RESEARCHREPORT
ANIMAL SCIENCE
pork checkoff

Title: Modeling Conductive Heat Transfer Through and Around Grow-Finish Pigs - **NPB # 16-056**

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Industry Summary

As pig genetics and feeding programs advance, the heat production and environmental needs of pigs also change. Grow-finish pigs are especially susceptible to hot weather conditions that our existing ventilation systems cannot completely mitigate. There are various ways to further cool pigs using evaporation, convection and conduction, but each heat transfer method also requires additional resource inputs in the form of water or energy, which have associated costs.

The long-term goal of this research is to understand the effects of floor temperature control on conductive heat transfer through the skin of the pig, swine performance, and management implications of utilizing this technology. An initial knowledge gap we set out to answer is ”With modern genetics and leaner pigs, how has the tissue resistance of the animals changed?” Specifically, the objectives were to: (1) Evaluate the postural (resting, standing) effects on heat flux and tissue thermal resistance; (2) Refine existing animal growth models to accommodate conductive heat transfer and activity, for modern pigs; and (3) Develop a monitoring methodology to measure the postural effects of floor tempering in group-housed animals.

Heat flux (flow of heat energy per unit area and time) measurements were collected from twelve individually-housed active barrows in the average (±standard deviation) weight ranges of 95.6±15.5 kg (210±34 lb) and 111±13.9 kg (245±31 lb), and referred to as Trials 1 and 2, respectively. Heat flux measurements were collected every minute from the right and left sides and rumps of the pigs over a six hour period. An overhead video camera system recorded pig behavior and positioning within a pen throughout the trials.

The average measured heat flux from the side of a 50 kg pig was 131 W/m^2, and the heat flux decreased 2.64 (SE 0.83) W/m^2 for every 10 kg (22 lb) increase in pig mass, up to 120 kg (265 lb). Fat and thicker skin and muscle tissue provides more resistance to heat flow, thus decreasing the rate of heat flow for a given area. The heat flux measurements were collected from a shaved area, so the variable impact of the pig’s coat was not considered.

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Tissue resistance is related to both pig mass/size and ambient temperature conditions. In the limited ambient temperature window of 20ºC to 25ºC, the tissue resistance (coat not included) for the barrows in these trials was less than tissue resistance values prescribed in the early 1990s. Tissue resistance values estimated for these project pigs suggest a minimum and maximum tissue resistance of 0.0015 and 0.014 ºC m^2/W for ambient temperatures of 39ºC and 0ºC, respectively.

Behavior monitoring provides insight into how environment influences positioning and activity, which in turn affects feed conversion. Video cameras and game cameras were used in this project, though not simultaneously. Our experience showed that the camera positioning and picture frequency were more influential than the technology used. Daily patterns of feeder occupancy and number of pigs lying on the solid floor are suitable variables to measure with time lapse or motion detection technology available in relatively inexpensive game cameras.

Heat production and flux or transfer to the environment are affected by many factors including nutritional plane, growth rate, internal temperature, environmental temperature, evaporation from the skin and respiratory tract, airflow rate, surface temperatures, and body position. This study captured heat flux data from active grow-finish pigs. In the course of detecting heat flux patterns and conditions based on the lying or standing position, the influence of other environmental factors like manure on the skin surface or air gaps were also evident. As animal and environmental models progress, including conduction along with convection and evaporation (planned and unplanned) will add more complexity, but will ultimately help us better evaluate an animal's response to varying environments and management strategies to promote efficient production and animal welfare in all conditions.

Key Findings:

- The average measured heat flux from the side of a 50 kg (110 lb) pig was 131 W/m^2, and the heat flux decreased linearly to 113 W/m^2 for a 120 kg (265 lb) pig.
- Tissue resistance estimates were 0.023 to 0.034 ºC m^2/W for 40 to 130 kg (88 to 287 lb) pigs, respectively, in the ambient temperature conditions of 22.5ºC (72.5ºF).
- Daily patterns of feeder occupancy and number of pigs lying on the solid floor are suitable variables to measure with time lapse or motion detection technology available in relatively inexpensive game cameras.

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Keywords

Grow-finish, heat flux, tissue resistance, floor cooling

Scientific Abstract

As we look to novel temperature control strategies in swine grow-finish facilities, we require updated data on heat loss data for modern genetic pigs. The project objectives were to: (1) Evaluate the postural (resting, standing) effects on heat flux and tissue thermal resistance; (2) Refine existing animal growth models to accommodate conductive heat transfer and activity, for modern pigs; and (3) Develop a monitoring methodology to measure the postural effects of floor tempering in group-housed animals. The long-term goal of this research is to understand the effect of floor temperature control on conductive heat transfer through the skin of the pig, swine performance, and management implications of utilizing this technology.

Heat flux (flow of heat energy per unit area and time) measurements were collected from twelve individually-housed active barrows in the average (±standard deviation) weight ranges of 95.6±15.5 kg and 111±13.9 kg,

and referred to as Trials 1 and 2, respectively. Heat flux measurements were collected every minute from the right and left sides and rumps of the pigs over a six hour period during each trial. An overhead video camera system recorded pig behavior and positioning within a pen throughout the trials.

When standing, the average heat flux from the rear of the pigs (124 ± 67 W/m^2) was greater than the heat flux from the sides of the animal (117 ± 60 W/m^2) ($p<0.05$, n=24). A linear regression model ($R^2 = 0.3154$, n =24) with an intercept of 145 W/m^2, suggests the heat flux decreases 0.265 W/m^2 for each 1 kg increase in pig mass. Fat and thicker skin and muscle tissue provides more resistance to heat flow, thus decreasing the rate of heat flow for a given area. The heat flux measurements were collected from a shaved area, so the variable impact of the pig's coat was not considered.

Tissue resistance is related to both pig mass/size and ambient temperature conditions. An existing model of tissue resistance related tissue resistance to pig mass and ambient temperature, between a maximum at 0ºC and minimum beyond 39ºC. Based on the limited pig mass and ambient temperature conditions of this project between 20ºC and 25ºC, the suggested minimum and maximum tissue resistance values are 0.0015 and 0.014 ºC m^2/W, which are approximately 60% of the tissue resistance estimated from the 1990s. Repeating the measurements in a broader set of ambient temperature conditions is necessary to further fine-tune tissue resistance models.

Behavior monitoring provides insight into how environment influences positioning and activity, which in turn affects feed conversion. Game cameras are a relatively inexpensive option for picture and/or video collection, for both short and long-term use. Using game cameras with movement detection, we monitored partial areas of group-housed animals over multiple days. Daily patterns in terms of feeder occupancy and number of pigs lying on the solid floor are suitable variables to measure with time lapse or motion detection with appropriate camera positioning.

As animal and environmental models progress, including conduction along with convection and evaporation (planned and unplanned) will add more complexity to heat production and transfer estimates, but will ultimately help us better evaluate an animal's response to varying environments and management strategies to promote efficient production and animal welfare in all conditions.

Introduction

Floor temperature control, or tempering, is a means of mitigating the impact of seasonality on productivity. For newly weaned pigs, providing additional heat creates a warmer microenvironment and helps ease the transition from the farrowing room. For larger animals, conductive cooling reduces heat stress while conductive heating in winter months would reduce the amount of feed energy needed by the pig for thermoregulation. With proper design, control and management, floor tempering accomplishes both heating and cooling needs in a variable climate such as the Midwest US, and this is especially needed in Wean-to-Finish barns. The costs and benefits of floor tempering, however, have not been studied since the 1970's, and the modern pig genetics we have today are much leaner and generate more heat per animal. Also, those studies occurred in a smaller research setting and not in production-scale situations.

The influence of floor tempering on pig comfort and production performance relies on conductive heat transfer, which past research has shown to be a function of tissue resistance, coat resistance and the surrounding conditions (Kelly et al., 1964; Spillman and Hinkle, 1971; McArthur, 1981). Kelly et al. (1964) and Spillman and Hinkle (1971) measured the rate of heat transfer for a limited numbers of pigs on cooled floors and found there was an optimum floor and air temperature combination, and not necessarily the lowest floor temperature tested, for maximum heat transfer from the animal through the floor. There was also significant heat movement to the floor from the surrounding air for areas not covered by animal (Kelly et al, 1964). These studies based heat flux measurements on the rate of heat gain by the surface when pigs were lying. There now exist heat flux sensors and related apparatuses that have been used to monitor heat flow from animals in dynamic environments, including swimming animals (i.e. Willis and Horning, 2005), that have not been used with modern pigs.

While various genotype-specific growth models exist, estimating the impact of the animal's thermal environment on growth requires a strong thermal balance component in a pig growth model. The NCPIG model (Bridges et al. 1992) is a process-based model that incorporates a heat balance sub-model described by Usry et al. (1992), which draws on tissue resistance estimates by Bruce and Clark (1979). The NCPIG heat balance model considers convective and radiative heat loss, but assumes the animal is continuously standing and thus no conductive heat transfer occurs. This model provides a strong base, but whose application can be strengthened with updated research on thermodynamic factors with today's pigs.

While the concept of floor tempering is not new, there are gaps in both basic and applied science principles to fill. With modern genetics and leaner pigs, how has the tissue resistance of the animals changed? Under what air and floor temperature conditions is conductive heating and cooling significant to the overall heat balance of the animal? What is the predicted impact of floor tempering on pig growth long-term for various climates? The project objectives address these three questions and more.

Innovative housing systems require evaluation of changes to animal comfort and production, energy use, environmental impact, and of course, cost. The industry will benefit from continued exploration into the function and management of microenvironment control on heat transfer and animal performance as envision and design farm production systems for the future.

Objectives

The long-term goal of this research is to enhance the energy efficiency of pigs by efficiently using floor tempering as a means of mitigating the impact of seasonality on productivity. The objectives of the research project were to:

1. Evaluate the postural (resting, standing) effects on heat flux and tissue thermal resistance;
2. Develop a monitoring methodology to measure the postural effects of floor tempering in group-housed animals; and
3. Refine existing animal growth models to accommodate conductive heat transfer and activity, for modern pigs.

Materials & Methods

Experiment 1: Measuring Heat Flux and Tissue Thermal Resistance Relative to Posture

Data Collection

Heat flux data were collected from 12 barrows in October and November of 2016 at the South Dakota State University Swine Education and Research Wean-Finish Research Unit. The experimental protocol was reviewed and declared exempt by the SDSU Animal Care and Use Committee (Approval number 16-051E).

In each of two monitoring periods, or trials, data were collected over three consecutive days for each weight range, using four pigs per day. The room ventilation control setpoint was set at 25ºC (77ºF). Four different pens with varying floor temperature setpoints were used (68ºF, 70ºF, 72ºF and no control), and every 90 minutes the animals under test rotated between pens. The pigs were restricted to the solid floor area of each pen, with feed available and access to water every 90 minutes. Floor temperature was measured by a temperature sensor embedded in the concrete of the pen floor, in addition to the room temperature. Temperature data were averaged and recorded every 30 minutes by the floor temperature control system (Metasys; Johnson Controls, Milwaukee, WI).

During each trial, heat flux sensors (HFP01, HuksefluxUSA, Center Moriches, NY) were positioned on the right and left side midway between the midline and underline at approximately the 10th rib and on the hip. Sensors were attached with Elastikon tape wrapped around the animal. The sensors were connected to a miniature data logger (UX120-006M, Onset Computer Corporation, Bourne, MA) attached using the Elastikon tape along the backbone (Figure 1).

The pigs were weighed and ultrasonically scanned for backfat depth measured prior to each trial. Rectal temperatures were collected from active pigs during Trial 2.

Before and after each test period, heat flux sensors were collocated in a water bath at temperatures of 28ºC and 36ºC to verify common response characteristics, and enable correction for the influence of the Elastikon tape.

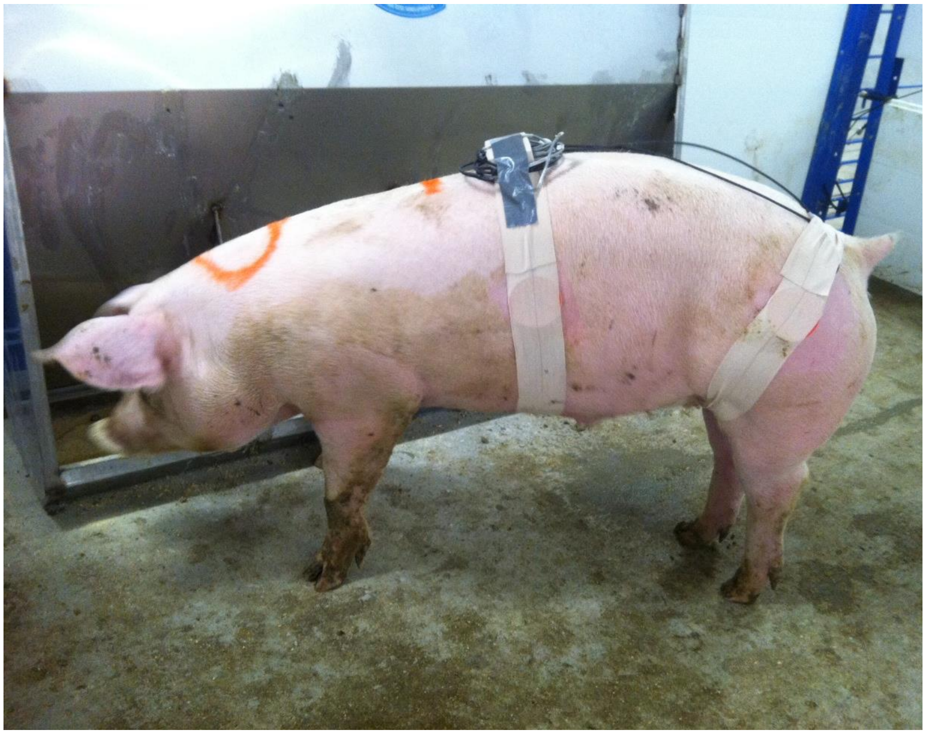


Figure 1. Heat flux sensors (appear as circles) on the left side and rear of a pig, with the datalogging system attached along the backbone.

Ceiling mounted cameras captured continuous video of pig position over the monitoring periods.

During the monitoring periods, project personnel remained in the room and noted instances of sensor displacement, activity outside of the camera view angle, and presence of manure on the sensor tape cover.

Data Processing

Recorded video were reviewed by two observers. The pig position at the start of each minute was recorded using the descriptions in Table 1. The positions noted by the two observers were compared and crosschecked for compatibility, in the event of incongruous findings the video was rechecked and position verified.

Table 1. Position descriptions for pig behavior in the current study.

Code	Description
SL	Lying on left side, all 4 legs out to side
SR	Lying on right side, all 4 legs out to side
BLW	Lying on belly, leaning to left against wall, less than 4 legs exposed
BRW	Lying on belly, leaning to right against wall, less than 4 legs exposed
BLC	Lying on belly, leaning to left without touching a side wall, less than 4 legs exposed
BRC	Lying on belly, leaning to right without touching a side wall, less than 4 legs exposed
BC	Lying on belly, without touching a side wall, less than 4 legs exposed
W	Standing or walking

F	Standing at feeder or water pan
U	Unknown
T	Sitting on back end, propped by two front legs

The minute-based heat flux data were reviewed relative to the corresponding pig position, and field notes/observations recorded during the trial. Preliminary review of the data indicated the following common instances of erroneous data: (1) manure on the sensor resulted in higher than normal heat flux measurements; and (2) an air gap between the sensor and the skin surface of the pig, which was more likely to occur if the pig was leaning against a wall or in the center of the pen, resulted in lower than normal heat flux data. The following data processing protocol was employed for limiting erroneous data:

- All data less than 60 W/m2 were voided.
- If data were higher than 160 W/m^2, the data were voided unless the sensor was possibly in direct contact with the floor (i.e. the pig was lying or leaning on the side of the sensor reporting the high heat flux values).

Data Analysis

For each pig in each trial, the minute-based measured heat flux from the right and left side sensors and the right and left rear sensors were supported by the corresponding floor temperature (based on the occupied pen), room temperature, position, and elapsed time in position. Each change in position was referred to as a new segment.

For each pig in each trial, when the pig was standing or walking (Positions W or F; Table 1), the left and right side heat flux measurements, and the average side and average rear heat flux were calculated and compared using a paired t-test (n=24, $\alpha = 0.95$). The average side heat flux, when standing or walking, also compared to the corresponding pig mass and backfat depth.

Preliminary review of the heat flux data demonstrated interesting patterns, but large variations in the heat flux from the pig to the floor when the pig was in a lying position. A whisker-box plot of the right and left side mean heat flux from each pig in each trial was created for the various lying positions.

Descriptive statistics (count, mean, standard deviation, minimum, maximum) and whisker-box plots were generated using SAS 9.4 software (SAS Institute Inc., Cary, NC). Regression and Student's t-test calculations were generated in Microsoft Excel (2016).

Experiment 2: Measuring the Postural Effects of Floor Tempering in Group-Housed Animals

Data Collection

Two pens of group-housed animals, 14 animals per pen, were monitored over 2 days. The pigs were part of a different trial reviewed and declared exempt by the SDSU Animal Care and Use Committee (Approval number 17-036E). The floor temperature of one pen was controlled to maintain a setpoint of 22ºC, while the floor temperature of the other pen was not under any temperature control scheme.

Game cameras (StealthCam, Grand Prairie, TX) were placed on a wall such that the angle of each camera captured the solid floor area of a partially-slatted floor pen. Overhead from outside of the pen space was limited by feed lines blocking the view.

This angle also captured activity by the four-space feeder. The game cameras were set to passive infrared (PIR) mode, with a delay time of 2 minutes. This means that when the PIR sensor within the camera detected motion in front of the camera the camera was instructed to capture an image. Once an image was captured the camera would be unresponsive to the motion sensor for 2 minutes. After 2 minutes the PIR sensor could call for the camera to capture an image when motion was detected. The maximum frequency of images in this configuration is one image every two minutes.

Data Processing

Camera still images were reviewed by a single observer. The number of pigs exhibiting the following behaviors were recorded along with the date and time stamp of the image:

- Feeding: wherein the pig's head is completely inside the feeder, or the rear of the pig in the background aligns with the rear of a pig who is feeding in the foreground.
- Lying: Pig is lying on its belly or side, and at least half of the pig in in the image foreground (on the solid versus the slatted floor area).

Data Analysis

The number of images for each day and pen were noted. The behavior captured in each image was assumed to represent the behavior in the proceeding minutes before the next image was captured in order to create a continuous, minute-based behavior record.

Feeder occupancy was calculated by the time-weighted average of the number of total feeder spaces (four) filled by feeding pigs.

Experiences with the game cameras are also discussed relative to the video data captured in Experiment 1.

Experiment 3: Refining Existing Animal Growth Models to Accommodate Conductive Heat Transfer and Activity, for Modern Pigs

Data Collection

Heat flux data collected as part of Experiment 1 and thermal images were used in this experiment and model evaluation. At least once during each rotation, thermal images of the pigs and the surrounding conditions were captured with a thermal image camera (Model E6; FLIR, Wilsonville, OR)

Data Processing

Thermal images were processed using FLIR Tools (version 5.9.16284.1001, Wilsonville, OR). In each time-stamped image, the surface temperatures of the side and rear sensors, two locations of the skin on either side of each sensor, and ear temperature were recorded, and the corresponding animal position and heat flux data for the respective sensor and time segment were combined.

Model of Tissue Resistance

This project focused on refining the sensible heat loss model, and in particular, the tissue resistance model (Usry et al. 1992) for warm weather conditions (>20°F) (Figure 2).

The maximum (Eq. 1) and minimum (Eq. 2) values for the model shown in Figure 2 are based on body weight and based on work by Bruce and Clark (1979). For variable ambient conditions, the tissue resistance is a function of the slope of the line between the maximum and minmum tissue resistance (Eq. 3).

$$R_{t,max} = 0.025W^{0.33} \text{ (Eq. 1)}$$

$$R_{t,min} = 0.0025W^{0.33} \text{ (Eq. 2)}$$

$$R_t = R_{t,max} + \mathrm{T}_a \frac{(R_{t,max} - R_{t,min})}{(0-39)} \quad \text{(Eq. 3)}$$

Where R_t = tissue resistance, $m^{2o}C/W$ (max: maximum, min: minimum); W = pig mass, kg; and T_a = ambient temperature, °C.

Data Processing

For the time-stamped images, the segment-average heat flux data were obtained. Position in the image versus the data were compared and verified for agreement.

For tissue resistance estimation, we assumed steady state conductive heat transfer, and that the heat flux from the pig surface through the sensor (Eq. 4) was equal to the heat flux through the pig's tissue (Eq. 5). Thus, tissue resistance estimates were based on surface temperatures captured to the side of the sensors in the thermal images (Eq 6).

$$q = \frac{(T_{skin} - T_{sensor})}{R_{sensor}} \text{ (Eq. 4)}$$

$$q = \frac{(T_{core} - T_{sensor})}{R_{sensor} + R_t} \text{ (Eq. 5)}$$

$$R_t = \frac{(T_{core} - T_{skin})}{q} \text{ (Eq. 6)}$$

Where q = heat flux, W/m^2; R_{sensor} = resistance of the sensor, $m^{2o}C/W$; and T = temperature, °C of the skin, sensor, or core.

Data Analysis

The model-based tissue resistance data (Eq. 3) were compared to measurement-based estimates using Equation 6. Using the same relationship between temperature, mass and tissue resistance, the sum of squares of differences between measured and modeled were minimized by altering the maximum and minimum tissue resistance values in the model. The correlation (R^2) and standard error for the modeled relative to the measured values were calculated for both the existing and proposed maximum and minimum tissue resistance settings.

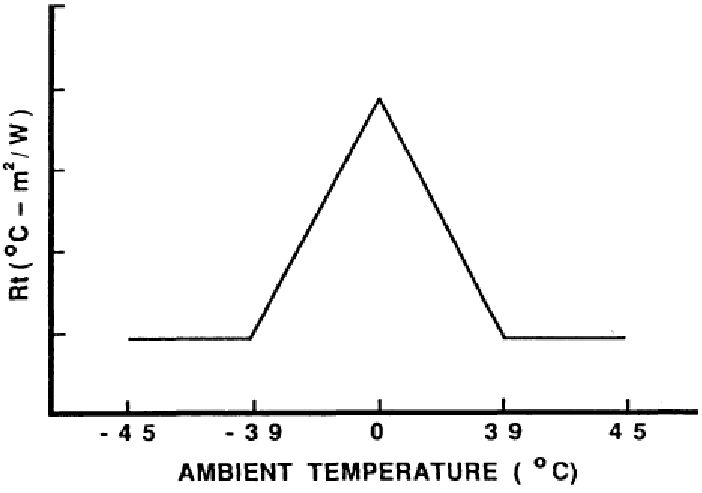


Figure 2. NCPIG model for tissue resistance (R_t) to heat flow as a function of temperature (From Usry et al. 1992).

Results

The average pig weights at times of heat flux monitoring (referred to as Trials) were 95.6±15.5 kg and 111±13.9 kg, for Trials 1 and 2, respectively. The average Trial 1 and 2 backfat measurements were 1.5±0.4 cm and 1.7±0.4 cm, respectively. Figure 3 demonstrates the relationship between pig mass and backfat depth. Average rectal temperatures were 38ºC to 39ºC.

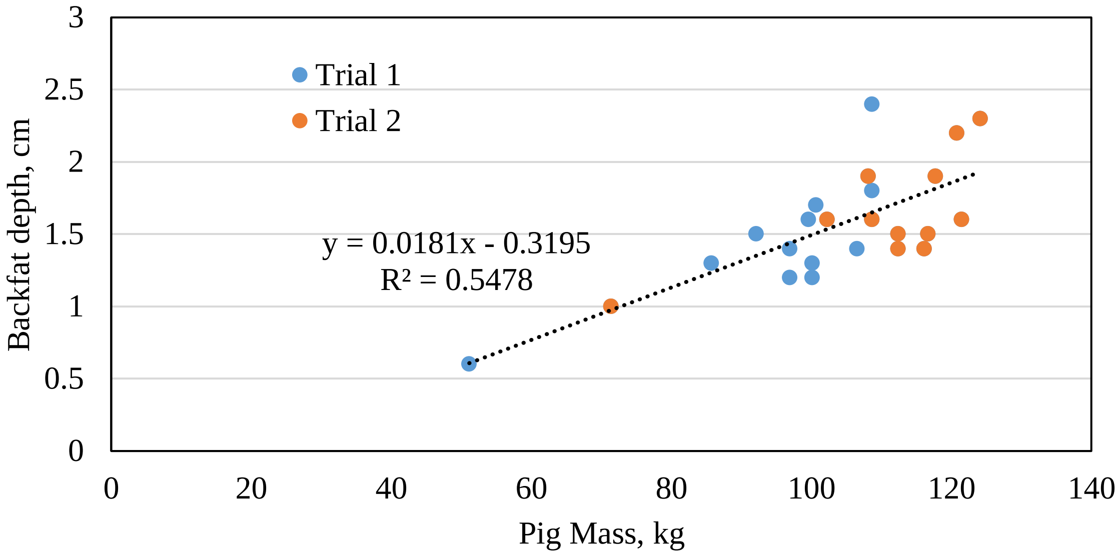


Figure 3. Backfat measurements relative to the corresponding pig mass for twelve barrows during the Trial 1 and Trial 2 monitoring periods.

Objective 1. The Postural Effects on Heat Flux and Tissue Thermal Resistance

When standing, the heat flux sensor detected the heat loss from the pig's skin to the surrounding environment. Assuming there was no acclimation to the differences in floor temperature among the pens, all data over the monitoring period were combined for each pig. When standing, there was no significant difference ($P>0.05$, df=23) in a paired t-test comparison between the average of the mean (±SD) heat flux by pig and trial from the left side of the animal (118 ± 61 W/m^2) compared to the right side of the animal (117 ± 75 W/m^2).

The mean (±SD) rear heat flux among pigs and trials (124 ± 67 W/m^2) was significantly greater ($P<0.05$, df=23) than the mean side heat flux (117 ± 60 W/m^2) based on a paired t-test and shown in Figure 4. The difference may be attributed to the likely higher proportion of fat to lean tissue in the side of the animal compared to the rear muscles.

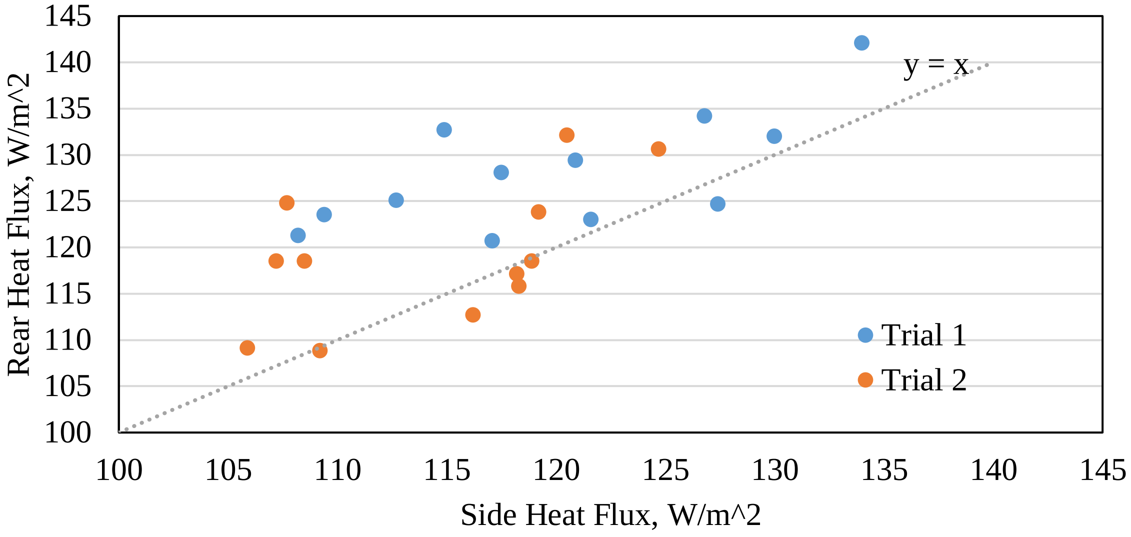


Figure 4. Mean heat flux from the rear measurements versus the side measurements for each pig in Trial 1 and 2, when the pigs were standing.

When standing, the average heat flux was linearly-related with pig mass ($P<0.01$), and less so with backfat ($P<0.1$). The average side heat flux decreased 2.64 (SE 0.83) W/m^2 for every 10 kg increase in pig mass, for the pigs under study that ranged from approximately 50 to 120 kg, as shown in Figure 5.

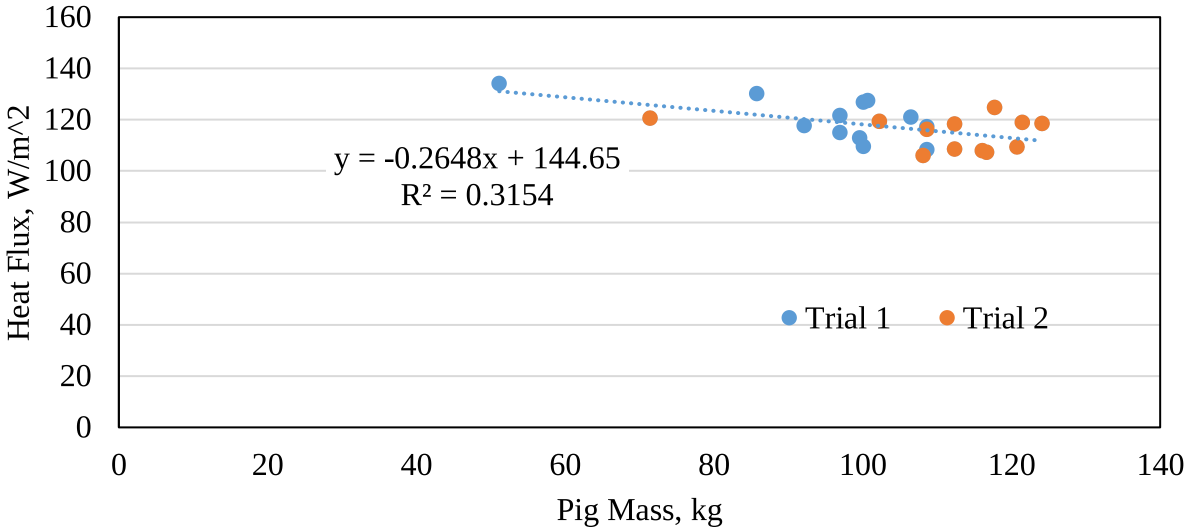


Figure 5. Mean average side heat flux measurements relative to pig mass for each pig in Trial 1 and 2, when the pigs were standing.

When lying, there was evidence of higher heat flux from the body to the floor versus body to the air. The magnitude of heat flux was variable and likely related to the specific floor temperature, the response of the floor temperature control system and the presence of water or feces between the sensor and the floor. Figure 6 demonstrates the range of the average side heat flux measurement for individual pigs in both trials. Data were only included if there were more than 10 minutes of data for the individual pig in the stated position. The difference in heat flux was more pronounced between sides when the pig was lying completely on his side, and there was the greatest contact between the floor, sensor and pig. When a pig was leaning, particularly against a wall or feeder, field notes indicate there was a greater chance of an air gap for all sensors on a pig.

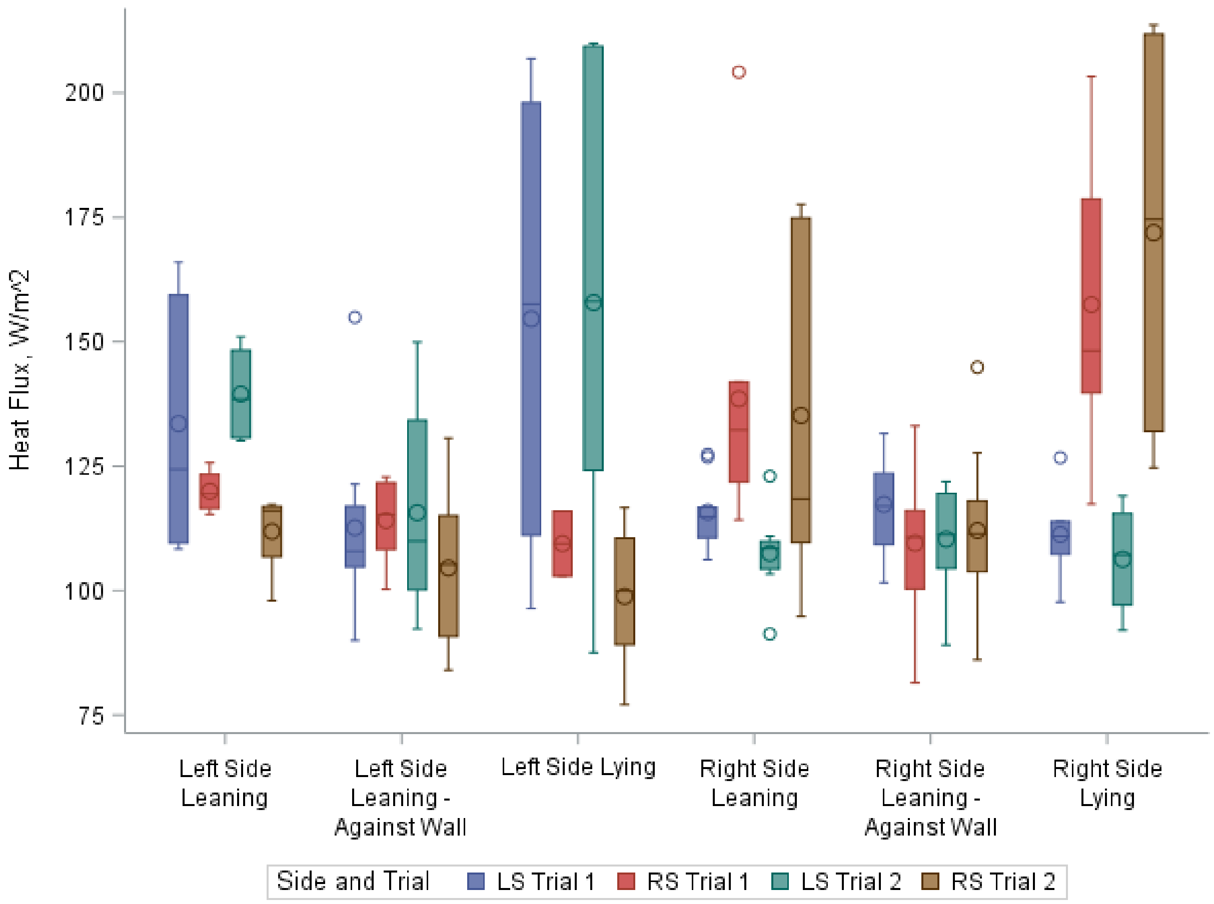


Figure 6. Average mean heat flux measurements from the left and right side of the pigs for each trial in the various lying positions. Whiskers represent the maximum and minimum, boxes represent the upper and lower quartiles, horizontal bars are the medians, solid-filled circles are the means, and hollow-circles are outliers.

Objective 2. A Monitoring Methodology to Measure the Postural Effects of Floor Tempering for Group-Housed Pigs

Using game cameras, there are numerous options for the timing of pictures (and videos, depending on the camera model). This project used two different game camera models, but a common setting and camera placement.

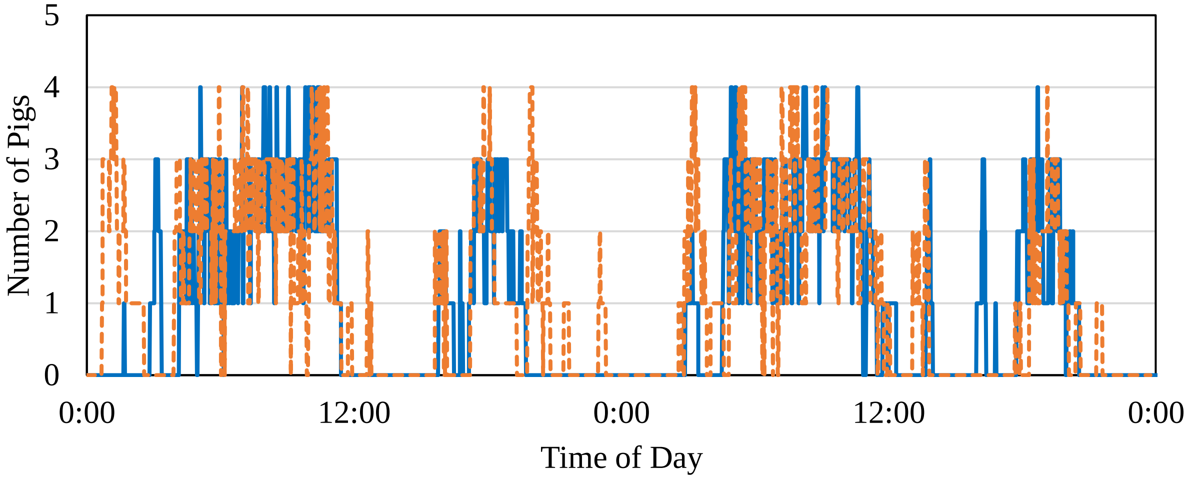
Example images of group-housed pigs when room lighting is on and off are shown in Figure 7 for two pens monitored with the two camera types. Lighting did not seem to affect the observer’s ability to record lying and feeding behavior.

Lying behavior can be captured from multiple angles. From our experiences reviewing the game camera stills and video (in Experiment 1), a side angle makes it easier to differentiate between standing and lying on belly positions, compared to a direct overhead image. When video is available, animal activity and movement can support differentiating standing and belly lying behavior.

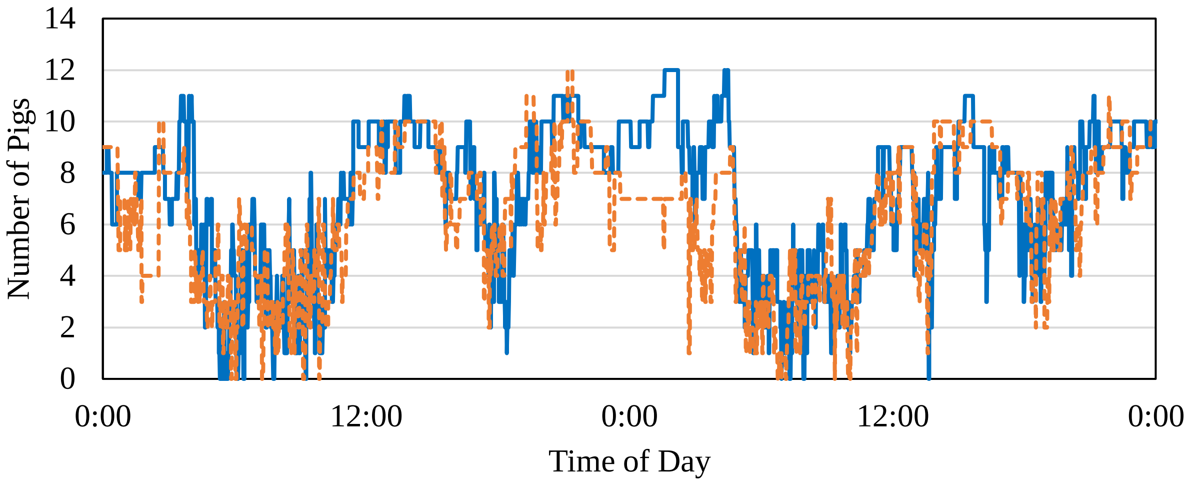
The observer’s ability to count the number of pigs feeding at one time was more susceptible to the camera angle. Feeding space was limited to one pig per space for the pigs in Figure 7. Thus the observer was able to count the number of backs, rumps or sets of legs in the feeder area, with a maximum of four pigs in the general area. For smaller pigs and variable feeder spaces, an overhead or higher-angle image would be more conducive for behavior monitoring.

Figure 7. Example game camera images used to monitor feeding and lying behavior. Left images are from a different model of game camera than the right images, for periods with (top) and without (bottom) room lighting. For example, top left image shows four pigs feeding and 2 pigs lying on the solid floor.

Over the 2-day monitoring period, the lying and feeding patterns were inverse of one another, with the greatest feeding activity in the morning and evening. Additional data is required to investigate differences in behavior relative to floor temperature conditions.



(a)



(b)

Figure 8. Number of pigs observed feeding (a) and lying on the solid floor (b) over two days in a pen without (solid blue) and a pen with (dashed orange) floor cooling, using game camera images.

With a minimum 2-minute picture frequency, 1440 images per pen for the 2-day monitoring period were possible. The PIR setting of the cameras reduced the number of images for review to 704 images for the pen without floor cooling, and 834 images for the pen with floor cooling.

Applicability of the method will depend on barn and pen layout and dimensions. The following are some general comments on the use of game cameras to monitor posture of group-housed animals:

- Desired behaviors should dictate the camera angle. Capturing lying behavior benefits from a lower side angle (e.g. 45º), whereas monitoring feeding behavior would benefit from an overhead or higher side angle (e.g. 60º).
- When installed on the back wall in a pen, ladders should be avoided with pigs in the pen. Thus, for frequent removal, a lower position (within worker reach) is important.
- Camera mounts that facilitate quick and easy camera removal are possible, but should ensure a consistent angle among cameras.
- Camera images will include insignia of the camera manufacturer, however, the images can also include the time stamp and temperature in some cases (subject to verification).

Objective 3. Tissue Resistance of Modern Pigs to Accommodate Conductive Heat Transfer and Activity Models

The tissue resistance values for the pigs are shown in Figure 9. The tissue resistance values were calculated based on measurements collected from the sides and rears of animals exposed to the air, for animals in both laying and standing positions. The tissue resistance measurements do not include the influence of hair in limiting heat loss from a pig’s body. McArthur (1981) suggests the thermal resistance offered by the coat may be 10 times that of the tissue or the environment.

The model proposed by Usry et al. (1992), and based on work by Bruce and Clark (1979) assumes that subcutaneous tissue depth is proportional to pig mass to the exponent 0.33, and that the level of vasoconstriction and tissue resistance changes as a function of ambient temperature. For a 40-kg pig, the predicted resistance is 0.036 to 0.045 m^2 ºC /W for a temperature range of 25 to 20ºC. At 130 kg, the nominal and range of tissue resistance values for an ambient temperature range of 25 to 30ºC increases to 0.053 to 0.067 ºC m^2/W. The Usry et al. (1992) model did not capture the variability and nominal tissue resistance values measured, as reflected by a low R^2 value of 0.138 and standard error of 0.0037.

Using the same relationship between temperature, mass and tissue resistance, the sum of squares of differences between measured and modeled were minimized using a minimum and maximum tissue resistance of 0.014 and 0.0015 ºC m^2/W, respectively. The R^2 between the proposed model estimated and measured tissue resistance values remained low at 0.138. However, the standard error between the proposed model and measured values was decreased to 0.0018.

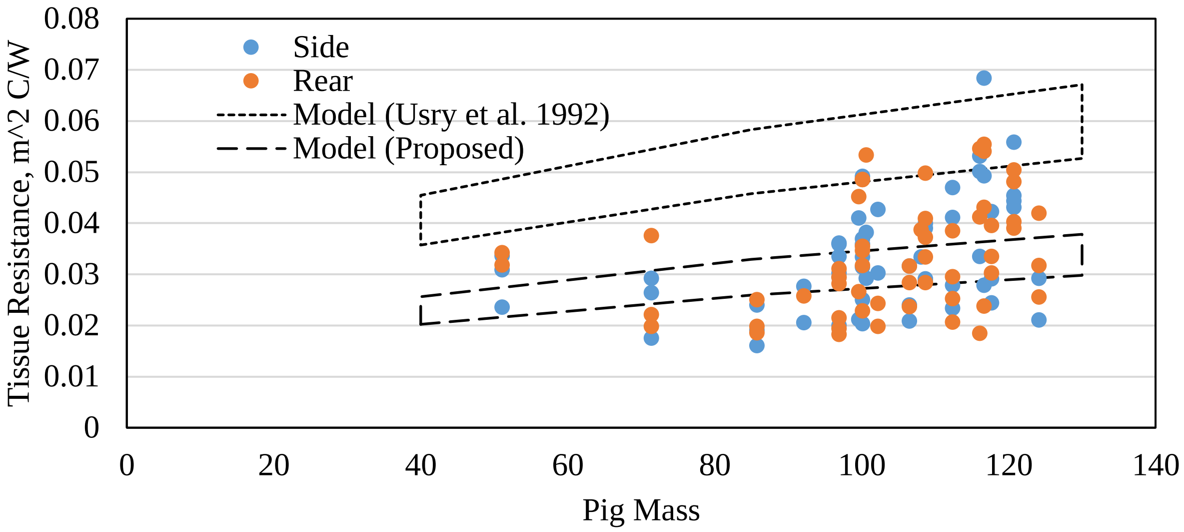


Figure 9. Measured tissue resistances in this study compared to the range of model-estimated tissue resistances for ambient temperature conditions between 20ºC and 25ºC, using minimum/maximum tissue resistance factors of 0.0025/0.025 ºC m^2/W (Usry et al., 1992) and 0.0015/0.014 ºC m^2/W (Proposed).

Discussion

The heat flux data collected in Objective 1 were highly variable with time, and were greatly supported by minute-based behavior monitoring data. Considerable data processing was needed to reduce variation from external factors. The influence of manure and wet conditions on the skin/sensor surface were evident, and reflect common conditions for active animals. Smaller heat sensors that can be easily glued to the skin surface may reduce some noise caused by air gaps. Animal growth models that consider conductive heat transfer can be fine-tuned by considering both the position of the animal, as well as the degree of fouling of the pig and/or surrounding area.

The average measured heat flux values for 96 kg pigs were 117 and 124 W/m^2 from the side and rears of the animals, for ambient temperature conditions between 20ºC and 25ºC. Spillman and Hinkle (1971) reported heat flux measurements between 123 and 192 W/m^2 for three 68 kg pigs, for floor and air temperatures of 24ºC and 28ºC, respectively. This previous study also demonstrated large variability in heat flux data between animals. The higher heat flux rates may be attributed to the absence of the air boundary layer when heat absorbed by the floor was measured.

Heat flux measurements from the pig to the floor, for pigs in a lying position, often showed initially high heat flux, followed by decreasing heat flux measurements with time. For a constant floor temperature, this would indicate a change in tissue resistance over time. However, thermal images wherein a pig had recently moved from a laying position indicate that the floor temperature under the animal increases as well from absorbed animal heat loss. Thus, the decreasing heat flux is likely related to both a chance in vasoconstriction within the pig's tissue, but also a decreasing temperature gradient between the pig's internal temperature and skin surface/floor surface.

Objective 2 was meant to serve as proof of concept for a long-term methodology to monitor standing versus lying behavior, to ultimately relate behavior to pig growth and feed efficiency with tempered floor conditions. Feeding behavior monitoring was also possible given the camera positioning in this project. The proposed approach is relatively low-cost and low-complexity. Data storage, view angle, lighting, picture quality and image type and frequency are highly variable among cameras. However, these cameras are typically weatherproof and are provided video viewing software, making them flexible for use in a barn environment. The appropriate frequency depends on what you are matching the behavior up to.

This project was the first to collect heat flux data directly from active pigs in both standing and lying positions. Variations in heat flux were largely attributed to changes in the external environment, like the presence of moisture and degree of contact with the floor surface. Tissue resistance data showed a trend of increasing with pig mass per a previously proposed relationship with surface area. Conversely, heat flux decreased with increasing pig mass. Additional data will fine-tune the relationship of tissue resistance with pig mass and ambient temperature conditions. However, it appears that the tissue resistance of modern-day pigs is considerably lower than previously measured. This means there is even more potential for cooling mechanisms to improve the comfort of pigs and in turn, pork production. However, cost-efficient means to deliver this cooling still need to be realized.

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