emissivity. This may be less pronounced in looser skin of the ear base and the udder. However, this effect was to some degree avoided by including more surrounding skin area in the ROI definition for the $T_{top5\%,median}$ calculation. In most cases the ROI circle was with a radius of 10 pixels, however, in cases with high hair density, the radius was lowered to 4 pixels. This would include less hair in the ROI, which otherwise could affect $T_{top5\%,median}$.

An additional test was carried out to see how much impact the correction of 0.20 °C had on the emissivity calculations for the measurements performed while the sows were alive. While the standard deviations remained roughly the same, the impact on the average values was large. The highest change in standard deviation was for the ear base, where the corrected standard deviation was 0.002 lower than its uncorrected counterpart. Using the lower uncorrected IR measured skin temperatures in the emissivity calculation lowered the emissivity by an average of 0.018. The difference in emissivity between the sites was not impacted much by the correction.

In 11% of the calculations the correction resulted in an emissivity value higher than 1.00 due to $T_{skin,needle}$ being lower than $T_{skin,IRT}$. When this happened, the emissivity was set to 1.00, since value greater than 1 are impossible. We believe that the results are still valid, since these values can be explained by uncertainties and assumptions. No measurements were removed for the data analysis. In 4.3% of the calculated emissivities the value was below 0.89. They were all of the shoulder ROI.

The emissivities found in this study are higher than those found in other studies. Metternick-Jones and Skevington (1992) found lower emissivity values when they investigated the emissivity of skin on pig carcasses in chillers in a similar way as in this study. Their reference thermometer was thermo probes inserted through the carcass from the side of the rib cavity, but where on the other side of the carcass the probe came out to measure the subcutaneous temperature was not explained in detail. Speculating from the description in the article they may have measured dead skin on the side that had been treated, with the hairs removed. This process

may have changed the emissivity of the skin considerably, which may explain the difference to our results. They found emissivity values between 0.8 and 0.93, while we found and emissivity of 0.96 for a comparable site; the clipped shoulder.

Kelly et al. (1954) did not describe their emissivity calculation in detail. They investigated pigs weighing between 180 and 260 lbs (82–118 kg) with a radiometer measuring radiation from a hairy skin area, including temperatures of hairs and skin in between hairs. They adjusted their emissivity value to 0.955 due to other investigations performed on humans (Hardy, 1934) and some on pigs (private communication, no reference). Which skin area they investigated was not described, but their results should be and are indeed comparable to the shoulder skin area results in this work. These can also be compared to the results from Gariepy et al. (1989) who used the tape method to measure the emissivity of the dorsal area in two slaughter pigs and found it to be 0.95. The tape method may be slightly problematic when the tape is applied to a hairy area. Air pockets between the hairs could lower the tape surface temperature, which may result in inaccurate emissivity calculation.

Furthermore, none of the mentioned emissivity studies performed on pigs included sows weighing 250+ kg as in this study. As mentioned earlier, the hair coat density is higher on such older animals and also the skin composition itself may be different.

Our results are within the reported emissivity values found in other studies investigating human skin (Gartner et al., 1964; Hardy, 1934; Sanchez-Marin et al., 2009; Steketee, 1973; Togawa, 1989; Villasenor-Mora et al., 2009). Even though the studies on human skin have been performed under more controlled environmental conditions than the pig skin emissivity studies, there is still a wide range of found emissivities (0.93–1.00). Is it possible to compare the human skin emissivity to that of the pig skin? Our study supports that it is. There are issues with the coarser and hence higher hair density found in pigs. However, pigs do have proper skin areas with little or no hair, where the skin is bare, e.g. the ear base and the udder.

When using IRT for measuring the body surface temperatures in sows it is necessary to measure surfaces that are dry, clean and without much hair. In doing so the measurements may be used to detect temperature anomalies that may be caused by disease. It is however imperative to keep in mind that it is only the surface temperature that is measured. The body core temperature can only be estimated indirectly. If looking for elevated body temperatures due to fever, factors like ambient temperature, environmental conditions and thermoregulation should be accounted for. However, the emissivity of skin was found to be between 0.96 and 0.98 in living sows in this study. With an emissivity that high, it is possible to measure absolute temperature using IRT with good degree of certainty, making IRT a potential reliable method for fever detection.

5. Conclusion

The bare-skinned surface areas in sows were found to have emissivity values comparable to that of humans. However, pigs have a denser hair coat than humans, with hair density increasing with age. The presence of hairs and reduced blood perfusion to the skin must be taken into account in the IR measurements as they lowered the emissivity values in this study.

The results presented here indicate that bare sow skin has emissivities between 0.96 and 0.98 in the 7.5–13.5 μm wavelength range. Using standard long-wave microbolometer IR cameras that are sensitive in this range may be used for accurate, reliable bare skin temperature measurements, if the conditions are right and the equipment is calibrated. Correcting for thermoregulation, these skin temperature measurements may be used for temperature related surveillance health screening, even fever detection. However, to ensure reliable measurements in animal facility situations, a guideline including general recommendations should be prepared in future research, similar to the recommendations for fever screening humans (IEC, 2008).

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References

Ammer, K., Ring, E.F.J., 2005. Application of thermal imaging in forensic medicine. Imaging Sci. J. 53, 125–131.
Bedford, R.E., Ma, C.K., 1974. Emissivities of diffuse cavities: isothermal and nonisothermal cones and cylinders. J. Opt. Soc. Am. 64, 339–349.
Chung, T.H., Jung, W.S., Nam, E.H., Kim, J.H., Park, S.H., Hwang, C.Y., 2010. Comparison of rectal and infrared thermometry for obtaining body temperature of gnotobiotic piglets in conventional portable germ free facility. Asian Australas. J. Anim. Sci. 23, 1364–1368.
Collin, A., Vaz, M.J., Le Dividich, J., 2002. Effects of high temperature on body temperature and hormonal adjustments in piglets. Reprod. Nutr. Dev. 42, 45–53.
Dewulf, J., Koenen, F., Laevens, H., de Kruif, A., 2003. Infraroodthermometrie is Ongeschikt Voor de Detectie van Koorts bij Varkens (in Dutch, with English abstract). Vlaams. Diergen. Tijds. 72, 373–379.
Edelman, G.J., Hoveling, R.J.M., Roos, M., van Leeuwen, T.G., Aalders, M.C.G., 2013. Infrared imaging of the crime scene: possibilities and pitfalls. J. Forensic. Sci. 58, 1156–1162.
Flir Systems, 2010. User's manual – FLIR 600 series. Publ. No. 1558550, Revision a442, English.
Gariepy, C., Amiot, J., Nadai, S., 1989. Ante-mortem detection of Pse and Dfd by infrared thermography of pigs before stunning. Meat Sci. 25, 37–41.
Gartner, W., Gopfert, H., 1964. Topographische Untersuchungen Uber Die Strahlungseigenschaften der Lebenden Menschlichen Haut. Pflugers Arch. – Eur. J. Physiol. 280, 224–235 (in German).
Gartner, W., Gopfert, H., Ling, K., 1964. Uber Die Abhangigkeit der Temperaturstrahlung der Lebenden Menschlichen Haut Von der Durchblutung. Pflugers Arch. – Eur. J. Physiol. 280, 236–242 (in German).
Hammel, H.T., 1956. Infrared emissivities of some arctic fauna. J. Mammal. 37, 375–378.
Hardy, J.D., 1934. The radiation of heat from the human body III. The human skin as a black-body radiator. J. Clin. Investig. 13, 615–620.
Henken, A.M., Brandsma, H.A., Vanderhel, W., Verstegen, M.W.A., 1991. Heat-balance characteristics of limit-fed growing pigs of several breeds kept in groups at and below thermal neutrality. J. Anim. Sci. 69, 2434–2442.
IEC, 2008. Medical Electrical Equipment-part 2–59 Standard: Particular requirements for the basic safety and essential performance of screening thermographs for human febrile temperature screening. IEC 80601-2-59. International Electrotechnical Commission.
Jiang, L.J., Ng, E.Y.K., Yeo, A.C.B., Wu, S., Pan, F., Yau, W.Y., Chen, J.H., Yang, Y., 2005. A perspective on medical infrared imaging. J. Med. Eng. Technol. 29, 257–267.
Kelly, C.F., Bond, T.E., Heitman, H., 1954. The role of thermal radiation in animal ecology. Ecology 35, 562–569.
Loughmiller, J.A., Spire, M.F., Dritz, S.S., Fenwick, B.W., Hosni, M.H., Hogge, S.B., 2001. Relationship between mean body surface temperature measured by use of infrared thermography and ambient temperature in clinically normal pigs and pigs inoculated with *Actinobacillus pleuropneumoniae*. Am. J. Vet. Res. 62, 676–681.
Machin, G., Chu, B., 2000. High-quality blackbody sources for infrared thermometry and thermography between −40 and 1000 °C. Imag. Sci. J. 48, 15–22.
Magnani, D., Gatto, M., Cafazzo, S., Stelletta, C., Morgante, M., Costa, L.N., 2011. Difference of surface body temperature in piglets due to the backtest and environmental condition. Conf. Proc. Int. Soc. Anim. Hyg. 3, 1029–1032.
Malmkvist, J., Pedersen, L.J., Kammersgaard, T.S., Jorgensen, E., 2012. Influence of thermal environment on sows around farrowing and during the lactation period. J. Anim. Sci. 90, 3186–3199.
Metternick-Jones, S.L., Skevington, S.G., 1992. Evaluation of noncontact infrared thermometry for measuring the temperature of pig carcasses in chillers. Meat Sci. 32, 1–9.

Nanni Costa, L., Redaelli, V., Magnani, D., Cafazzo, S., Amadori, M., Razzauoli, E., Verga, M., Luzi, F., 2010. Preliminary study on the relationship between skin temperature of piglets measured by infrared thermography and environmental temperature in a vehicle in transit. Conf. Proc. Ital. Soc. Vet. Sci., 193–197.

Plassmann, P., Ring, E.F.J., Jones, C.D., 2006. Quality assurance of thermal imaging systems in medicine. Thermol. Int. 16, 10–15.

Preston-Thomas, H., 1990. The International Temperature Scale of 1990 (ITS-90). Metrologia 27, 3–10.

Ring, F.J., Ammer, K., Wiecek, B., Plassmann, P., Jones, C.D., Jung, A., Murawski, P., 2007. Quality assurance for thermal imaging systems in medicine. Thermol. Int. 17, 103–106.

Sanchez-Marin, F.J., Calixto-Carrera, S., Villasenor-Mora, C., 2009. Novel approach to assess the emissivity of the human skin. J. Biomed. Opt. 14, 024006-1–024006-6.

Sapritsky, V.I., Prokhorov, A.V., 1992. Calculation of the effective emissivities of specular-diffuse cavities by the Monte-Carlo method. Metrologia 29, 9–14.

Savary, P., Hauser, R., Ossent, P., Jungbluth, T., Gygax, L., Wechsler, B., 2008. Eignung der Thermographie zur Erfassung von Entzündungen an den Gliedmassen von Mastschweinen. Deut. Tierarztl. Woch. 115, 324–329 (in German, with English abstract).

Schmidt, M., Lahrmann, K.-H., Ammon, C., Berg, W., Schön, P., Hoffmann, G., 2013. Assessment of body temperature in sows by two infrared thermography methods at various body surface locations. J. Swine Health Prod. 21, 203–209.

Sivanandam, S., Anburajan, M., Venkatraman, B., Menaka, M., Sharath, D., 2012. Medical thermography: a diagnostic approach for type 2 diabetes based on non-contact infrared thermal imaging. Endocrine 42, 343–351.

Skala, T., Kolaric, D., Dujmovic, A., 2010. Extremities perfusion stimulation and dynamic evaluation by thermography analyses. Period. Biol. 112, 475–478.

Soerensen, D.D., Joergensen, E., Pedersen, L.J., 2011. Validation techniques for thermography in veterinary medicine. InfraMation 2011 Proc. 12, 35-1–35-6.

Steketee, J., 1973. Spectral emissivity of skin and pericardium. Phys. Med. Biol. 18, 686–694.

Sykes, D., Couvillion, J., Cromiak, A., Bowers, S., Schenck, E., Crenshaw, M., Ryan, P., 2012. The use of digital infrared thermal imaging to detect estrus in gilts. Theriogenology 78, 147–152.

Szentkuti, A., Kavanagh, H.S., Grazio, S., 2011. Infrared thermography and image analysis for biomedical use. Period. Biol. 113, 385–392.

Tabuaciri, P., Bunter, K.L., Graser, H.U., 2012. Thermal imaging as a potential tool for identifying piglets at risk. AGBU Pig Genetics Workshop, October 24-25, 2012. Animal Genetics and Breeding Unit, University of New England, Armidale, Australia.

Togawa, T., 1989. Noncontact skin emissivity – measurement from reflectance using step change in ambient radiation temperature. Clin. Phys. Physiol. Meas. 10, 39–48.

Traulsen, I., Naunin, K., Muller, K., Krieter, J., 2010. Untersuchungen zum Einsatz der Infrarotthermographie zur Messung der Körpertemperatur bei Sauen. Zuchtungskunde 82, 437–446 (in German, with English abstract).

Villasenor-Mora, C., Sanchez-Marin, F.J., Calixto-Carrera, S., 2009. An indirect skin emissivity measurement in the infrared thermal range through reflection of a CO_2 laser beam. Rev. Mexic. Fisica 55, 387–392.

Warriss, P.D., Pope, S.J., Brown, S.N., Wilkins, L.J., Knowles, T.G., 2006. Estimating the body temperature of groups of pigs by thermal imaging. Vet. Rec. 158, 331–334.

Wendt, M., Eickhoff, K., Koch, R., 1997. Die Messung der Hauttemperatur als Methode zur Erkennung fieberhaft erkrankter Schweine. Deut. Tierarztl. Woch. 104, 29–33 (in German, with English abstract).

Zinn, K.R., Zinn, G.M., Jesse, G.W., Mayes, H.F., Ellersieck, M.R., 1985. Correlation of noninvasive surface-temperature measurement with rectal temperature in swine. Am. J. Vet. Res. 46, 1372–1374.